TOOL AND MANUFACTURING ENGINEERS HANDBOOK

FOURTH EDITION

VOLUME VIII
PLASTIC PART MANUFACTURING

A reference book for manufacturing engineers, managers, and technicians

Philip E. Mitchell, CMfgT
Handbook Editor

Produced under the supervision of the SME Publications Resources Committee

Society of Manufacturing Engineers
One SME Drive
Dearborn, Michigan 48121
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The first edition, published as the Tool Engineers Handbook in 1949, established a useful and authoritative editorial format. It was successfully expanded and improved in the publication of highly acclaimed subsequent editions. Further expansion of the Handbook is needed because of advances in manufacturing technology, increasing competitive pressure, and a significant diversification of information requirements for modern manufacturing.


The scope of this edition is multifaceted, offering a ready reference source of authoritative manufacturing information for daily use by engineers, managers, and technicians, yet providing significant coverage of the fundamentals of manufacturing processes, equipment, and tooling for study by the novice engineer or student. Uniquely, this blend of coverage has characterized the proven usefulness and reputation of SME Handbooks in previous editions and continues in this edition to provide the basis for acceptance across all segments of manufacturing.

In this, and other TMEH volumes, in-depth coverage of all subjects is presented in an easy-to-read format. Each chapter has an extensive bibliography compiled to provide further user resources. A comprehensive index cross-references all subjects, facilitating quick access to information. The liberal use of drawings, graphs, and tables also speeds information gathering and problem solving. Because the number of new TMEH volumes has increased, a master index of all of the handbooks is now available.

The contributors and reviewers in this volume are listed at the beginning of each chapter. No written words of appreciation can sufficiently express the special thanks due to these professionals. Their work is deeply appreciated by the Society; but more important, their contributions will undoubtedly serve to advance the understanding of manufacturing throughout industry and will certainly help spur major productivity gains in the years ahead. Industry as a whole will be the beneficiary of their dedication. Much effort was made to acknowledge other material used in the book and is listed in the references section of each chapter.

Philip E. Mitchell
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- **John Coleman**
  Director of Publications
- **Karen Wilhelm**
  Publications Manager
- **Philip Mitchell**
  Handbook Editor
- **Larry Binstock**
  Senior Editor
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- **John Edwards**
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  Editor
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- **Sandi Suggs**
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**TYPESETTING**
- **Kathy Allison**
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**GRAPHICS**
- **Donna Hicks**
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The Society of Manufacturing Engineers, headquartered in Dearborn, Michigan, USA, is an international professional society dedicated to serving its members and the international manufacturing community through the advancement of professionalism, knowledge, and learning. The specific goal of the Society is to advance scientific knowledge in the field of manufacturing and to apply its resources to research, writing, publishing, and disseminating information. “The purpose of SME is to serve the professional needs of the many types of practitioners that make up the manufacturing community. The collective goal of the membership is the sharing and advancement of knowledge in the field of manufacturing for the good of humanity.”

The Society was founded in 1932 as the American Society of Tool Engineers (ASTE). From 1960 to 1969, it was known as the American Society of Tool and Manufacturing Engineers (ASTME), and in 1970, it became the Society of Manufacturing Engineers. The changes in name reflect the evolution of the manufacturing engineering profession and the growth and increasing sophistication of a technical society that has gained an international reputation for being the most knowledgeable and progressive voice in the field.

Associations and Groups of SME—The Society provides complete technical services and membership benefits through a number of associations and groups. Each serves a special interest area. Members may join these associations and groups in addition to SME. They are:

- Association for Electronics Manufacturing of SME (EM/SME)
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- Forming Technologies Association of SME (FTNSME)
- Machine Vision Association of SME (MVA/SME)
- Machining Technology Association of SME (MTNSME)
- North American Manufacturing Research Institute of SME (NAMRI/SME)
- Plastics Molders and Manufacturers Group of SME (PMMG/SME)
- Rapid Prototyping Association of SME (RPNSME)
- Robotics International of SME (RI/SME)

Members and Chapters—The Society has more than 70,000 members in 70 countries, and sponsors some 300 chapters, districts, and regions, as well as 240 student chapters worldwide.

Publications—The Society is involved in various publications activities encompassing handbooks, textbooks, videotapes, and magazines. Current periodicals include:

- Manufacturing Engineering
- Forming & Fabricating
- Manufacturing Insights (a video magazine)
- SME Technical Digest
- SME News
- Journal of Manufacturing Systems

(cont)
Technical Quarterlies:
Composites in Manufacturing
Electronics Manufacturing Engineering
Machining Technology
Plastics
Rapid Prototyping
Robotics Today
The Finishing Line
Vision

Certification—This SME program formally recognizes manufacturing managers, engineers, and technologists based on experience and knowledge. The key certification requirement is successful completion of a two-part written examination covering (1) engineering fundamentals and (2) an area of manufacturing specialization.

Educational Programs—The Society sponsors a wide range of educational activities, including conferences, clinics, in-plant courses, expositions, publications, educational/training media, professional certification, and the SME Education Foundation.
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<thead>
<tr>
<th>Symbol</th>
<th>Abbreviation</th>
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</thead>
<tbody>
<tr>
<td>ABA</td>
<td>Acrylonitrile-butadiene-acrylate</td>
</tr>
<tr>
<td>ABFA</td>
<td>Azobisformamide</td>
</tr>
<tr>
<td>ABS</td>
<td>Acrylonitrile-butadiene-styrene</td>
</tr>
<tr>
<td>ABS/PVC</td>
<td>Acrylonitrile-butadiene-styrene/polyvinyl chloride (blend)</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>ACS</td>
<td>Acrylonitrile, chlorinated polyethylene, and styrene</td>
</tr>
<tr>
<td>ADC</td>
<td>Allyl diglycol carbonate</td>
</tr>
<tr>
<td>AEC</td>
<td>Atomic Energy Commission</td>
</tr>
<tr>
<td>AFD</td>
<td>Automatic frequency control</td>
</tr>
<tr>
<td>AFDMA</td>
<td>Acrylonitrile/methyl methacrylate</td>
</tr>
<tr>
<td>AN</td>
<td>Acrylonitrile</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>APPS</td>
<td>Amorphous polyphenylene sulphide sulfone</td>
</tr>
<tr>
<td>ASA</td>
<td>Acrylic-styrene-acrylonitrile</td>
</tr>
<tr>
<td>ASR</td>
<td>Automotive shredder residue</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ATBN</td>
<td>Ammonium terminated nitrile rubber</td>
</tr>
<tr>
<td>ATH</td>
<td>Aluminum trihydrate</td>
</tr>
<tr>
<td>AVP</td>
<td>Added-value polymers</td>
</tr>
<tr>
<td>BA</td>
<td>Butyl acrylate</td>
</tr>
<tr>
<td>BCB</td>
<td>Bisbenzocyclobutene (monomers)</td>
</tr>
<tr>
<td>BDO</td>
<td>Butanediol</td>
</tr>
<tr>
<td>BeCu</td>
<td>Beryllium copper</td>
</tr>
<tr>
<td>BMC</td>
<td>Bulk molding compound</td>
</tr>
<tr>
<td>BMI</td>
<td>Bismaleimide</td>
</tr>
<tr>
<td>BOPE</td>
<td>Biaxially oriented polyethylene</td>
</tr>
<tr>
<td>BOPP</td>
<td>Biaxially oriented polypropylene</td>
</tr>
<tr>
<td>BOPS</td>
<td>Biaxially oriented polystyrene</td>
</tr>
<tr>
<td>BPO</td>
<td>Benzoyl peroxide</td>
</tr>
<tr>
<td>Br</td>
<td>Bromine</td>
</tr>
<tr>
<td>BR</td>
<td>Butadiene rubber</td>
</tr>
<tr>
<td>Btu</td>
<td>British thermal unit</td>
</tr>
<tr>
<td>BUR</td>
<td>Blowup ratio</td>
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</tbody>
</table>

### C-D-E

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Carbon, Celsius</td>
</tr>
<tr>
<td>C-PET</td>
<td>Crystallized polyethylene terephthalate</td>
</tr>
<tr>
<td>CA</td>
<td>Cellulose acetate</td>
</tr>
<tr>
<td>CAB</td>
<td>Cellulose acetate butyrate</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>Calcium carbonate</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-aided design</td>
</tr>
<tr>
<td>CAD/CAM</td>
<td>Computer-aided design/computer-aided manufacturing</td>
</tr>
<tr>
<td>CAF</td>
<td>Computer-aided engineering</td>
</tr>
<tr>
<td>CAFE</td>
<td>Corporate average fuel economy</td>
</tr>
<tr>
<td>CAID</td>
<td>Computer-aided industrial design</td>
</tr>
<tr>
<td>CAM</td>
<td>Computer-aided manufacturing</td>
</tr>
<tr>
<td>CAP</td>
<td>Cellulose acetate propionate</td>
</tr>
<tr>
<td>CAS</td>
<td>Chemical abstract service</td>
</tr>
<tr>
<td>CASING</td>
<td>Cross-linking by Activated Species of Inert Gases</td>
</tr>
<tr>
<td>CB</td>
<td>Carbon black</td>
</tr>
<tr>
<td>CBA</td>
<td>Chemical blowing agent</td>
</tr>
<tr>
<td>cc</td>
<td>Cubic centimeter</td>
</tr>
<tr>
<td>CE</td>
<td>Concurrent engineering</td>
</tr>
<tr>
<td>CEF</td>
<td>Controlled environment foaming</td>
</tr>
<tr>
<td>CF</td>
<td>Cresol-formaldehyde</td>
</tr>
<tr>
<td>CFC</td>
<td>Chlorofluorocarbons</td>
</tr>
<tr>
<td>CIM</td>
<td>Computer-integrated manufacturing</td>
</tr>
<tr>
<td>CI</td>
<td>Chlorine</td>
</tr>
<tr>
<td>CLTE</td>
<td>Coefficient of linear thermal expansion</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeter</td>
</tr>
<tr>
<td>CMC</td>
<td>Carboxylic cellulose</td>
</tr>
<tr>
<td>CMMS</td>
<td>Computerized maintenance management system</td>
</tr>
<tr>
<td>CN</td>
<td>Cellulose nitrate (celluloid)</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer numerical control</td>
</tr>
<tr>
<td>COE</td>
<td>Coefficient of expansion</td>
</tr>
<tr>
<td>COF</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>CP</td>
<td>Cellulose propionate</td>
</tr>
<tr>
<td>CPE</td>
<td>Chlorinated polyethylene</td>
</tr>
<tr>
<td>CPET</td>
<td>Crystalline polyethylene terephthalate</td>
</tr>
<tr>
<td>CPVC</td>
<td>Chlorinated polyvinyl chloride</td>
</tr>
<tr>
<td>CR</td>
<td>Chloroprene rubber</td>
</tr>
<tr>
<td>CS</td>
<td>Casein</td>
</tr>
<tr>
<td>CSA</td>
<td>Canadian Standards Association</td>
</tr>
<tr>
<td>CSG</td>
<td>Constructive solid geometry approach</td>
</tr>
<tr>
<td>CSM</td>
<td>Chopped-strand mat</td>
</tr>
<tr>
<td>CTA</td>
<td>Cellulose triacetate</td>
</tr>
<tr>
<td>CTBN</td>
<td>Carboxylic terminated nitrile rubber</td>
</tr>
<tr>
<td>CTFE</td>
<td>Chlorotri fluor oethylene</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>CVD</td>
<td>Chemical vapor deposition</td>
</tr>
<tr>
<td>D</td>
<td>Derivative</td>
</tr>
<tr>
<td>DAC</td>
<td>Dially chloro enate</td>
</tr>
<tr>
<td>DAF</td>
<td>Dially fur arate</td>
</tr>
<tr>
<td>DAIP</td>
<td>Dially isophthalate</td>
</tr>
<tr>
<td>DAM</td>
<td>Dially maleate</td>
</tr>
<tr>
<td>DAOP</td>
<td>Dially orthophthalate</td>
</tr>
<tr>
<td>DAP</td>
<td>Dially phthalate</td>
</tr>
<tr>
<td>DBP</td>
<td>Dibutyl phthalate</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DCF</td>
<td>Directed-chopped fiber</td>
</tr>
<tr>
<td>DCP</td>
<td>Dicapryl phthalate</td>
</tr>
<tr>
<td>DEHP</td>
<td>Di (2-ethylhexyl) phthalate</td>
</tr>
<tr>
<td>DFM</td>
<td>Design for manufacturability</td>
</tr>
<tr>
<td>DFMEA</td>
<td>Design failure mode and effects analysis</td>
</tr>
<tr>
<td>DGEBAn</td>
<td>Diglycidyl ether of bisphenol A</td>
</tr>
<tr>
<td>DIBK</td>
<td>Diisobutyl ketone</td>
</tr>
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<td>DIDA</td>
<td>Diisodecyl adipate</td>
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<tr>
<td>DIDP</td>
<td>Diisodecyl phthalate</td>
</tr>
<tr>
<td>DIP</td>
<td>Deutsches Institut für Normung</td>
</tr>
<tr>
<td>DINP</td>
<td>Diisononyl phthalate</td>
</tr>
<tr>
<td>DIOA</td>
<td>Diisooctyl adipate</td>
</tr>
<tr>
<td>DIOP</td>
<td>Diisoctyl phthalate</td>
</tr>
<tr>
<td>DMDI</td>
<td>Diphenylmethane diisocyanate</td>
</tr>
<tr>
<td>DMT</td>
<td>Dimethyl terephthalate</td>
</tr>
<tr>
<td>DNP</td>
<td>Dinonyl phthalate</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>DOA</td>
<td>Dioctyl adipate</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of experiments</td>
</tr>
<tr>
<td>DOI</td>
<td>Gloss, distinctness of image</td>
</tr>
<tr>
<td>DOP</td>
<td>Dioctyl phthalate</td>
</tr>
<tr>
<td>DOS</td>
<td>Dioctyl sebacate</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>DOZ</td>
<td>Dioctyl azelate</td>
</tr>
<tr>
<td>DPCF</td>
<td>Diphenyl cresyl phosphate</td>
</tr>
<tr>
<td>DPG</td>
<td>Diphenylguanidine</td>
</tr>
<tr>
<td>DPM</td>
<td>Discrete polymer modifier</td>
</tr>
<tr>
<td>DPOF</td>
<td>Diphenyl 2-ethylhexyl phosphate</td>
</tr>
<tr>
<td>DSC</td>
<td>Differential scanning calorimetry</td>
</tr>
<tr>
<td>DTUL</td>
<td>Deflection temperature under load</td>
</tr>
<tr>
<td>DWV</td>
<td>Drain, waste, and vent</td>
</tr>
<tr>
<td>EA</td>
<td>Ethylene acid (copolymer)</td>
</tr>
<tr>
<td>EAA</td>
<td>Ethylene-acrylic acid</td>
</tr>
<tr>
<td>EAU</td>
<td>Energy-absorbing unit</td>
</tr>
<tr>
<td>EBM</td>
<td>Electron beam</td>
</tr>
<tr>
<td>EBA</td>
<td>Ethylene butyl acrylate</td>
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<td>EBXLI</td>
<td>Electron beam cross-linking</td>
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<tr>
<td>EC</td>
<td>Ethyl cellulose</td>
</tr>
<tr>
<td>ECTFE</td>
<td>Ethylene-chlorotrifluoroethylene</td>
</tr>
<tr>
<td>EDD</td>
<td>Engineering design database</td>
</tr>
<tr>
<td>EDM</td>
<td>Electrical discharge machining</td>
</tr>
<tr>
<td>E/E</td>
<td>Electronic/electrical</td>
</tr>
<tr>
<td>EEA</td>
<td>Ethylene-ethyl acrylate copolymer</td>
</tr>
<tr>
<td>EG</td>
<td>Ethylene glycol</td>
</tr>
<tr>
<td>EHA</td>
<td>Ethylhexyl acrylate</td>
</tr>
<tr>
<td>EMA</td>
<td>Ethylene methacrylate acid, electromagnetic (bonding)</td>
</tr>
<tr>
<td>EMAA</td>
<td>Ethylene methacrylic acid</td>
</tr>
<tr>
<td>EMAC</td>
<td>Ethylene methacrylic copolymer</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic interference, 2-ethyl-4-Methylimidazole</td>
</tr>
<tr>
<td>EnBA</td>
<td>Ethylene n-butyl acrylate</td>
</tr>
<tr>
<td>EP</td>
<td>Epoxy resin or epoxide</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>EPC</td>
<td>Ethylene propylene copolymer</td>
</tr>
<tr>
<td>EPDM</td>
<td>Ethylene-propylene diene rubber</td>
</tr>
<tr>
<td>EPM/EPDM</td>
<td>Ethylene-propylene monomer/ethylene propylene diene monomer</td>
</tr>
<tr>
<td>EPR</td>
<td>Ethylene-propylene rubber</td>
</tr>
<tr>
<td>EPS</td>
<td>Expanded polystyrene</td>
</tr>
<tr>
<td>ESCA</td>
<td>Electron spectroscopy for chemical analysis</td>
</tr>
<tr>
<td>ESCR</td>
<td>Environmental stress crack resistance</td>
</tr>
<tr>
<td>ESD</td>
<td>Electrostatic discharge</td>
</tr>
<tr>
<td>ESR</td>
<td>Electroslag remelt, electron-spin resonance spectroscopy</td>
</tr>
<tr>
<td>ETE</td>
<td>Engineering thermoplastic elastomer</td>
</tr>
<tr>
<td>ETFE</td>
<td>Ethylene-tetrafluoroethylene</td>
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<tr>
<td>ETO</td>
<td>Ethylene oxide</td>
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<td>EV</td>
<td>Efficient vulcanization</td>
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<td>Ethylene-vinyl acetate</td>
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<td>EVOH</td>
<td>Ethylene-vinyl alcohol</td>
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<td>F</td>
<td>Fluorine</td>
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<td>Federal Aviation Administration</td>
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<td>M</td>
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<td>---</td>
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</tr>
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<td>LC</td>
<td>Liquid chromatography</td>
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<td>LCB</td>
<td>Long-chain branching</td>
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<td>LCM</td>
<td>Liquid-composite molding</td>
</tr>
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<td>LCP</td>
<td>Liquid-crystal polymer</td>
</tr>
<tr>
<td>L/D</td>
<td>Length-to-diameter ratio</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low-density polyethylene</td>
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<td>The Society of the Plastics Industry, Inc.</td>
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<td>yd³</td>
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**SYMBOLS**

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<td>Copyright sign</td>
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<tr>
<td>°</td>
<td>Degree sign</td>
</tr>
<tr>
<td>α</td>
<td>Greek alpha</td>
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<tr>
<td>B</td>
<td>Greek beta</td>
</tr>
<tr>
<td>µ</td>
<td>Greek mu, also a prefix meaning micro (one-thousandth of)</td>
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In the manufacturing world, plastic processors have always played an integral role in moving products to market quickly. Since the plastic industry’s infancy, the efficient way that many molders have worked with their customers has been a major factor in this group’s tremendous growth. Today, manufacturing in general is desperately trying to increase efficiencies and improve productivity, and the plastics industry is no exception.

BUSINESS ENVIRONMENT

The marketplace clearly wants no more tradeoffs and is driving manufacturers to bring better products to market faster, with higher quality and lower cost. Major factors in this business environment are:

- Shorter product life cycles (five years on the average and as short as two years).
- A need for fast-paced innovation and more differentiation.
- A more consumer-conscious buying attitude with sensitivity to quality, service, and responsiveness.
- Rapidly changing niche markets (here today, gone tomorrow).
- Globally based competition.
- Rapidly improving and changing manufacturing technologies.
- Outsourcing of services to supplier base.

To be successful, molders must be innovative in the implementation of the latest technologies to compete in today’s time-based marketplace. Technology tools such as computer-aided design/manufacturing (CAD/CAM), computer numerical control (CNC) machining, solid modeling, stereolithography (SLA), and simulation software are finally achieving the labor savings promised ten years ago. The issue of concern today is no longer “Do they work?” but rather “How do I optimize the potential power available in these technology tools?”

COST CONTROL FACTORS

Studies by various companies have shown that design decisions made during new product development directly affect between 70 and 80% of final manufacturing costs (see Fig. 1-1). An example is making a choice between a screwed-together assembly and two parts that snap together. The snap-fit design has much lower assembly costs than the screwed-together parts, yet the tooling is cheaper with the screwed-together version. Such choices occur throughout the design process and ultimately define the final manufacturing process.

Other choices involving material, labor, and overhead offer a very limited opportunity to reduce the product cost once a design direction is chosen. A designer’s decision to use nylon for material leaves very few opportunities for a buyer of nylon to affect the overall cost, since the price varies little among suppliers. A designer, on the other hand, could make a design choice that would eliminate the need for an engineering resin and permit the use of a commodity resin, a potential 50% cost savings.

Figure 1-2 illustrates the “cradle to grave” costs of a manufactured product. Notice that although design has the greatest influence on these total costs, it is the smallest contributor, typically 5% or less. Over the long term it is material that is generally the largest cost in manufacturing. The lesson to learn, if you are a designer, is to make sure the molder and material supplier are involved in the design process.

This chapter illustrates how to properly execute the issues of design for manufacturability (DFM) and concurrent engineering (CE) so that these cost multipliers are prevented. Although most of the examples and illustrations will focus on injection-molded products, the basic principles apply to all plastic processing methods.

DESIGN FOR MANUFACTURABILITY

Design for manufacturability (DFM) is one of the fundamental components of the product development process. Design for manufacturability considers all of the customer’s demands, technology constraints, and the manufacturing process throughout the entire product design process. Traditional product development tends to address these issues sequentially rather than as a simultaneous activity, with the result that manufacturing provides input after the product design is frozen (see Fig. 1-3).
Slow product development evolved in the 1960s when the National Aeronautics and Space Administration (NASA) initiated the concept of phased project planning. This is a wonderfully seductive process that sequentially steps a project from department to department, each getting involved when it is its turn. The sequential process is a loosely coupled group of operations, many adding nothing to the final product value. Each functional area gets involved only when it is its turn, which often makes backtracking impossible and the cost of redesign excessive. Phased project planning worked in the business climate of the 1960s, but it does not work in the globally competitive marketplace of today.1

**DFM INPUTS**

Design for manufacturability considers input from many directions and tries to give manufacturing an equal voice. When done correctly, a new product development process considers many aspects. Table 1-1 lists a few of the most common considerations.

<table>
<thead>
<tr>
<th>Function</th>
<th>Cost</th>
<th>Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivery</td>
<td>Quality</td>
<td>Tolerancing</td>
</tr>
<tr>
<td>Reliability</td>
<td>Serviceability</td>
<td>Shipping</td>
</tr>
<tr>
<td>Safety</td>
<td>Ergonomics</td>
<td>Upgrading</td>
</tr>
<tr>
<td>Customization</td>
<td>Styling</td>
<td>Differentiation</td>
</tr>
<tr>
<td>Recycling</td>
<td>Processing</td>
<td>Pollution</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Marketing</td>
<td>Packaging</td>
</tr>
</tbody>
</table>

(Courtesy CIM Press)

When this synergistic approach is achieved, a development process similar to that in Fig. 1-4 is possible. Marketing reflects the voice of the customer, while engineering utilizes existing technology to meet the customers’ demands, and manufacturing makes sure everyone is aware of capabilities and limitations. Because the concept of DFM is based on simple communication across functional lines, the process works best in smaller companies where everyone knows another person’s job, at least enough to get by in an emergency. All employees are intimately involved in the details of the daily business. Larger companies are trying to emulate small companies. Skunk works is a term coined by large companies to identify product development teams that are authorized to work independently of the rest of the corporation’s systems and procedures. These teams have a shortened chain of command and are empowered to make critical decisions.

Benefits of DFM in the plastics industry are the obvious ones of lower costs, higher quality, and faster to market. Benefits to the molder are designs that fit existing presses and secondary operation equipment. It is important to note that the design dictates the manufacturing process; the situation should never be the other way around. For example, if the product would be better molded in acrylonitrile butadiene styrene (ABS) with pad-printed graphics, do not mold it in polycarbonate and hot-stamp the graphics to accommodate your current molder. Finding another molder that has manufacturing capability to suit your product’s needs is the correct choice.
Positive Trends

Despite this negative aspect of the processor-customer relationship, it is important to note there are positive trends occurring between many molders and their customers. Many new plastic products are being jointly designed and developed by in-house engineering and a handful of outside suppliers, all working together as a unit. This approach is being touted as a new breakthrough in supplier-customer relations. In reality, molders and designers are returning to a working relationship that made the plastics industry successful in the first place.

It was common practice for the part designer and molder to sit down together before the design was complete to review its moldability and discuss part function. Both knew their roles well. The molder did not pretend to be the expert on the part function and the designer was willing to listen to the molder’s concerns arising from experience. Even material suppliers became involved by providing design input on how their materials could best be used. This was an efficient process that quickly got designs off the drawing board and released for tooling.

Eventually, purchasing and designers became much more knowledgeable about plastics while “procurement procedures” became the new rule to reduce the problems of direct communication. Written authorizations, competitive bids, and formal purchase orders all became commonplace. Some companies did not even allow their designers to talk to the molder.

The molding industry had to make a transition from supplying local customers, supported by an in-house sales staff, to serving larger geographical areas, supported by sales representatives. Very few of these representatives had the ability to provide a designer with design input. Even material suppliers sensed a change and focused their attention on the end users. The design-to-production process had reached a low point in terms of efficiency in the majority of customer-molder relationships.

The 1990s have witnessed a return to an early and deeper involvement by many customers with their molders. For the first time in many years, end users are starting to ask molders, material suppliers, and other experts for advice on how to reduce lead times, improve quality, and reduce costs.

Time-to-Market Issues

The initial dilemma of any major product design is that there is little time and so much that is unknown at the project outset.

Once into the project, the main obstacle to quick product development is our old linear way of doing things. Decisions in most organizations move slowly, step by step, up and down the chain of command. Each level must do its bit in order to justify its existence. The tough part comes when multiple functions (engineering, manufacturing, marketing, and sales) must cooperate to launch the new product into the marketplace. Traditionally, our ability to get people to work together across functional lines has been abysmally poor. It is not for lack of ability; we just have not been trained to do it properly.

Competitive Advantages

Three competitive advantages can occur from a fast development cycle. The most obvious but least important is that the product’s sales life is extended. A product introduced sooner usually does not become obsolete sooner. Every month added to the front end usually adds one month of extended life to the back end.

The second benefit is the increase in market share. First to market grabs 100% of the market. That historically has meant a long-term lock on the majority of the market because it is often difficult for buyers to switch to a competitor.

Higher profit margin is the third benefit. A new product has more pricing freedom because of the lack of competition. This advantage erodes over time for individual products, but the lead in the manufacturing learning curve should continue the competitive advantage to successive products.
CHAPTER 1

DESIGN FOR MANUFACTURABILITY

Few companies put as much effort on creating strategies for exploiting time as they do on budgeting, cost reduction, and sales planning. Time remains an untapped source of competitive advantage. Lost time must be viewed as a consumed resource and part of a product’s total cost.

Concurrent engineering is a relatively new term that refers to the concept of multifunctional teams working together in an effort to compress overall lead times, yet make a better product. It is a concept that works very well with plastic products. There are many overlapped activities along with a wealth of knowledge available from molders that can optimize the production phase.

CONCURRENT ENGINEERING DEFINED

Concurrent engineering (CE) is a method of product development that begins with early supplier involvement, utilizes an active multifunctional team concept, and benefits from an aggressive time-based program management style. When a molder is a participant in new product development, it is critical that the customer also believe in these concepts. When combined with technology tools, such as CAD, computer-aided engineering (CAE), CAM, stereolithography (SLA), and computer-numerical control (CNC), the benefits to the customer are maximized. When the concurrent engineering process is optimized, better products are brought to market faster, at a lower cost, and with higher quality for the customer.

The following discussion covers four elements of CE.

Four distinct phases have evolved over time to define today’s version of concurrent engineering. Each of the following four phases can stand alone and improve the product development process, but it is together that they become very powerful.

- Multifunctional teams.
- Early supplier involvement.
- Time-based program management.
- Exploitation of technology tools.

MULTIFUNCTIONAL TEAMS

The multifunctional team phase is considered on an individual and group basis. Individuals can have multiple talents; for example, a toolmaker may also be adept at design or a process technician may feel at ease in project engineering. People with multiple talents provide an invaluable service to the company as they tend to think beyond their current role and help keep the overall team size smaller. Small companies use a people-oriented process for
design and manufacturing as a matter of survival. This small company mentality is fundamental to future success.

Multifunctional groups or teams require representation from various departments. For a custom molder the team concept enters another level of complexity as customers are required to be active participants, and this often means working with other suppliers for industrial design, tooling, and automation.

EARLY SUPPLIER INVOLVEMENT

A typical custom molder will critique only the final design of a customer for moldability. This is often too late to make significant part design changes, if required. The result is a compromise for the molder and a less than optimized design for the customer.

It is very time-consuming and costly to go back to engineering for a redesign once the product hits the manufacturing phase. It often occurs that an assembly is too hard to put together or the processing window is too small; more attention to detail early on could have avoided the problem.

Cradle-to-Grave Costs

Customers fear that making a commitment to a molder without going through the competitive bid process will result in more expensive parts and a loss of control. The reality is that “cradle-to-grave” costs resulting from a molder’s contribution at the design stage will almost always beat out a competitive bid process executed later with no design input by a molder. The earlier the injection molder is allowed to participate in a multifunctional design team, the better the final molded part will be.

The designer is going to be very close to the ultimate customer’s needs and know the electronic or mechanical uniqueness of the product. What the molder offers is a perspective from the plastic manufacturing and assembly point of view. The molder’s goal is to maintain the industrial designer’s aesthetic intent while still satisfying the needs of manufacturing.

TIME-BASED PROGRAM MANAGEMENT

Program management based on time is the foundation of CE. When activities by individual team members can be overlapped without undo risk, the advantage of time compression occurs. From the molder’s perspective, the critical task leading to concurrent events is the creation of a three-dimensional (3D) database. The completion of the part design phase should end with the creation of a 3D CAD-based model. This CAD model creates the opportunity for concurrent events to happen (see Fig. 1-5). Although

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**Fig. 1-5 Three-dimensional CAD model is a critical time-to-market event that creates the proper environment for concurrent events.**
CAD technology provides the opportunity, it is often wasted in sequential execution of manufacturing events through poor time management. With proper scheduling the four events of CAE analysis, CAD-based mold design, CAM manufacturing, and part detailing can all begin at the same time.

One-stop Shop Concept

A common mistake buyers make is to outsource the individual phases of part design, modelmaking, CAE analysis, prototype tooling, and production tooling. The opportunity for feedback to people working on the next phase is lost when many suppliers are involved. Molders capable of providing a “one-stop shop” have the greatest opportunity to optimize the downstream manufacturing process. Figure 1-6 illustrates this optimized manufacturing process.

In the box labeled “CAD Modeling,” it is important to note that two-dimensional (2D) CAD modeling is not included as a critical time-to-market event. A philosophy that good molders and tool shops have adopted is that stopping the part design at 2D slows down the process overall except for the most basic of designs. Numerical control (NC) programmers and toolmakers often have problems with errors and missing information when CAD is used as an electronic drafting board. What seems like a short-cut for the part designer ends up taking more time in the tool building phase.

![Fig. 1-6 Concurrent engineering flow path for manufacturing activity.](image-url)
APPRAOCHES

Every design project has the same basic activities that must occur in order to get beyond the concept stage and into production. Shortcutting any of the nine basic steps outlined in Table 1-2 goes against the principles of DFM and can result in disappointment at the most critical phase, manufacturing. The subactivities vary with each program and require input from a multifunctional team to optimize the details of the time line. The three generic time lines in Figs. 1-7, 1-8, and 1-9 reflect these possible variations in execution. The decision factors in choosing one time line over another requires balancing the issues of risk, cost, and time.

Conservative Approach

Figure 1-7 illustrates a conservative approach to the design-for-manufacture process. Nevertheless, the elements of DFM and concurrent engineering are still utilized, as many of the nine basic steps have overlapping activities. The reason this time line is labeled conservative is that it requires a rapid tooling phase to develop the product function and/or the manufacturing process. This development process is typically applied to higher-volume products that require extensive product testing procedures before approval can be given to go into manufacturing. Typical product markets are automotive and medical. Historically these products will take well over one year to reach the marketplace.

From the plastic processor’s point of view, there is a window of opportunity in which to become involved early in the development phase (as shown on the time line). Ideally this supplier involvement would begin during the conceptual design phase before many of the design features are locked in. This window is found in all three time line scenarios.

Highest-Risk Approach

Figure 1-8 illustrates the highest-risk approach to the design-for-production process. The risk factor comes from dropping the rapid tooling phase and going directly into production tooling. All other factors being equal, this scenario brings a new product to market two months faster than the conservative approach—maybe. Eliminating the extra tooling step also reduces the overall costs—maybe. The obvious risk factor is that both the cost and time savings could disappear quickly with an unanticipated problem with product performance, tool design, or manufacturing and assembly. The cost to go back and rework designs and tooling can well exceed the cost of prototype tooling. This is not an appropriate time line scenario for products with many unknowns.

This scenario does work well for low-volume products where the future production revenue will not support two sets of tooling. This is where functional models are critical in debugging the product design. The expectations may have to be lowered when it comes to fine tuning the manufacturing process to a high-speed automated process. These products may require numerous secondary operations and manual labor as additional tooling costs cannot be justified.

Fastest-to-Market Approach

Figure 1-9 illustrates the fastest-to-market approach of program management. All other factors being equal, this approach is five months faster than the conservative approach and three months faster than the high-risk approach. The key difference is in how the rapid tooling phase is utilized. Instead of tooling built for design refinement only, it is also utilized for market entry. The penalty for speed to market in this scenario is that the total tooling costs will be the highest of all three scenarios.

This scenario fits well with products that have a potential for high volume and are sensitive to market entry timing. Consumer goods such as cameras, toys, and sporting goods fit this scenario. The single-cavity tooling will generally support filling the distribution pipeline while buying time for the molder to build multiple sets of multicavity tooling.

PROJECT MANAGEMENT

Typically, any project involving the development of multiple parts is assigned specialists. Figure 1-10 illustrates a typical program where only one person is dedicated to the program full time. Eighty percent of the people on the team have an average dedication to the program of only 10%. A better concept is to have teams with more generalists and not so many specialists.

The design team will be more effective if it has a smaller number of people who spend more time on it. A classic management failure is to assign too much work to people on new projects. A handful of key individuals tend to show up repeatedly on various projects. The justification is that these individuals are so valuable that it is important they have no idle time. The intent is to have a project wait for the key resource rather than have the resource wait for a new project. While that seems to make sense, it rarely works in practice.
The problem is that an individual’s productivity is maximum when he or she is assigned only two projects, as Fig. 1-11 shows. Research by a variety of different firms shows that the percent of value-added time drops dramatically beyond two projects. At two projects, the engineer no longer has to wait for the activities of others if involved in a single project. Instead the engineer can float back and forth between the two. The addition of multiple projects dramatically drops the time spent on value-adding tasks. Because of the increased time required for coordinating, remembering, or tracking down information, the engineer becomes a bottleneck on all assigned projects.

Fig. 1-7 Generic time-line for conservative approach to product development and production launch.

Fig. 1-8 Generic time-line for highest-risk approach to product development and production launch.
Molder and Customer Interface with CAD/CAM

A molder may have to deal with a customer’s CAD information only in the very basic formats of a 2D drawing or 3D wire-frame, but quite often the more complex part designs are surface or solid models. Regardless of the CAD system or method of part representation by the designer, the custom molder must be able to efficiently and cleanly handle the data exchange between systems.

Being able to accept the customer's database files and use them in the manufacturing side of the process is not always enough. World-class molders also provide part design assistance by putting the finishing touches on a design for manufacturability reasons. The smart companies understand that plastic part design is always a compromise between industrial designers, engineering, manufacturing, and what the end-use customer really wants. Who better to represent the manufacturing concerns of the part design than the company responsible for the molded part?

Many molders who became efficient on the CAM side of the business are finding it cost-effective to also fill in the gap on the manufacturing side of the process is not always enough.
CAD side by providing a niche service. This service started as merely a critique of the part design by a project engineer or toolmaker. The customer was always left with going back and revising the database as discussed and agreed to. This works, but is not very efficient. There are several pitfalls to this process.

- Information conveyed by the molder does not always end up on the part design as desired (for example, addition of draft in the wrong direction).
- Although a change may be agreed to between the designer and molder, unanticipated problems often crop up when the database is actually modified (for example, an interference problem with a mating part that cannot change).
- The previously agreed to changes may be overruled by a design committee back at the customer’s facility. The designer is unable to adequately defend the molder’s position on the requested change.

These miscommunication problems slow down the process by creating too much queue time and less than optimum compromises in the part design. Figure 1-12 flow-charts this more traditional process that tends to leave large chunks of queue time while the molder waits for the customer.

The more proactive approach requires interfacing with the customer’s design team earlier in the process. This concept requires the use of CAD by the molder as illustrated in Fig. 1-13. Note the more streamlined flow of work, with the molder taking a more active role rather than waiting for decisions to come from the customer.

**TECHNOLOGY TOOLS**

Technology provides the opportunity to make significant improvements in lead time reductions and make products better. People have known how to work well together for a very long time; it is the implementation of technology that provides the opportunity to optimize the process further.

The technology side of concurrent engineering is made up of four basic tools that are utilized throughout the design to manufacturing process, as illustrated in Table 1-3. These four basic tools are discussed next in this chapter.
CAD/CAM Technology

The effective use of CAD/CAM technology is a key factor in the whole time reduction and quality increase process. This computer technology provides the following advantages:

- Precise accuracy in transfer of information. Dimensions, geometry, and specifications are transferred between compatible systems without the fear of human intervention error.
- Multiple outputs from single inputs. Geometry created in the early design concept stage is easily used to create the final engineering design, stereolithography files, information for failure effect analysis (FEA) and mold flow analysis, NC cutter paths for models, prototype/production tooling, detailed drawings for quality, and secondary operations fixtures.
- Superior machining capabilities. The CAM side of today’s advanced computer power provides instructions for CNC machinery that is capable of generating complex surfaces, superior quality finishes, and highly accurate cuts for models and tooling at faster speeds than were possible as little as ten years ago.
- Revolutionize time lines. The combination of CAD, with the power of CAM, CNC machining, and stereolithography, can bring a design off the screen and into your hand in a matter of days and sometimes hours. This art-to-part concept allows more team members to provide input at an early stage.
- Opportunity for simultaneous events. The single CAD database concept provides the opportunity for several people to be making progress toward production by utilizing the final design simultaneously for SLA, machined models, simulation analysis, and tool design.
- Increased innovation and creativity. The efficient use of CAD/CAM technology can increase the speed and accuracy of the entire process, allowing more time for team members to try alternative designs, materials, and processes without jeopardizing the end date.

TABLE 1-3

<table>
<thead>
<tr>
<th>Technology Tools Available to Plastic Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
</tr>
<tr>
<td>CAD</td>
</tr>
<tr>
<td>Surfacing</td>
</tr>
<tr>
<td>Solids modeling</td>
</tr>
<tr>
<td>CAE</td>
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<tr>
<td>Mold cooling simulation</td>
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<tr>
<td>Part warpage analysis</td>
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<tr>
<td>Stress analysis</td>
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<tr>
<td>CAM</td>
</tr>
<tr>
<td>Interface for stereolithography</td>
</tr>
<tr>
<td>CNC</td>
</tr>
<tr>
<td>CNC EDM</td>
</tr>
<tr>
<td>Stereolithography machine</td>
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</tbody>
</table>

CAD Data Transfer

An issue that has plagued the custom molder and customer relationship for a long time is the exchange of CAD part geometries (databases) between systems. The subject of data exchange revolves around a standardized file format such as the Initial Graphics Exchange Standard (IGES). Exchange is a two-step process that requires a database to be converted into IGES and then translated back again into the target computer system format (Fig. 1-14).

The technology available to exchange CAD data has progressed over the years. The problem is usually a lack of knowledge by people not intimately involved with CAD on a daily basis.
Unfortunately, delays can occur in the overall process if engineers, purchasing, and sales people assume that the data exchange will be easy and clean every time.

A common mistake is thinking that IGES will transfer text from one system to another. The ability to transfer text is the exception, not the rule. A typical database exchange between molder and toolmaker consists of geometry only. Most toolmakers today are capable of building molds directly from a database. A reference print with dimensions is unnecessary and quite often a source of confusion. There are still CAD users today who do not integrate the part file with the dimensioned print. This creates confusion for the toolmaker or modelmaker when the two do not agree.

**CAD Modeling Methods**

The typical custom molder must accept CAD databases from a variety of systems and formats. Molders and their customers often have problems when trying to communicate through the world of CAD data. A basic problem is that each company has a different focus in mind when it purchases software and hardware. The molder’s focus is on the CAM side of CAD/CAM technology, as profits center on mold building. The molder does not assign as high a priority to making drawings, ease of making revisions, or parametrics capability as a part designer does. The molder’s two main concerns are reading the data from another CAD system and quickly developing cutter paths for a model or mold.

The concerns of the customer’s engineer or designer revolve around the ease of creating a database of the final design rather than manufacturing’s use of that database. The burden of resolving problems falls onto purchasing or the computer expert who recommended the system. Designers also will make the assumption that a design created in CAD can be machined and molded into a plastic part. Manufacturability is often addressed too late in the process.

Today, molders and their customers have realized that the needs of both are of equal importance. If the CAD side does not integrate well with the CAM side, there can be delays and mistakes along the way to production. The last thing a designer wants is for a toolmaker to interpret or recreate the database because all the surfaces did not transfer to the molder’s CAM package.

**2D Wire-frame**

CAD systems available today allow designers to develop their designs in various degrees of geometric precision. On the bottom of the scale are 2D drawings and on the other end of the spectrum is solids modeling. CAD systems that operate in 2D are no more than electronic drafting machines.

If a designer sends a 2D database to a molder today, the NC programmer or toolmaker will have to convert the 2D information to a 3D wire-frame. This method of using CAD is only slightly more efficient than working from a fully dimensioned pencil and paper drawing. The only advantage of 2D CAD geometry over a paper drawing is that questions about missing dimensions can be answered with an inquiry of the geometry.

Before the computer, designers and engineers were accustomed to using descriptive geometry to design products. The transition to a CAD-based design method has not been a natural one.

**3D Wire-frame**

The most common design format today is three-dimensional wire-frame. It is relatively easy to learn and brings with it a 3D quality to part design. A big disadvantage for the untrained eye is that complex parts look like a jumble of spaghetti. The transparent qualities of wire-frames make it difficult for some members of a multifunctional design team to provide input while looking at a
computer screen or even a plot on paper. The advantage is that 3D wire-frame does support a variety of other manufacturing processes and analysis programs. The limitations in terms of accurate representation of the part are:

- Inability to properly produce blended and rounded surfaces.
- Lack of information about the surface mathematics of an object.
- Inability to differentiate between the interior and exterior of the part.
- Different skills required to interpret and create than those used for board drawings.

The marketplace has driven product designs to require geometries much more complex than can be adequately described in a wire-frame format. The concept of surface modeling was introduced to accommodate the trend toward complex shapes and blends.

**History of Surfacing**

One of the earliest surfacing techniques was the Coons patch, a four-sided, curved surface component. This technique was developed in the United States in the early 1960s to design ship hulls, which required large, relatively simple curved surfaces with few radical changes in direction. The automotive industry had different needs, requiring smaller surfaces, radical direction changes, and frequent revisions for aesthetic reasons. This technology was limited by changes in boundaries only and did not allow for changes of the patch interior.

The Bezier curve, also developed in the 1960s, is a spline with fixed end points capable of being pulled by control points not on the curve itself. It offers the advantage of easier representation and manipulation of curves required in the automotive industry.

The basis spline, or B spline, was the next level in curve development, occurring in the 1970s. Although similar to the Bezier curve in its use of a control polygon, there are some differences. B splines use a succession of polynomial segments to represent a curve as opposed to Bezier’s single segment. The net result is that more complex curves are represented by a single continuous entity.

In the late 1970s rational equations were added to the B spline. The notable difference is that control points, weighted by a fourth component, allow for representation of an arc or conic without approximation.

**NURBS-Based Surfaces**

The highest order of curve in commercial use today is the nonuniform rational B splines (NURBS). Users of the various software favor systems based on the more complex formulas because they provide the user greater flexibility in constructing and manipulating a form. The nonuniform property of NURBS refers to the manner in which the curve progresses between the segment ends. As Fig. 1-15 illustrates, the ripples and loops that occur between unequally spaced points are eliminated with a NURBS-based curve.

There are three advantages to NURBS-based surfaces over other surfacing methods: fewer surfaces to construct, easier editing, and more accurate data transfer.

A critical problem with most surfacing methods is the proliferation of patches when adjacent surfaces are connected. As the number of patches increases, so will the gaps or ripples. Poor patches show up later in NC programming and CNC machining as problems to be reworked. There is an average of 75% fewer surfaces with NURBS-based designs (see Fig. 1-16). NURBS curves are considered to be low-degree geometry, which affects the number of control points per curve. NURBS allows more than 3000 control points per curve compared to Bezier’s 10–40 limit. This allows NURBS to have larger curves and to define surfaces as a single entity with a small chance of a surface wiggle (as often occurs in high-degree geometry).

Editing of surfaces is very easy in Bezier technology. The only complaint of users is that changes are global in nature. Movement of a single control point affects the entire surface. NURBS technology carries editing one step further by providing the ability to...
edit surfaces locally. This can be a time-saving feature if only minor changes are desired without redoing larger areas.

Because each higher level formula uses more variables to express a single surface, it has the mathematical capability to exactly express any surface created with a lower form. What this means for the molder or designer with NURBS capability is assurance that surface data will transfer from other systems regardless of the original format or construction technique used. Non-NURBS surfaces are converted to NURBS surfaces with no loss in accuracy. Solid-based models can also be reduced to trimmed curves and surfaces converted from IGES into NURBS; there is no IGES conversion software today that goes from one solid-based system to another.

An important distinction needs to be made in how 3D surfaces are represented. Some CAD systems project 3D shapes as a grid of X, Y, and Z coordinates. Others represent shapes as a series of parallel curves, more like equally spaced cross sections. Still others represent shapes as a mesh of perpendicularly intersecting curves. While these formats can be used to generate machine tool cutter paths, they are in fact not true representations, as much of the form remains undefined. True surfaces (such as Bezier and NURBS) use mathematical formulas to determine every point on the surface. The surface is defined as a single entity; it has no holes. With formula-based representation, the CAD/CAM models are not representations of the shape, they are the shape.

**Solid Modeling**

Solid modeling is the only CAD software capable of complete, unambiguous representation of parts. Solid models are constructed in one of two ways: with primitives or with boundary definition. Both methods build complex geometry by combining simple geometric shapes.

The constructive solid geometry approach (CSG, or primitive method), requires basic geometric shapes to be combined in building block fashion with the Boolean logic commands of union, difference, and intersection.

With boundary definitions, two-dimensional (2D) surfaces are swept through space to trace out volumes. A linear sweep extrudes the profile in a straight line. A rotational sweep produces shapes with axial symmetry, while a compound sweep moves a surface through a compound curve.

Figure 1-17 illustrates both of these methods. When solid modeling hit the marketplace initially, it could not precisely describe any geometry requiring complex blends and intersections. A method of faceting was used to approximate those curves. The computer power at that time was not capable of handling the large files that solid modeling created. Only in the last few years has the combination of increase in computer speed, reduction in hardware costs, and improved software accuracy made solid modeling a viable tool for part designers.

Most plastics processors have seen little need for solid modeling to date, as it is more a part design tool than a manufacturing software tool. For processors that have invested in solid modeling, there is usually a key customer relationship that made it justifiable.

There is progress being made to improve on the negative aspects of solid modeling. A key will be the integration of NURBS-based surfacing capability with the solid capability of associativity and parametrics. Continuous advances in computer speed may make file size a nonissue. Integrated CAM software has also been released by some software developers. So the future looks bright.
CHAPTER 1

DESIGN FOR MANUFACTURABILITY

for software integration to minimize the disadvantages of each type of system.

CAM

The financial success of a tool shop depends on a versatile and efficient CAM software package that is compatible with the customer's CAD software package. If the customer is creating part designs in solids or with NURBS surfaces and the CAM software is based on a simple surfacing package, there will be a loss of part geometry in the IGES transfer.

Most molders staff internal tool shops to handle only 50% of their tool building needs. That means they must also deal with outside tool shops that may not be able to afford the more sophisticated CAM systems available. That limits the ability to out-source parts with more sophisticated geometries. The pressure to have more sophisticated machining software comes from the increased complexity of part designs. Boxy, prismatic shapes are out of style. Free-form shapes and ergonomic concerns are in.

Today's NC programmers work from the same part database that the designer created. Most interactive graphics systems can simulate the cutter path on the display screen. This enables the programmer to watch the cutter in full animation while looking for accuracy and possible collisions or gouges. Another valuable feature on higher end CAM software is surface shading. This allows the designer and NC programmer to look at the quality of the surface on the screen before possibly wasting time running the cutter path program on a CNC machine. This technology shift has made the NC programmer responsible for developing efficient cutter paths and choosing the most efficient cutter sizes for the CNC machine operator to execute.¹⁰

Computer-aided Engineering

Computer-aiding in the molding business usually means the molder is using a software package that is capable of simulating the molding process.

The process of molding-simulation software is the same as for any other simulation software: to find and resolve problems before committing to tooling. With a skilled operator, this analysis can be very valuable in helping predict problems related to filling, warpage, stress, cooling, and gating, to name a few. The accuracy of these analysis tools has improved over the years through the efforts of user groups and constant software improvements. When combined with the increased speed of computers today, the analysis can be completed before the mold design is complete. With proper scheduling the mold filling analysis should not end up on the critical path. If the analysis brings to light a serious part design problem from the molding point of view, it then becomes part of the critical path. Mold filling analysis is not an expert engineering tool that will suggest part design or processing changes. The analysis is an iterative process that requires trial and error efforts to prove out the effect of each part design change on the molding process.

A major difficulty with most analysis software is its inability to utilize the part design database directly. Conversion software or complete re-creation of the part is often required before the analysis can be executed. The trend is continued improvement of the conversion programs that are specific for each brand of CAD software.

Modelmaking Methods

Modelmaking is a very important step in the part design process, especially in a DFM and CE environment. Like many of the other steps in the process, modelmaking also has a history of not being executed to maximize its potential contribution to overall product quality or speed to market.

Historically, particularly in the automotive industry, models were made by hand from clay or foam to help visualize the exterior appearance of a product. This was a useful step in helping the industrial designer firm up the aesthetic look that was being sought. From the manufacturing point of view, appearance models were of little help, as they were rarely shared beyond the walls of marketing and design.

For designers who are more CAD literate, appearance models are CNC machined from solid blocks of plastic or wood right from the CAD database. This has the added advantage of proving that the part is machinable and brings more skilled people into the process for valuable input. Parts for which ergonomics is a major concern benefit the most from the appearance model concept.

The next level of modelmaking is the fully functional model. These are usually CNC machined out of ABS plastic blocks with a minimum amount of fabricating to reflect the molded part as precisely as possible. Once again, the original part database is utilized for programming cutter paths, with the exterior cutter paths usually reused from the appearance model to save time. The level of complexity possible from these models is truly amazing at times.

A typical scenario is for the customer to have models machined at a modelshop where the goal is only to build a model, with no emphasis put on future manufacturability. If the molder has modelmaking capability, however, the model will be regarded and constructed as if it were a molded part and include such things as draft allowance. The molder will share the model with the tool designer, toolmakers, and manufacturing for additional input and “buy-in.”

DESIGNING WITH SOFTWARE

The benefits of computer-aided engineering are well proven for designing and manufacturing injection-molded parts. Flow analysis, for example, is used to determine wall thicknesses and processing conditions that ensure mold filling. Similarly, stress analysis is used to determine geometric details that guarantee structural requirements.

The process of plastics design, however, cannot be broken into separate entities. Key decisions, such as component geometry, material selection, wall thickness, number and position of gates, and shrinkage allowances, are interrelated. Flow affects part performance and conversely part design affects ease of manufacture.

This section proposes a methodology in which all plastic analysis software and appropriate design principles are used to determine a part design that:

- Uses material most efficiently.
- Controls the effects of flow (weld lines, orientation, differential shrinkage, and residual stresses) for acceptable part quality.
- Can be manufactured easily.
- Finalizes the design for efficient mold building.

The methodology is illustrated by optimizing a support bracket, with particular emphasis on reducing cycle time and material content.
3D PLASTIC ANALYSIS SOFTWARE

Computer-aided engineering software for plastics is numerical simulation software that shows how plastic flows, cools, shrinks, warps, and performs under varying load conditions.

Plastic analysis software is typically classified according to the process simulated. Flow analysis, for example, used to evaluate polymer flow within the mold, is used to optimize mold cavity layout, material selection, and mold processing conditions for the filling and packing phases of the molding cycle.

Heat Transfer Analysis
Three-dimensional heat transfer analysis is used to assess the effects of mold cooling on polymer flow and to optimize cooling line geometry and processing conditions. The coupling of flow and cooling analyses gives a fully dynamic evaluation of the complete molding cycle.

Warpage Analysis
Three-dimensional warpage software performs shrinkage and warpage analyses of plastic components based on flow and cooling results. The effect of processing on product geometry is simulated, and the dominant causes of warpage are isolated so that any distortion is corrected in the mold design and product tolerances are satisfied.

Structural Analysis
Three-dimensional structural analysis takes into account the effect of processing on polymer properties. The behavior of a plastic component under the influence of external effects, such as applied loads, temperature increases, and vibration, is considered. This information provides material usage and gate location for maximum structural integrity.

Special features include predicting fiber orientation and distribution for short-fiber-filled thermoplastics.

Shrinkage Analysis
Three-dimensional shrinkage analysis is used to dimension mold cavities using shrinkage values determined from grade-specific material shrinkage data and flow analysis results.

Process Optimization
The software automatically optimizes material flow within a mold by generating optimum filling and packing profiles.

Gas Flow Analysis
Gas flow analysis is used to evaluate polymer and gas flow within the mold and to optimize mold cavity layout, material selection, and mold processing conditions for the filling and packing phases of the gas injection molding cycle.

PART DESIGN OPTIMIZATION
While most of the plastic analysis products can be used separately, total design optimization comes from using all appropriate analysis software in a predefined sequence. This sequence is referred to as the optimization methodology.

Optimization Methodology
The proposed methodology involves developing the design from a basic form, continually assessing the impact of design decisions on function and manufacture. Figure 1-18 shows the analysis sequence that defines the methodology.

This methodology is applicable to a wide range of products, providing appropriate design information while minimizing design and analysis time.

Optimization begins by modeling a simple 3D computer-aided design (CAD) model with minimal rib detail or wall thickness.
variation. Rapid flow and structural analysis is then performed to determine preliminary structural and processing information. Geometry changes are made subject to this information. Design optimization continues with more detailed flow and stress analysis until filling, packing, and structural requirements are met. The mold cooling system is then designed and optimized. The optimization work is periodically checked with a warpage analysis, and corrections are made where necessary. Once geometry and processing conditions are established, a linear shrinkage analysis is performed to determine final mold sizes.

### Stereolithography Models

A newer approach to modelmaking is a method that builds models in an additive or layered process, directly from the model material, usually a photosensitive polymer or plastic powder. The trade journals have yet to agree on a generic name and have used rapid prototyping, instant prototyping, desktop manufacturing, layered prototyping, and stereolithography all to mean the same thing. The generic concept is that models are created layer by layer versus the conventional subtractive process of machining. Table 1-4 is a sample of the various layered modeling processes.

One thing all these systems have in common is that they require a solid- or surface-based CAD model in order to build the physical model. The solid database is the quickest because it is unambiguous. A surface database will require additional CAD time to clarify how the surfaces are connected. Conversion software is required, similar to that required for most CAE applications. The interface between the CAD software and modeling software is critical for ease of use.

<table>
<thead>
<tr>
<th>Company</th>
<th>Location</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D Systems, Inc.</td>
<td>California</td>
<td>Stereolithography (SLA)</td>
</tr>
<tr>
<td>BPM Corp.</td>
<td>South Carolina</td>
<td>Ballistic particle manufacturing — jetting</td>
</tr>
<tr>
<td>C-Met</td>
<td>Germany/Japan</td>
<td>Solid object ultraviolet plotting</td>
</tr>
<tr>
<td>Cubitall Ltd.</td>
<td>Israel</td>
<td>Solid ground curing (SGC)</td>
</tr>
<tr>
<td>D-MEC Ltd.</td>
<td>Japan</td>
<td>Solid creation system — stereolithography</td>
</tr>
<tr>
<td>DTM Corp.</td>
<td>Texas</td>
<td>Selective laser sintering (SLS)</td>
</tr>
<tr>
<td>E-Systems</td>
<td>Virginia</td>
<td>Jetting technology</td>
</tr>
<tr>
<td>EOS GmbH</td>
<td>Germany</td>
<td>Stereolithography</td>
</tr>
<tr>
<td>Helisys</td>
<td>California</td>
<td>Laminated object modeling (LOM)</td>
</tr>
<tr>
<td>Laser 3D</td>
<td>France</td>
<td>Stereophotolithography</td>
</tr>
<tr>
<td>Light Sculpting, Inc.</td>
<td>Wisconsin</td>
<td>Masked printing</td>
</tr>
<tr>
<td>Soligen, Inc.</td>
<td>California</td>
<td>Direct shell production casting</td>
</tr>
<tr>
<td>Stratasys, Inc.</td>
<td>Minnesota</td>
<td>Fused deposition modeling (FOM)</td>
</tr>
</tbody>
</table>

(Courtesy Rapid Prototyping Report)

The speed at which models can be created has attracted a lot of attention. A typical part that exists in solids on CAD can be created on an SLA machine in two days versus two weeks by CNC machining. The factors that slow down or speed up a CNC machined model are completely different from the factors affecting an SLA model. CNC machining is affected by the complexity of the surface, amount of detail, and surface area. SLA model building is purely a function of material volume and height. The laser solidifies material at a constant rate with no concern for the path required. Model height slows down the process slightly because the laser has to stop while the tank height is adjusted for the next layer. Figure 1-19 illustrates the SLA model building process.

The SLA models of several years ago were extremely brittle and fragile. Much work has been done to generate materials with properties similar to molded acrylonitrile-butadiene-styrene (ABS) resins. A lack of dimensional accuracy and warpage is still a problem with most shapes, due to the ultraviolet (UV) light curing process. When compared to a CNC machined model, SLA is best suited for complex parts and sizes smaller than a 10 in. (254 mm) cube. Dimensional precision of ±0.015 in. (0.381 mm) is normal with some shapes repeatable to ±0.005 in. (0.127 mm). In general, the more complex the part, the more cost-effective SLA will be compared to machining methods. Table 1-5 details these pros and cons.

#### TECHNOLOGY TOOLS IN PERSPECTIVE

In the past, there was a bias toward the technological solution. A technological home run was sought rather than the mundane series of base hits. The technology approach is not inappropriate, it is just an inappropriate place to start. Technology tools are valuable because they support the development process managed by people. A potential technology approach may be to place a CAD workstation in manufacturing so that manufacturing people can review new product designs as they develop. There are several flaws to this approach. Manufacturing engineers are generally too busy with daily “hot jobs” to even take the time to look at what is com-

<table>
<thead>
<tr>
<th>TABLE 1-5</th>
<th>Surface Modeling versus Solids Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pros</td>
<td>Intuitive to use and learn</td>
</tr>
<tr>
<td>Cons</td>
<td>Limited to prismatic designs</td>
</tr>
<tr>
<td>Import data from other systems</td>
<td>Fully associative—model to drawings</td>
</tr>
<tr>
<td>Drives all CAM-based systems</td>
<td>Parametric capabilities</td>
</tr>
<tr>
<td>Relatively low cost</td>
<td>Hidden lines removed when viewing</td>
</tr>
<tr>
<td>Speed not related to model size</td>
<td>Fast generation of 2D drawings</td>
</tr>
<tr>
<td>Difficult to learn</td>
<td>Requires fast computer</td>
</tr>
<tr>
<td>Images are difficult to view</td>
<td>No effective link to CAM</td>
</tr>
<tr>
<td>No associativity of model to drawing</td>
<td></td>
</tr>
</tbody>
</table>
ing down the pipeline. If they do take time to look, they wonder how to react to something that is continuously evolving from a state of “What is it?” to “It’s too late to change.” The basic design decisions may have occurred before a line is generated on CAD, which puts manufacturing’s involvement in CAD too late. The greatest time-saving opportunities often have little connection with technology tools, and one may be distracted from seeing the real opportunities by an unclear beginning to a new product design project. This period begins when the company could have started a project until the time it actually did.

For example, consider the time savings of completing a drawing on CAD in one hour versus two hours on the board. This is a seemingly impressive savings of 50%. The real opportunity may occur in the 20 hours the work order sat in queue, before anyone started working on it. The investment in eliminating the queue time is minimal compared to the cost of the CAD station. Instead of allowing ourselves to be dazzled by technology, we must make sure we keep things in perspective and look at the big picture.

Benefits of Technology Tools
It may be dangerous to rely on technology tools in totality, but it would be equally foolhardy to ignore the great potential that technology offers when applied properly. The benefits of technology tools come in three forms.

- Direct savings in labor. This is where CAD generally beats board-based design several times over, especially if the project is on a critical path. A side benefit is that the designer is now free to contribute in another way to the project or start another sooner.

- Reduction of technical risk. This risk reduction usually comes as a result of simulation software that uses the part-design database for analysis of the molding process or for finite-element stress analysis of the part under use. Although these analyses can consume large amounts of time, they can take place concurrently with other events, off the critical path. With complex parts and tools that are influenced by many unknown factors, simulation may still reduce the overall time cycle.

- Enhanced communication. A type of buy-in occurs when shared databases are readily available to multiple groups of people. This is especially true when all functions in the process are not located in the same place, where they would normally readily communicate.

All successful new plastic product designs are built on five basic elements: defined user requirements, part design, material selection, mold design, and manufacturing (see Fig. 1-20). It would be difficult to pick one element as more important than another. Fundamental to the execution of DFM and concurrent engineering is the multifunctional team effort that pays equal attention to each element.

Part design is successful when the voice of the customer is heard, basic needs are met, an accurate 3D database is provided by engineering, and a multifunctional team is involved in the process. Material selection is successful when a variety of potential factors are considered: customer use, environment, recycling, moldability, etc. Mold design is successful when the factors of material flow, cooling, ejection, tool life, mold component wear, etc., are considered. Manufacturing is successful when the factors of assembly, packaging, shipping, and automation are considered. Table 1-6 compares NC machining with stereolithography.

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Fig. 1-19 Schematic of stereolithography (SLA) machine.\(^{11}\)
PART FACTORS
A key principle in designing products of any kind is to consider all goals and constraints early in the process. This DFM principle applies equally well to plastic product design. At the very minimum, the issues below should be discussed as early as possible in the design process. Most importantly, they should be discussed with the molder and toolmaker.

Part Function
- Strength (impact, flexural, tensile, creep).
- Chemical resistance (acids, solvents, caustic).
- Use temperature (hot, cold, duration).
- Flammability (flame retardant, flameproof).
- Dielectric (resistivity, conductivity).
- Wear (sliding, rotating).
- Recycling (reuse, reclaim, refuse).

Part Features
- Walls.
- Ribs and gussets.
- Bosses and standoffs.
- Holes and openings.

Appearance
- Color (clear, black, white, custom).
- Finish (texture, matte, high gloss).

Assembly
- Direction of assembly (top-down best).
- Snap fits (materials, strength, tooling).
- Sonic welding (materials, strength).
- Solvent bonding (solvents, materials, strength).
- Press fits (tolerances, materials, strength).
- Mechanical fasteners (screws, metal clips, threaded inserts).

Moldability
- Parting lines (straight, stepped, contoured).
- Slide-by shutoffs (steel wear and strength, part scuffing, match lines).

Decorating
- Pad print.
- Hot stamp.
- Silk screen.
- Paint.
- Plate.
- Laser engraving.
- In-mold decorating.
- Appliques.

Simplification
- Consolidation (part reduction).
- Separation (part increase).

If this open discussion by the designer with manufacturing does not occur, the potential benefits of DFM and CE will be lost.
PART FUNCTION

Defining a part’s function is the primary factor in material selection. Although there are thousands of plastics material combinations available to a designer, a single product requirement can narrow down the decision quickly to a single family of resins. For example, reusable medical products must be sterilizable in an autoclave. The polysulfones and polyether imides are among the few resins that meet this criterion. On the other end of the spectrum, many consumer products have very generous performance constraints and will function well in a multitude of materials. In this case, the issue of cost per pound usually drives the options down to the commodity resins of polypropylene, polyethylene, and polystyrene.

Once the material is chosen, or narrowed down to several candidates with similar shrink rates, there are still numerous questions to ask. Each plastic material fits certain methods of processing, some offer a variety of processing options, while some are very limited.

The issue of strength usually comes down to determining the minimum wall section required to do the job, since wall thickness relates directly to processing time and cost. Strength issues need to be looked at from various use and misuse points of view. A factor often neglected in defining a part’s function is the difference between intended use and actual use. The court system has shown little sympathy for products that fail even when clearly not used appropriately. American Society for Testing and Materials (ASTM) data are readily available in reference books and material suppliers’ manuals as a starting point. Use this data for relative material comparisons only and not as insurance that the product will perform as predicted; remember that the material suppliers developed the test procedures and test data, not independent sources. If material strength is a major concern, it is best to develop a test plaque that more closely reflects how the product will be employed and use it to determine your own test data.

The issue of part function can involve a wide variety of topics that require evaluation by functional experts. Do not be shy in asking for expert opinions. The plastics industry is still a relatively young and dynamic industry. Just because a certain approach or method did not work last month does not mean it will not work today. The issues are too complex for one person to expertly handle the broad range of possibilities today. Improvements are constantly being made in plastics materials and processes. To add to this information overload, legislative actions and court decisions continually change the rules of the game. Only multifunctional teams have any chance of clearing the path to a successful design.

PART FEATURES

Designers will commonly break down a complex design into simpler elements. Plastic products are often looked on as a collection of walls, ribs, bosses, gussets, holes, etc. There has been much written about using rules of thumb in designing these elements. Material suppliers and reference manuals are an excellent source for detailed information. Figure 1-21 is one example of how a molder may work with a designer and “walk through” the tooling options to satisfy the designer’s needs. Part design and tool design are intertwined and must be thought of together, not as independent activities.

Appearance

Decisions made over appearance can affect the final manufactured cost of any given design as much as 100%. Most methods of processing plastic are very precise and controllable, with quality issues over dimensional features usually resolvable by standard methods of capability studies, gage maintenance studies, and design of experiments (DOE). Aesthetic requirements, however, are often very subjective and emotional issues. Visual rejects will generally make up the majority of a molder’s quality problems. A designer needs to be aware that requirements such as clear material, high-gloss surfaces, and painting, pad printing, and other decorating methods all add to cost and quality concerns.

Assembly

The multitude of assembly options available for plastic products is one of the major reasons for their continued success in replacing other materials. Figure 1-22 illustrates various assembly techniques used for injection molded products. There are many variations of these basic methods available to designers. Once again it is critical for the designer to discuss the pros and cons of the method chosen to make sure it is appropriate for the application.

Moldability

Eventually, after all the development work is completed and the part design is approved, someone has to mold the parts. If DFM and concurrent engineering methods are utilized, the manufacturing phase will be a success. If the issues of sink, draft, gating, warpage, tolerances, weld lines, etc., are not adequately addressed, manufacturing will be a prolonged nightmare. Plastic products are quite often made in high volume. Successfully going through the product development phase with a few hundred parts is no guarantee of how one million parts will process.

The emphasis tends toward product design as the key to a successful manufacturing phase. Without a well-planned mold design and successful mold build, the manufacturing phase will be a disappointment. The process must work in harmony from beginning to end. Molders who utilize the same multifunctional teams to review mold designs as they do for part designs maximize the benefits of DFM. Figure 1-23 is one example of a DFM-based mold design checklist.

Decorating

Except for those that are processed by in-mold decorating, plastic parts are decorated after the molding process, which adds to the cost. Work-cell concepts sometimes help to keep costs down, but, in general, decorating is done in a separate department or even sent to a supplier. Some processes, such as painting and plating, are specialized, making it difficult to find a qualified supplier.

Simplification

A side benefit of plastic products has always been part reduction through consolidation. Snap fits, spring actions, and living hinges are all design elements that reduce part counts. A word of caution: overzealous consolidation can lead to parts so complex they cannot be manufactured. Occasionally, part separation makes more economic sense than consolidation.

DFM Checklist

Molders who are very involved in the design process will often ask a designer many questions to better understand the product requirements. A knowledgeable molder will also be prepared to provide the designer with adequate justification for why something should not be done or why something is very difficult to accomplish. The checklist in Fig. 1-24 can be used as a discussion tool for these molder-to-part-designer interfaces.

ENVIRONMENTAL DESIGN

With a renewed emphasis on environmental issues, designers have been given the added burden of creating environmentally sustainable products. The multitude of assembly options available for plastic products is one of the major reasons for their continued success in replacing other materials. Figure 1-22 illustrates various assembly techniques used for injection molded products. There are many variations of these basic methods available to designers. Once again it is critical for the designer to discuss the pros and cons of the method chosen to make sure it is appropriate for the application.
responsible designs. With few guidelines and a lack of solid information to go by, designers have been commissioned to design for recycling, use recycled materials, and provide easy disassembly. Practical information for designers is shown in Table 1-7.

The Center for Design at the Royal Melbourne Institute of Technology (RMIT) in Australia is another source of practical information. The Institute provides the following guidelines in designing products that will use recycled plastics:

- Use thicker wall sections because nonvirgin resins generally have lower physical properties.
- Use applications where color is not critical because recycled resins are usually gray.
- Use molding processes with wide operating windows because nonvirgin resins have a wider melt index range.

**TABLE 1-7**
Ten Attributes of An Environmentally Responsible Design

1. Easy to disassemble.
2. May be recycled.
3. Contains recycled materials.
4. Reduces use of energy and natural resources.
5. Manufactured without producing hazardous waste.
6. Avoids use of hazardous materials.
7. Reduces product chemical emissions.
8. Reduces product energy consumption.
9. Uses identifiable and recyclable plastics.
10. Uses nonhazardous and recyclable materials.

(Courtesy International Business Machines [IBM])

![Diagram of tooling options](image-url)
CHAPTER 1

DESIGNING WITH SOFTWARE

(a) Snap fit (with windows)

Advantages
- Disassembly is possible.
- Assembly is rapid and inexpensive.
- Tool costs are less than those for windowless snaps.

Disadvantages
- Windows can be visually unappealing.
- Difficult to seal interior from debris and moisture.

(b) Snap fit (no windows)

Advantages
- Assembly is rapid and inexpensive.
- Exterior is visually clean.

Disadvantages
- Tool costs are higher than those for most assembly methods.
- Disassembly is difficult if not impossible.

(c) Sonic weld

Advantages
- Hermetic seal possible with a limited number of materials.
- Mold cost is lower than that for snap-fit designs.

Disadvantages
- Requires high precision to mold.
- Requires fixture and horn.
- Sonic horn can scar visible surfaces.

(d) Hotplate weld

Advantages
- Hermetic seal.

Disadvantages
- Nests are required for both parts.
- Limited number of resins may be joined this way.

(e) Screw assembly (thread-forming)

Advantages
- Disassembly is possible.
- Method can be used with any resin.
- Tool costs are less than those required for snap fits.

Disadvantages
- Holes can be seen and felt.
- Bosses can cause sink.
- Cost of assembly is greater than cost of assembly for snap fits.
- Requires addition of gasket for airtight seal.
- Threadform in boss weakens with each reassembly.

Fig. 1-22 Assembly techniques for plastic parts. (Courtesy Jerry Grunstad)
Advantages
- Tool costs are less than those required for snap fits.
- Tool costs are less than those required for snap fits.
- Tool costs are less than those required for snap fits.
- Assembly is rapid and inexpensive.

Disadvantages
- Pins and bosses can cause sink.
- Assemblies are less secure than those with screws, snaps, and welds.
In design of plastic products that will some day be recycled, RMIT suggests the following guidelines:

- Use the same type of plastic throughout the product.
- Facilitate separation and identification of materials by using molded-in recycling codes.
- Provide break points for ease of separation.
- Use snap fits.

The last resort is chemical recycling, the chemical breakdown of plastic into its original building blocks. There are three such processes possible today: hydrolysis, methanolysis, and pyrolysis. The concept for all three methods is to reduce the polymers to monomers by using superheated steam and catalysts. Although not economically feasible now, there is much development work in progress. The major benefit of this method is that reused plastic resin has the same properties as virgin resin.

For designers of plastic products, the need for an environmental perspective is now an important factor in the material selection process. It is important to stay on top of the ever-changing legislation and technology improvements in this area.

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**Fig. 1-23 Checklist used by molders to evaluate mold designs.**

In design of plastic products that will some day be recycled, RMIT suggests the following guidelines:

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For designers of plastic products, the need for an environmental perspective is now an important factor in the material selection process. It is important to stay on top of the ever-changing legislation and technology improvements in this area.
Plastic materials are so incredibly varied, as are the processes for molding them into usable articles of almost any description, that we cannot possibly cover all the rules for plastic part design in a single chapter. However, basic rules and guidelines can be described for designing a molded part so that it meets the manufacturing criteria imposed by plastic materials and processes.

CONTACT THE VENDOR

It is highly recommended that plastic vendors be contacted for detailed information on design for specific processes and materials. Most publish design manuals that give detailed information for designing articles processed with their materials. A good designer should know the possibilities, limitations, and characteristics of the material and process to be used. Early involvement of the material supplier, the toolmaker, the molder, the engineer, the industrial designer, and the mechanical designer is always a safe bet for achieving a successful design.

MATERIAL AND DESIGN CONSIDERATIONS

Material considerations are extremely important; careful selection must be based on the right properties for a design and process. Some factors are environment (service conditions), electrical, chemical, and mechanical characteristics, and economics (cost). Material selection will be discussed more in chapter 2.

Key design considerations are:

- Environmental conditions. Electrical conductivity and electrostatic discharge, resistance to chemicals and solvents, continuous-use temperature and other thermal factors, moisture and humidity, expected time spent in environment.
- Appearance. Cosmetic shape, industrial design or styling, color, surface finish, optical qualities, decoration.
- Functionality. Ease of assembly, physical size, weight, product acceptance codes and requirements (UL, FDA, etc.), ruggedness. How long will it be used? How well does it perform intended purpose? Does it duplicate the function of another part in the product?
- Production. Quantity to be produced, process to be used, material to be used, shrinkage tolerances.
- Mechanical. Vectoral load; load time; deflection parameters; creep (cold flow); fatigue, tensile, compressive, and impact strengths; flexibility; hardness; dimensional stability.
- Economics. Material, process, and tooling cost; assembly methods that may be faster and simpler. Can certain parts be combined or eliminated by redesign? Are secondary or post-process operations required? Can any be eliminated?

Some of the difficulties with plastic part quality in manufacturing can be avoided by good product and tool design at the beginning of the development process. Among the many quality problems that can be minimized by good part design are weld lines, sink marks and blemishes, voids, and stress concentrations.

### Weld Lines

As molten plastic (or melt, as it is called in the industry) flows through a mold cavity, it may encounter an obstruction that will interrupt the flow front. It could be a core pin placed in the tool to form a hole or opening of some sort. When the flow front tries to converge around the obstruction, it must “knit” or weld itself together in order to resume filling the mold cavity. At the point where the two melt fronts meet, a weld line will form (see Fig. 1-25), causing a point of weakness in the part. On the cosmetic surfaces of the part it will appear as a groove, caused by trapped air and volatiles between the flow fronts. The grooves are visible on both mold faces of the part because the flow fronts of the melt meet in the middle first (see Fig. 1-26).

The groove acts like a notch; an impact at this point may cause a failure in a notch-sensitive plastic. Stress concentrations also form at notches. Flexural strength is affected, but not tensile properties. Different plastics have different degrees of weld line characteristics, but all plastics are weakened at a weld line, since it is an area of incomplete fusion between the flow fronts. Other causes of an interruption in the flow are multiple gating, intricate part geometry such as that in picture framing, and deceleration of flow in thick sections.

Weld lines can sometimes be avoided, but if they cannot, they should be placed away from points of mechanical loading or possible impact and areas of cosmetic importance, if possible. They can be moved around to an unimportant point by control of the gate location in the tool. Also, relatively large gate lands reduce the tendency for weld line formation.

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**Fig. 1-24 Example of checklist used by molders to evaluate part designs.**

<table>
<thead>
<tr>
<th>Primary concerns of product design (check all that apply)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low part cost</td>
</tr>
<tr>
<td>Low tooling cost</td>
</tr>
<tr>
<td>High strength</td>
</tr>
<tr>
<td>Appearance</td>
</tr>
<tr>
<td>Durability</td>
</tr>
<tr>
<td>Recyclable</td>
</tr>
<tr>
<td>Material FDA approved</td>
</tr>
</tbody>
</table>

**Product requirements that affect part cost**

| High gloss surface finish | Threads |
| --- |
| Thin tolerances | 100% testing |
| Heavy wall sections | High visual standards |
| Custom colors | Clear materials |
| Demanding material requirements |

**Product requirements that affect tooling cost**

| Openings in side walls | Slide by shutoffs |
| --- |
| Undercuts | Ejection constraints |
| Complex details | Gating constraints |
| Thin wall sections | Texture or high polish |
| Deep ribs | Secondary operations |
| Contoured parting line | Weak areas of steel |
| Steps in parting line |

**Product and tooling requirements that can affect part function or aesthetics**

| Sharp corners (high stress) | Inadequate draft (scuff marks, pin drive) |
| --- |
| Weak weld lines (low strength) | Uneven wall sections (warpage) |
| Poor mold cooling (warpage) | Thick wall sections (sink, warp) |
| Poor venting (visual burns) | Filled materials (surface blemish) |

---

1-24
The designer should try to place weld lines in thicker wall areas (preferably nominal wall thickness) where the melt has a better chance of mixing. Good practice for reducing the effect of weld lines is to specify two times the nominal wall thickness between holes and between a hole and the edge of the part to strengthen the weld. One trick for thickening the cross-sectional area where a weld will form is to design a rib opposite the cosmetic surface of the part. If a weld line would mar the appearance of a surface, another alternative is to design a decorative groove or line to hide the weld line.

Yet another way to reduce the effects of a weld line is to adjust the processing conditions. Increasing injection pressure and fill rate will alter weld lines, as will higher melt and mold temperatures, but not without tradeoffs: weld lines will be stronger, but cycle time will increase.

Sink Marks and Blemishes

Concave depressions and dimples that appear as defects on the surfaces of plastic molded parts are referred to as sink marks. They will form on the opposite side of a wall where there is a thick protrusion such as a rib, boss, or gusset, and where the nominal wall thickness specified for the design of the part has been exceeded.

Thick sections retain heat and are drawn down by contraction forces—especially crystallization, which involves a large density change. As a plastic material cools, shrinkage occurs and causes large internal thermal stresses. The result is a blemish on the outer skin (see Fig. 1-27). Sometimes it can appear as a lightly discolored spot, or be a concave crater-like dimple. This phenomenon can be reduced by controlling hold-on pressure to completely pack the plastic in the tool cavity during injection molding.

As a general rule, wall sections thicker than the nominal size specified for a part are to be avoided. If structural ribs are required for stiffening, they must be cored from the back, as in Fig. 1-28. If a sink mark or blemish is unavoidable, features such as beauty lines, grooves, engraved emblems, corrugated patterns, etc., should be designed onto that area of the part to hide the flaw. Underneath bosses, shallow coring in the form of a dimple or concave depression could be styled into the part (on a nonappearance surface, this is more acceptable) to eliminate the sink. If cosmetic surfaces of an article have a molded-in texture, sink marks on those surfaces will not be as visible, becoming less obvious as the texture gets deeper. Also, darker colors hide blemishes better than lighter colors, and glossier, more lustrous resins will make sinks and blemishes stand out more.
failure of the plastic part during service life. To prevent this, all on external loads and stress/strain, this could lead to premature
sharp corners are potential stress-crack propagators. Depending
plastic flow and bending the molecular chains of the material. All
the less stress concentrations built into the article.

warp. So the less distorting, twisting, and bending of molecules,
packed with equal pressure and uniformly cooled, the distribution
material cures, the stresses thus induced are frozen into the
shape of a mold cavity. Thermoplastics consist of long, chainlike

Stress Concentrations

In the process of molding a plastic part, heat exchange is
involved where complete and even curing (isotropic cooling) must
take place. However, thicker sections will cool more slowly than
thinner ones. When a large mass of plastic is being cooled too
quickly, the outer skin hardens first, resisting further sinking. Therefore, an internal void is created (see Fig. 1-29) as the mater-
ial continues contracting or shrinking to the mold face and the
internal layers of the material separate. The void resembles a vacu-
ous pocket within the thick wall section. This will usually happen
if the mold temperature is too cold.

Essentially, this is a design problem related to sink marks. The
same precautions for sink marks should be taken for voids, such
as ensuring correct wall thickness throughout the part. Voids will
be visible in a transparent part and lower its optical quality. Voids
might even impede structural performance, and should be designed
out of a part as much as possible.

Porosity

The many tiny bubbles that exist within plastic part walls after
curing are called porosity. They may be evenly distributed through-
out the part or concentrated in localized areas. Unless a part is
molded of clear or transparent plastic, porosity is not visually evi-
dent, since the tiny bubbles are not able to push out to the mold
face or outer skin of the part during processing. In injection-
molded solid-wall articles, porosity weakens the mechanical
properties of many plastics materials. (In foam molding, gas is
intentionally incorporated in the melt and/or molding process to
create bubbles and create “foam” material. Foaming should not be
confused with unwanted porosity.)

Porosity is caused by excessive moisture or volatiles in the
material. Before plastics are processed into a molten state for
molding, the material must be properly and thoroughly dried.
Otherwise, moisture will be present during molding. The existence
of moisture in many plastics will degrade the material in process-
ing, lowering its physical performance. The remedy for this condi-
tion is correct pre-process drying of the plastic material.

Shrinkage and Warpage

Molded plastics shrink as they change from a hot melt phase to
a cooled solid phase, and will continue to shrink as they cure after
removal from a mold.

Shrinkage is a major consideration in the selection of the mate-
rial. It can range from 0.001 in./in. (0.001 mm/mm) to over 0.050
in./in. (0.050 mm/mm), depending on the type of plastic, molding
conditions, flow direction, and part geometry. Generally speaking,
crystalline plastics have a higher shrinkage rate than amorphous
plastics. Designers as well as tool makers must know the shrink-
age rate for the selected material so part dimensions and mold
dimensions can be sized correctly. The rate differs biaxially across
the mold face, which is to say shrinkage is direction-dependent.
This directional shrinkage difference is referred to as anisotropy,
and results from differing shrinkage rates between axes parallel
and perpendicular to direction of flow.

Neat, or unfilled, plastics demonstrate greater shrinkage along
the direction of flow. Perpendicular to the direction of flow, the
shrinkage is from 70–98% of that parallel to flow, depending on
mold design factors such as gating and wall thickness (anisotropy
is not as much of a problem with thin-walled parts). However,
filled plastics exhibit the opposite behavior, shrinking more in the
direction perpendicular to flow rather than parallel to flow.
Moreover, glass-filled plastics shrink from 30–50% less than
unfilled plastics because the glass fibers oriented in the direction
of flow inhibit the free shrinkage that normally occurs.

Before building a mold, it is advisable to contact a technical
service representative or consult a manufacturer's plastic molding
handbook for exact information on calculating shrinkage allowances.
Warpage in a molded part due to shrinkage can be minimized
by proper choice of gate location. In a mold for a rectangular part,
gates should be located to orient the flow in a longitudinal path.
For circular parts, the gate should be centrally located for a radial flow path. Wherever the gate position is located, it should provide a uniformly oriented flow of plastic.

Warpage in an injection-molded part can also be minimized by manipulating moulding pressures. Shrinkage is greatest at the outermost edges of an article, and warpage due to shrinkage differences within a part is affected by a drop in pressure in attempts to fill a mold cavity evenly and completely. High pressure yields low shrinkage, but as the flow rate increases, pressure decreases. Therefore, large enough gates should be used to release melt into the thickest sections of an article. However, gates should not be too large or localized overpacking will occur. On the other hand, if a gate is too small, there will not be enough pressure to completely pack out the mold cavity and the melt front will freeze prematurely. A general principle for avoiding warpage due to a pressure differential is to locate the thickest wall sections centrally, or at the gates, and gradually thin out the wall thickness toward the perimeter of the part. This reduces the pressure drop from flow beginning at the gate to the flow ending at the edge of the part.

Other processing factors will help prevent warpage as well.

- Higher injection pressure.
- Increasing plunger forward time.
- Longer overall cycle time.
- Lower mold and melt temperature.
- Increased fill speed.

When a plastic part is designed correctly with consideration for the material and molding process guidelines, processing factors can be adjusted to help correct warpage. But if a plastic part is not designed correctly to begin with, tweaking process variables may have no effect on correcting warpage, and, in fact, might even make matters worse. A good rule of thumb to remember: there is no substitute for good design.

Tolerances

Tolerances are always an important concern in the design of a plastic part. Dimensional tolerances are calculated according to the process capabilities and material limitations. The shrinkage factor in plastics determines the variation in dimensional tolerance of a part.

Expressed as a rate of shrinkage, the tolerances are tabulated as plus or minus a numerical allowance per unit of linear measure, such as ±0.003 in (0.08 mm) for dimensions up to 0.500 in (12.7 mm) long. The table shows how tolerance values increase as linear dimension increases. The longer a distance through which plastics must flow, the more the shrinkage that must occur. The rate of shrinkage differs with the type of plastic and the molding process, as well as with the molding conditions.

Again, the material supplier and molder should be consulted for specific data on tolerances right at the beginning of the design cycle so that dimensions can be sized accordingly.

Tolerances may be classified as fine, standard, or coarse. This will be determined by the molder's equipment capabilities and level of expertise, and molding conditions during the process. The tolerance classification will determine the cost level of the part.

A fine tolerance requires exceptional equipment, process control, expertise, and molding conditions, all of which command higher cost to achieve greater accuracy and closer tolerances. Longer cycle times and higher reject rates will also result from fine tolerances.

Standard tolerance represents the dimensional control acceptable under average or normal conditions of manufacture. It naturally lowers the cost of a part from the level of a fine tolerance.

Coarse tolerance is specified on dimensions where the limit on variation is not important or critical. If it is functionally impractical to produce a dimension to the level of accuracy required for standard or fine, coarse should suffice. Cost savings will result.

If standard or fine tolerances are positively required for dimensional accuracy, but the cost of that accuracy is too high, an alternative material or process might be needed.

Flow Path

It is important to understand the path that plastic will take as it flows through an injection mold cavity, for determining wall thicknesses and locations of features and avoiding problems such as sinks, voids, weld lines, flow lines, and molded-in stresses. The success of an injection-molded part is directly related to the behavior of the material flowing through the mold. For example, material can flow around a pocket or depression and leave it unfilled unless adequate pressure builds and forces material to pack out these areas. Or, because of improper restrictions and obstructions, material flow can hesitate momentarily until adequate pressure develops to overcome the resistance to flow. This forces the material to jet forward, causing portions of the melt front to freeze. Then, when converging melt fronts weld together, surface defects will result.

Overall part quality depends on conscientious attention to the flow path of plastics in the mold cavity. Starting from the gates of an injection mold, the material must fill smoothly and evenly, mixing thoroughly around cores and shutoffs, not jetting or surging. It should move quickly and efficiently to minimize cycle time and to prevent any chance of premature freezing of the melt front. As the plastic flow encounters features, it should fill them in without affecting movement uniformity. Obstructions should be placed far enough apart so that fill-in can occur. Impingements must be minimal and follow guidelines for thickness transition. Also, holes should be spaced apart at a minimum distance equal to or greater than the hole diameter (the farther the better), and the same minimum thickness should lie between a hole and a wall or an edge of the part. Another rule of thumb is to provide two times the nominal wall thickness between holes or between holes and edges.

Gate size and location are very important for orienting the direction of the flow path. If the gate is too small, the plastic freezes too soon, causing inadequate fill (void-type holes in the part) and improper packing. Too small a gate can also result in gate blash, cold flow, and gate jetting which inhibits the formation of a substantial melt front in the material flow. Too large a gate will cause improper flow orientation, backflow, and inadequate packing as well as difficult degating, which may require secondary machining.

Choosing the proper gate type, size, number, and location is a tool design concern, not within the scope of this chapter. However, proper flow can be ensured during part design by obeying proper guidelines. These guidelines will be presented in the discussions of wall thickness and placement of features within a molded part, below. If features such as ribs, bosses, holes, pockets, and depressions are placed properly and wall thickness and transition rules are followed, the material flow path should be the most efficient possible for the tool design.

A common problem that arises from disregard for fundamental flow consideration is “picture framing.” Any fluid, whether Newtonian or non-Newtonian, will take a flow path that exerts the least amount of resistance to it. Figure 1-30 shows a basic example in which a rectangular part has a perimeter wall with a thicker cross section than the central web. As the material flows from the gate, it moves quickly through the thicker perimeter wall. But as it
reaches the thinner central web, it meets with greater resistance, slowing down the flow through this area. Meanwhile, the material races through the entire perimeter wall forming what looks like a picture frame around the thinner web before it can fill completely. The flow front cools down critically and freezes, usually resulting in a void-like hole in the thin section because of insufficient fill. Usually this phenomenon is not apparent until the part is actually molded, unless a computer-aided analysis is done with plastic molding simulation software. This allows engineers to preview the flow characteristics of a part on a computer screen to resolve a problem before it happens in manufacturing. Through tool design and corrective measures in part design, picture framing can be prevented. By reducing the perimeter wall thickness and increasing the central web thickness, filling will be improved. Repositioning the gate to the part’s center of gravity and ensuring adequate venting of the mold cavity are also helpful options.

**CHAPTER 1**

**BASIC RULES AND GUIDELINES**

**DESIGN CONSIDERATIONS**

**WALL THICKNESS**

The most important design aspect of a plastic part is the nominal wall thickness. This is the basis of the part to which all other features, details, attributes, etc., will be added. The principal concept is to keep the thickness consistent throughout the entire part.

There are a number of things that influence the choice of wall thickness for a part. The first item is selection of material. Tables 1-8 and 1-9 show ranges of preferred wall thicknesses for a variety of thermoplastic and thermostet materials respectively.

Requirements of use and manufacturing are also an influence on the determination of wall thickness. An analysis of these interrelated requirements will usually indicate a nominal wall size and choice of material. Requirements of use include:

- Structure.
- Molding.
- Weight.
- Strength.
- Insulation.
- Dimensional stability.
- Assembly.

Manufacturing requirements include:

- Flow.
- Ejection.

**The Thinner, the Better**

From an economics standpoint, too thick a wall section can be very costly. Not only is more plastic consumed during manufacture, but curing time is longer, lowering production rates. Ideally, a part should be designed for the thinnest nominal wall possible while meeting structural requirements. But even if material strength is not an issue in use, it should be sufficient for mold ejection and assembly operations.

A factor affecting minimum wall thickness is how far a plastic can flow through a mold cavity from the gate. The plastic’s viscosity determines its ability to flow and fill the cavity and dictates a minimum wall thickness distinct from that based on the function of the part itself. The viscous melts produced by many plastics can flow only so far three-dimensionally in a thin wall before they freeze. This information can be acquired from a material supplier.

All of this does not mean a large part cannot be thin-walled or that a tiny part cannot be thick-walled. These guidelines are a place to begin designing a part.

**Coring**

Careful attention should always be given to areas where the nominal wall thickness has been exceeded. These areas should be
**TABLE 1-8**

Typical Nominal Wall Thicknesses for Various Thermoplastic Molding Materials

<table>
<thead>
<tr>
<th>Thermoplastic Material</th>
<th>Working Range, In.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>0.030–0.168</td>
</tr>
<tr>
<td>Acetal</td>
<td>0.015–0.125</td>
</tr>
<tr>
<td>Acrylic</td>
<td>0.025–0.250</td>
</tr>
<tr>
<td>Cellulotics</td>
<td>0.025–0.187</td>
</tr>
<tr>
<td>FEP Fluoroplastic</td>
<td>0.010–0.500</td>
</tr>
<tr>
<td>Ionomer</td>
<td>0.025–0.750</td>
</tr>
<tr>
<td>Liquid Crystal Polymer</td>
<td>0.008–0.120</td>
</tr>
<tr>
<td>Long-fiber Reinforced Plastics</td>
<td>0.075–1.000</td>
</tr>
<tr>
<td>Modified Polyphenylene Ether</td>
<td>0.045–0.140</td>
</tr>
<tr>
<td>Modified Polyphenylene Oxide</td>
<td>0.030–0.375</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.010–0.125</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.040–0.375</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.025–0.125</td>
</tr>
<tr>
<td>Polystyrene Elastomer</td>
<td>0.025–0.125</td>
</tr>
<tr>
<td>Polyethylene (low density)</td>
<td>0.020–0.250</td>
</tr>
<tr>
<td>Polyethylene (high density)</td>
<td>0.035–0.250</td>
</tr>
<tr>
<td>Ethylene Vinyl Acetate</td>
<td>0.020–0.125</td>
</tr>
<tr>
<td>Polyphenylene Sulfide</td>
<td>0.020–0.180</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.025–0.300</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>0.005–0.150</td>
</tr>
<tr>
<td>Polytetrafluoroethylene</td>
<td>0.025–1.500</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.030–0.250</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>0.005–0.150</td>
</tr>
<tr>
<td>Polytetrafluoroethylene</td>
<td>0.025–1.500</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.030–0.250</td>
</tr>
<tr>
<td>Styrene-acrylonitrile</td>
<td>0.040–0.375</td>
</tr>
<tr>
<td>Styrene-acrylonitrile</td>
<td>0.030–0.250</td>
</tr>
</tbody>
</table>

**TABLE 1-9**

Typical Nominal Wall Thicknesses for Various Thermoset Molding Materials

<table>
<thead>
<tr>
<th>Thermoset Material</th>
<th>Working Range, In.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkyd, glass-filled</td>
<td>0.040–0.500</td>
</tr>
<tr>
<td>Alkyd, mineral-filled</td>
<td>0.040–0.375</td>
</tr>
<tr>
<td>Diallyl Phthalate</td>
<td>0.040–0.375</td>
</tr>
<tr>
<td>Epoxy/glass</td>
<td>0.030–1.000</td>
</tr>
<tr>
<td>Melamine, cellulose-filled</td>
<td>0.035–0.187</td>
</tr>
<tr>
<td>Urea, cellulose-filled</td>
<td>0.035–0.187</td>
</tr>
<tr>
<td>Phenolic, general purpose</td>
<td>0.050–1.000</td>
</tr>
<tr>
<td>Phenolic, flock-filled</td>
<td>0.050–1.000</td>
</tr>
<tr>
<td>Phenolic, glass-filled</td>
<td>0.030–0.750</td>
</tr>
<tr>
<td>Phenolic, fabric-filled</td>
<td>0.062–0.375</td>
</tr>
<tr>
<td>Phenolic, mineral-filled</td>
<td>0.125–1.000</td>
</tr>
<tr>
<td>Silicone Glass</td>
<td>0.050–0.250</td>
</tr>
<tr>
<td>Polyester Premix</td>
<td>0.040–1.000</td>
</tr>
</tbody>
</table>

cored or thinned out in some way to prevent sink marks, voids, and warpage (Fig. 1-31 shows typical methods of maintaining nominal wall thickness). Coring refers to the addition of steel to the mold for the purpose of reducing plastic material in that area. Generally, cores should be parallel to the direction of pull (line of draw) of the mold. This is for simplicity and lower tool costs, since placing cores in any other direction would require them to slide out of the way via hydraulic, pneumatic, or cammed action to facilitate part removal. Moving cores can also increase cycle time for molding.

Any impediments to the flow of the material are not allowed. If different wall thicknesses are required in the part, then the wall should be gradually tapered from thick to thin. Wall thickness transitions should be performed with progressive blends, facilitated by fillets and ramps, and must always get thinner, never thicker (see Fig. 1-32).

**THE RIB**

Perhaps the most basic detail in plastic part design is the rib. A structural feature, the rib is mainly utilized for stiffening and adding rigidity to the part without increasing nominal wall thickness or section modulus.

In certain designs, such as large parts with long flow distances between detail areas, ribs can also aid flow rate by increasing the cross-sectional flow area without sacrificing any design integrity. If designed correctly, ribs will prevent many flow-related problems.

When properly used, they can prevent warpage in a plastic part during cooling. However, most experienced design engineers tend not to add ribs to a part unless they are deemed necessary after careful analysis. If there is any question of their structural value, they are generally avoided, because they may worsen warpage and appearance problems. But, if the need for any ribs should be discovered downstream, adding them to the mold is easy and economical, since it entails the removal of steel.

Proper guidelines must be followed in order to avoid problems such as sink marks, voids, warping, long cycle times, and flow-related problems. First of all, at the base of the rib where it attaches to the nominal wall, the width should be no more than 70% of the nominal wall thickness. Other authoritative sources suggest two-thirds nominal wall thickness, or even one-half of nominal wall thickness for ribs opposite cosmetic surfaces (see Fig. 1-33).

Anything thicker will result in a heavy mass of plastic that can cause a sink mark and/or void. However, if a very low shrinkage material is used, a heavy texture is applied to the opposite surface of the protrusion, or the part is packed out sufficiently during molding, a dimension of 75% of the adjoining wall can often be used satisfactorily. If sufficient space is available, multiple thin ribs should be used instead of a single thick rib. The general idea is to make ribs as thin as possible.

**Rib Dimensions**

The height of a rib should not be any greater than three to five times nominal wall thickness. At the top of a rib there should be a thickness of at least 0.030–0.050 in. (0.76–1.27 mm), or in very thin-walled parts at least enough material to avoid a feathered edge. This is because plastic tends not to completely fill in tight corners. The tendency of the viscous melt in any feathered edge is to form a rounded tip, from 0.005–0.015 in. (0.13–0.38 mm) in radius, with waviness along the length of the rib. Therefore, all feathered edges should be avoided. Width, length, height, draft, etc., should be carefully analyzed to minimize the internal stresses associated with irregular wall thickness. Draft, fillets, and radii as applied to ribs will be discussed later.

Another guideline is to avoid crossing ribs perpendicularly to each other (see Fig. 1-34), or a heavy mass of material may result at the base of the intersection. Proper design would be to jog the rib (center to center) by twice the cross-sectional rib thickness, as shown in Fig. 1-34. Any two parallel ribs should be no less than twice the nominal wall thickness apart (see Fig. 1-35).

**BOSSES**

Bosses are a common feature usually incorporated to accommodate a fastener. They are essentially protrusions that amount to...
a circular rib that forms a tube projecting from the nominal wall. Therefore, the guidelines for ribs must be followed in boss design. By referring back to Fig. 1-27, you can see how a thick section beneath a boss can cause problems such as sink marks and voids due to stresses during cooling.

Figure 1-36 illustrates the typical boss design. It is sometimes advised that the height be limited to twice the inside diameter for meeting strength requirements, but taller bosses can be designed in injection-molded parts at an experienced designer’s discretion. During compression molding, taller bosses tend to trap air, especially during straight compression molding and when the core half of the mold is forming the boss.

When a boss is designed to accept a self-tapping screw, close attention must be paid to the inside diameter and wall thickness where hoop stress can build up and cause it to crack. A good boss design should have a lead-in at the opening at least equal to the nominal diameter of the fastener. Material suppliers’ design manuals can give exact dimensions for the proper boss design according to type, style, and size of screw.

**Boss Positioning**

For tall bosses and bosses that may encounter lateral forces, gussets should be incorporated for structural rigidity. Bosses should be positioned, if possible, at the far corners, outer perimeters, or edges of a part. Also, if they are located at the apex of a corner, or where the wall changes direction abruptly, a better balance of flow is achieved. When bosses are placed near each other or on a wall, ribs should be incorporated to connect them together (see Fig. 1-37). This is a great help for the flow. Proper rib design rules must be adhered to if a boss is connected to an appearance surface, otherwise sink mark defects will result. A good guideline to follow is limiting the thickness of ribs connecting a boss to a wall at one-half the nominal wall thickness. Sometimes extra cooling is needed in these areas if there is too large a mass of plastic, so a bubbler should be placed across from the boss in the cavity half of the mold to reduce the effect of a sink mark on the outer wall.

Threaded inserts may be molded into a boss for machine screws. However, this will add cost to manufacturing the part. If inserts with an outside diameter (OD) less than 0.25 in. (6.35 mm)
are used, the boss OD should be at least twice the insert OD. Radial ribs should be used on bosses with inserts to increase strength.

**SHAPING THE PART**

All plastic part designs should avoid sharp corners. As mentioned previously in connection with stress concentration, all corners must have fillets and radii. This produces an article with much less stress, much more strength, and less probability of cracking because of notch sensitivity.

Fillets and radii should be made as large as a design can allow. This practice will also help the plastic flow through the mold by providing a smoother (thus less stressed) path and more consistent fill. Filleting sharp corners will aid ejection of the part from the mold as well.

Another benefit is longer tool life. Sharp corners retain more heat than radiused ones, which softens and prematurely fatigues the tool in this area. Shear heat from the molten plastic abrading the sharp corner will also wear away the mold.

**Judging the Radius**

The usual minimum radius on any given edge is 0.015 in. (0.38 mm) inside corners, preferably 0.020 in. (0.51 mm), with outside corners equal to the inside radius plus material thickness. Another rule of thumb is to size the radius of an inside corner to 50% of nominal wall thickness, and again to make the outside radius equal to the inside radius plus material thickness, to maintain constant wall thickness. The single most important thing is to radius all corners and edges.

**Surface Factors**

In order to remove a plastic part from a mold, the surfaces parallel to the axis of release must be tapered to assist in the part’s ejection. This taper is generally known as draft in the direction of draw. As plastics cool, they shrink tightly onto the cores of molds, which makes ejection difficult. This is why all surfaces of a part (inside and out) must have draft in the direction of any movement. This includes side pull pieces and lifters (sliding core pieces) that form undercut features.

If a surface is vertical and a no-draft situation is unavoidable, then a high-luster polished finish should be applied so the article is more easily released.

**Draft Factors**

The deeper the draw of a part, the more the draft that should be designed in. This will reduce the increased level of friction and resistance to release caused by a greater vertical area between cavity and core. When a texture is specified for a surface in the direction of pull, at least 1" per side of draft is needed for every 0.001 in. (0.025 mm) depth of texture.

Generally, the amount of draft required for a molded plastic part will vary according to the molding process, depth of part,
type of plastic, and wall thickness. In most cases, 0.5° draft per side is considered the minimum, and 1–3° per side is often recommended. Just as design engineers should make the nominal wall thickness as thin as the design can tolerate, they should also give the most draft possible to a design. It will pay dividends down the line in ease of manufacture.

Table 1-10 provides the taper for various draft angles and draw depths. Figure 1-38 illustrates the relationship of draft angle, depth, and taper.

HOLES AND IMPRESSIONS

Any holes and impressions through sidewalls and into vertical sections are to be considered undercuts. If holes and impressions are parallel or almost parallel to the direction of draw, they are easy to make. But if they are perpendicular to the direction of draw, they must be made with core or cavity projections that will move or retract so that the article can be released. This complicates the tool design and increases the cost substantially, especially with compression molding. Molding cycle time also increases because moving core pieces and side pulls must first be slid out of the way by some mechanical means, before the part can be removed from the mold. These problems are not as critical with injection or transfer molding as with compression molding. However, the complexity of the tool design remains and certain precautions must be taken by the toolmaker and designer. Enough room for internal lifters (as moving pieces in a mold’s core side are called) to operate has to be considered, and whether a side pull can be feasibly included in the design needs careful analysis, just as examples.

Fig. 1-36 A typical boss (left) and a tall boss (right).

Fig. 1-37 Ribs should be used with bosses when they are located near each other or near a wall.

A = 2.0 to 2.4D
D = nominal diameter of thread
d = diameters should be acquired from material supplier per type of resin being used
h = D/2
T = nominal wall thickness
T = maximum T to 1/2T minimum
R = 0.005 – 0.015 in. (0.127 – 0.38 mm) minimum
There are a few exceptions where parts can be released from a mold with undercuts and not need moving pieces. For example, elastomers and some of the more flexible thermoplastics will stretch over a shallow protruding core piece, the depth of which is easily obtainable from a material supplier. However, there are certain very important factors to consider before the design of such a part is finalized. Some of these factors are the allowable part strain in stripping the article from the tool, the mold temperature, molding cycle, forces required for ejection, as well as the geometry of the undercut.

It is highly recommended that alternative tool design methods and part design techniques be utilized, if possible, to achieve the article’s desired geometry. For example, sliding shutoff design can be substituted for moving pieces in the tool perpendicular to the direction of draw (Fig. 1-39), simplifying the tool design. It usually requires a draft angle of at least 5° from the vertical to provide room for the mold core and cavity to touch at the desired point of shutoff. This point of contact between the two mold halves where an undercut or vertical hole is created is referred to as the “kiss-off.” Kiss-off angles are never less than 3°, with most toolmakers requesting a minimum of 5°.

**MASS PRODUCTION**

When products consisting of plastic parts are manufactured in mass quantity/high-volume production, snap-fit joint designs are a very fast and inexpensive method of assembly. Money is saved by reducing or eliminating the number of separate fasteners in an assembly; doing away with additional special equipment such as power drivers for screws, ultrasonic welding equipment, and messy adhesives or solvents; and simplifying the assembly, thus reducing the cycle time. Also, correctly fitting one part together with another can be assured by design and carried through into the tooling.

**Snap Design**

A snap employs a protrusion with a hook, hole, bead, or some form of undercut that temporarily deflects to catch another joining piece to form an assembly, then springs back to its original unstressed position. A successful snap design will provide enough holding strength for its intended task but will not exceed the material’s elastic limit, otherwise physical failure will occur. In the best snap designs,

<table>
<thead>
<tr>
<th>Draft Angle (degrees)</th>
<th>Depth of Draw, In.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8</td>
<td>0.0022</td>
</tr>
<tr>
<td>1/4</td>
<td>0.0044</td>
</tr>
<tr>
<td>1/2</td>
<td>0.0066</td>
</tr>
<tr>
<td>1</td>
<td>0.0088</td>
</tr>
<tr>
<td>2</td>
<td>0.0110</td>
</tr>
<tr>
<td>3</td>
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<tr>
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<td>0.0176</td>
</tr>
<tr>
<td>6</td>
<td>0.0198</td>
</tr>
<tr>
<td>7</td>
<td>0.0220</td>
</tr>
</tbody>
</table>

![Fig. 1-38 Relationship of draft angle, draw depth, and taper.](image)

![Fig. 1-39 Sliding shutoff tooling.](image)
the flexing members are able to move only in the direction they were intended to.

The snap fit may be permanent (it will be used only once) or reusable (capable of repetitive cycles), depending on the geometry of the hook or undercut. The load required to deflect and thus disassemble the members will differ substantially with design. It is important to know during the design development the mechanical load applied to the snap during the assembly procedure and the force needed to disassemble.

Outside the scope of this handbook, but found in many good supplementary texts, are beam equations for determining the various stresses and strains encountered with any snap design geometry. There are formulas that can also calculate mating force, deflection force, and transpose to give dimensional components for a given design.

**Various Snap Designs**

The variety of snap configurations is limitless. However, there are several basic types that should be understood: the cantilever snap, the torsion snap, and the annular snap.

The cantilever snap is a tapered beam protrusion where the stress due to loading is all in flexural bending. Since the deflections and loads are usually small and very brief, yield point stress can be exceeded. Dynamic strain is commonly a concern in snap fits. When the beam is tapered down from the fixed end to the undercut, a more uniform stress distribution is produced. Also, since plastics are generally notch-sensitive, all corners should be filleted and radiused to avoid stress concentrations. A basic dimensional guideline for creating a typical cantilever snap fit design is shown in Fig. 1-40.

Because all snaps involve an undercut of some kind, a situation could present itself where mechanically moved pulls must be used in the tool to form the snap. Fig. 1-41a illustrates the way a sliding core piece is utilized for molding the undercut of a cantilever snap. The overhanging piece or detail in the snap above the undercut is sometimes referred to as the tang of the snap. The section of the snap right at the undercut is the throat. If at all possible, the undercut should be created with a shutoff design, as illustrated in Fig. 1-41b. This dispenses with the need for the complexity of mechanically moving pulls in the mold, thus reducing tooling cost and cycle time. However, the shutoff design necessitates a hole or window in the nominal wall of the part, which may not be good for electrical, cosmetic, or other reasons.

The cantilever snap can be used effectively in conjunction with a hook-type feature to create a way of securing a lid to a base part, forming a sealed-box assembly (Fig. 1-42).
The torsion snap (Fig. 1-43) functions much like a lever; the stresses due to loading act on the fulcrum entirely in shear. The pivot of the snap arm is formed as an axle or torsion shaft which takes all the shear forces. The snap is designed to operate like a rocker arm: when one presses down on the end opposite of the catch, the mating part is very quickly released. This makes for an extremely simple, effortless way to frequently assemble and disassemble parts. This design is molded as an integral feature of the plastic part. However, this is a complicated type of snap to design, although inexpensive compared to other methods of assembly, and is not commonly seen in thermoplastic parts.

Annular snap designs are commonly seen in plastic coffee can lids and plastic food containers for leftovers, just to name a few. They are found mostly on round parts that are symmetrical (Fig. 1-44), where the stresses due to assembly force are multiaxial (hoop stresses). The depth of undercut is usually shallow because the deflection distances are small, since a considerable portion of the part or even the entire part itself will flex during assembly. This lends itself well to simplicity of tooling: the part can be stripped or popped out of a mold very easily (depending on the material and undercut geometry) without shutoffs or mechanically moving slides and core pieces.

With all types of snaps, the depth of undercut is equal to the distance of deflection. But since an annular snap has the undercut encircling the part or on both sides of a snap, the depth of undercut can be only half as deep as that of a cantilever-type snap fit, for example. Because there is a greater overall contact area of undercut to mating part, very small undercuts give snap-fit joints considerable strength.
Rapid prototyping has been growing at an unrelenting pace since stereolithography was first revealed as a fast way to develop a preproduction model from a CAD file in a matter of hours instead of days or weeks.

Engineers immediately saw the benefits such a process could offer. With it, they are able to hold in their hands the physical model of a computer-generated design that they can review and analyze, then make changes to their database, in rapid sequence—all resulting in shorter product to market time. And this, many companies believe, could save millions of dollars a year in reduced development costs. Multiple iterations of a design can be rapidly prototyped in the same amount of time it used to require for one.

**CNC VERSUS RAPID PROTOTYPING**

Obviously, rapid prototyping’s strength is quick turnaround in creating a model. Computer-aided manufacturing will create a CNC-machined model in a durable, tough material, but not as fast as rapid prototyping (RP), and will cost more. The more complex a part is, the more practical RP becomes. A common rule of thumb to determine whether CNC or RP is the best choice for making a model is this: if it takes more than two or three setups for the CNC operation, then RP is the way to go. But for very simple parts that can be cut with standard machine-shop tools, such as lathes and millers, CNC can be of more benefit.

Also, there is a tradeoff in cost and time of CNC versus RP that depends on the quality of the data supplied. Nothing is gained if only sketches are given to an RP service. A service can create the CAD file required for the RP process if engineering drawings of a part are available. And, if the data are a 2D CAD file, more time and money is saved in generating an RP model. If a 3D wireframe CAD model is supplied, the time and cost drops even more in RP. This trend continues with 3D surface models and grows even greater with a generic solid model. Finally, the most desirable data are in a file format output from a CAD system specifically designed for RP, called STL. It is an industry standard that allows data entry is often done by the service bureau building the prototype, for an extra cost and with additional delay. Also, angled or radiused edges are produced with tiny sawtooth-like steps on their surface, because of the 0.005 in. (0.127 mm) thick layering construction. These rough surfaces might require sanding, and using the SLA part in real-life operation has limitations, namely in strength and flexure. SLA resin is very stiff, and until recently could not withstand the impact of being dropped even a short distance. Dimensional stability of the resin over time is not strong; eventually some long, thin-walled surfaces and beam-like features will begin to warp. Therefore, it is recommended by service bureaus to go right into a rubber mold and cast a part in a more stable resin. This material can be more easily decorated and give better surface finishes.

**Selective Laser Sintering**

The Sinterstation™, manufactured by DTM, Austin, Texas, utilizes a modulated laser beam to fuse special powdered materials like nylon, polycarbonate, and investment casting wax into physical models. The laser is guided by the data provided directly from a CAD file. Very strong, tough models are produced with the nylon and polycarbonate, but thermoplastics, ceramics, and metals are also being worked on for potentially stronger parts. This advantage of a greater variety of materials with better properties makes the SLS process more attractive to customers who must have models for testing in hostile environments, or where physical stresses are acting on them.

**Laminated Object Manufacturing**

Another variation of the CAD-guided laser-beam-generated prototype process, laminated object manufacturing (LOM) from
Helisys, Torrance, California, uses a laminated medium of heat-activated, adhesive-coated paper. The laser is guided over an x-y axis table by the data from CAD files and cuts a 2D cross section in the 150 µ in. (0.0038 mm) thick material. A platform under the table drops an increment equal to the thickness of a single layer of the material. The material is then advanced from a supply roller over the top of the previously cut cross-section, and another layer is cut by the laser beam. The cycle is repeated until the 3D object is completed.

Unlike other RP processes, LOM models can be utilized in a number of different manufacturing processes, for example, sand casting, where wooden patterns have always been used. Also, the materials are low-cost and nontoxic, the paper/adhesive medium is low, and requires no special handling because there is no hazardous or toxic waste. Another benefit of LOM is that it can produce larger prototypes than other processes.

**Solid Ground Curing**

Cubital Ltd., Raanana, Israel, makes the Solider™ rapid prototyper, which takes a CAD solid model, runs it through a slicer program, and constructs a prototype in layers with a photopolymer resin, like the SLA process. However, each thin layer is deposited on a platform and ultraviolet light is flashed through a glass plate that is masked with the negative image of the layer. Therefore, the UV-sensitive material is cured only in the areas where there should be solid material (thus the name solid ground curing). Uncured liquid resin is vacuumed away and replaced with liquid wax, which is then solidified by the application of a cooling plate. The wax performs the task of structural support during prototype construction. Then the layer is milled to ensure uniform thickness, after which a new film of liquid is deposited on top of it for the start of the next layer. Most models can be created in just a few hours or overnight. When the process is finished, the wax is dissolved, revealing single or multiple plastic models exactly matching the CAD solid model.

The innovation in this system is that the negative image of the part is printed on the glass plate by a technique similar to that used in a laser printer. The process can be used to construct large parts.

Models made with the Solider can be used for testing of form, fit, and function. They can also be used as patterns to generate molds for casting production parts. A Solider machine from Cubital can cost from $325,000 to $500,000.

**Fused Deposition Modeling**

Stratasys, Eden Prairie, Minnesota, has created a process using semiliquid thermoplastic material. The machine has a lightweight extruder head that moves in an x-y plane, depositing the material in thin layers on a fixture-baseless. The z-dimension, or height, of the prototype is constructed upward by the material-delivery head. The thermoplastic material is supplied in the form of wirelike filaments on a spool and is fed into the dispensing tip and heated to 400˚ F (204˚ C) so that each layer fuses to the previously deposited one—thus the label fused deposition modeling (FDM).

The main advantage of this system is its short turnaround time. Some finished models can be built in minutes instead of hours or even days with other RP systems; no postcuring is required because the material is not a photopolymer. There are currently five materials available: machinable wax, ABS, polyamide, polyolefin, and investment-casting wax. The Stratasys prototypes can be used for injection molding and investment casting besides appearance models. Another advantage is its application to hollow parts, because unused liquid polymer does not need to be drained.

**Tabletop CNC Machining**

For a direct CAD/CAM interface, Roland Digital Group, Irvine, California, makes the CAMM-3™ tabletop modeler. This machine works and looks like a traditional vertical-spindle miller, only it can fit on half the space of an office desktop and is 10 times as fast as a CNC milling machine. It can cut brass, aluminum, plastic, wood, graphite, and modeler’s wax to make rapid prototypes straight from the same CAD data used to generate engineering drawings on an x-y plotter. Cutting steel puts too much pressure on the spindle, but in softer materials, production work is done in a small fraction of the time it takes traditional full-size CNC machine tools to do it.

When a prototype part has geometry that can be completely machined in only one or two setups, then it makes more sense to use a process like tabletop technology. Anyone with a PC can create the CAD data, run it through any popular CAM program, and send it directly to the CAMM-3 where the model is then milled out of a wide variety of materials.

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**COMMON MISTAKES**

**CREEP**

Creep is a limitation found in thermoplastic materials to a far greater extent than in most other materials. Defined as the permanent deformation of the material with temperature, time, and pressure, creep is directly related to the elasticity of the resin. This relationship means that designers are confronted with a difficult choice. Shock absorbency, or ability to resist fracture, is directly related to the creep factor. The more resilient and pliable a material is, the more likely it is to exhibit creep. So the tradeoff between creep and impact absorption must be weighed.

We know that there are techniques for reducing creep’s effects. For example, reinforcement can increase creep resistance in a thermoplastic molded part. More heat-resistant materials and improved processing technology also reduce the immediate and short-range effect of creep.

**STRESS**

The word stress as it applies to plastic parts is used in two ways, both of which are important to the designer. Molded-in stress is a function of product and mold design and processing variables, and is created during the molding operation. Applied stress is caused by the mechanical or environmental strain or load inflicted on the product during use. Product stress failure often is a result of applied stress causing rupture or deformation in the areas of the part that contain molded-in stresses.

**Molded-in Stress**

There are several things designers can do to minimize molded-in stresses that are caused by nonuniformity of flow pattern and wall thickness and improper mold venting. Designers may reduce the differences in wall thickness, eliminate sharp corners, and introduce...
CHAPTER 1

COMMON MISTAKES

ribs and bosses in strategic areas. In addition, adequate clearance should be provided in an assembly where a difference in expansion and contraction is occasioned by use of dissimilar materials. These steps can help eliminate many of the failures that result from molded-in stresses.

Applied Stress

On the other hand, applied stress is not something that can be eliminated, but must be considered when material selection and part design are initiated. Applied stresses are less likely to cause part failure if you choose a material with the properties to suit your application and minimize the molded-in stresses.

Hostile Environment

Too often a product designer does not consider (or has not been told) where the product is used, and it is impossible to ward off all possible objectionable environments to which the product may be subjected. However, reasonable precautions must be taken. For example, if a product is going to be used in the bathroom, it can be exposed to volatile sprays that will cause crazing and cracking. Any kitchen product runs the risk of being inserted into the dishwasher and exposed to caustic solutions.

Plastic parts are subject to ultraviolet degradation, and molded parts used outdoors should compensate for this limitation and incorporate an ultraviolet inhibitor. There are many other environmental factors that may affect performance properties of a part, such as extreme heat or cold, odors, radiation, wear, or weathering. The important step for the designer is to determine what these might be before making a final material selection.

SHRINKAGE

After molding, plastic parts tend to shrink. Postmolding shrinkage is a problem often overlooked by the mold builder and the designer must correct for this. When a dimension for a finished part is specified and the material itself is indicated on the print, the mold builder will calculate the shrinkage of the material—often using the material supplier's tables provided for this purpose. However, the designer must recognize that after the part is taken out of the mold, it will continue to shrink (although most shrinkage occurs within 24-hours, it may continue for as long as 30 days), affecting the ultimate fit or misfit of the part.

Plastic parts in assembly with metallic parts have a different rate of expansion and contraction, and sufficient clearance must be given to accommodate this variation. In contrast to other materials, it is more difficult to make a plastic part smaller than to make it larger because of the nature of the tooling. Thus, it pays to have the part designed so that it is possible to remove metal (to make a larger part) rather than have to add metal to the mold (to make a smaller part).

COLOR VARIANCE

Another common misconception is failing to recognize that color in plastics is directly related to the thickness of the part; that is, the intensity of pigmentation varies with the mass. When parts are molded in translucent or semisolid colors and there is substantial variation in the wall thickness, there will appear to be differences in color on the surface of the part.

There are other appearance characteristics of a molded part that are not always evident on the drawing board. Wherever there is an opening through a piece of plastic, there will be a flow weld line, or not, whose visibility is accentuated by color. A clear part might show only a hairline knit mark, whereas a color-loaded material will have large, noticeable swirls. Not only is the weld line itself accentuated, but the entire pattern of pigmentation may be visible from the natural flow characteristics of the resin. Especially vulnerable to this weakness are resins with metallic pigment.

GATE MARKS

Every injection-molded part has a gate or screw mark. A gate is necessary in order to produce a part; therefore, the size and location of the gate should be considered by the product designer to avoid an objectionable appearance.

Parts also have to be ejected from the mold, and the method of ejection must be considered. If no particular instructions are given to the mold builder, objectionable ejector-pin marks may be found on a surface. But if instructions are given as to which surface areas must be free of any ejection marks, the mold can be designed by the mold builder to achieve a defect-free surface.

In most gate marks, umbilical strands are still attached. However, with runnerless molding, tunnel gates, hot sprues, and other molding techniques, the visible mark can be reduced substantially. There are gating system improvements employing valves and pressure gates that facilitate the flow of material and reduce the injection pressure required. However, this technology falls more in the process and manufacturing engineers’ realm than in the design engineers’. It is important to recognize that a gate mark is one thing; whether or not it is large, rough, and objectionable, is another.

INADEQUATE DRAFT

Many times draft or taper is omitted from the design and, accordingly, ejection is difficult or impossible. Even if ejection is not impossible, the surface is often badly scored as it is ejected. Many times a part is designed with a perfectly parallel outside surface for appearance reasons. If the mold is not split to permit the part to be ejected without scoring the surface, it is necessary to use a cam mold and provide some minimal taper on the core so that it can be physically removed from the mold. When asked, designers sometimes say, “Well, it really didn’t have to be perfectly straight. We could have had some draft on it. Why didn’t you let me know?” Another example of the classic lack of communication between the mold builder and the mold designer.

Inadequate draft remains a problem. Regardless of improvements in materials, draft is still required to readily remove a part from the mold. The advantages of having taper, even a very slight taper, must be impressed on the design engineer as more important than the theoretical aesthetics of a perfectly flat, straight, or cubic object.

SINK MARKS

A perfectly flat plastic surface is more difficult to maintain and produce than a surface that is either concave or convex or has ribs or other decorative features. Irregular masses of plastic—that is, substantial localized differences in thickness of parts due to hobs, bosses, and ribs—will create sink marks on the surface if they are not properly designed.

It is possible to incorporate bosses and ribs without any unreasonable sink marks by following the rules of good design. For example, a rib or boss should not have an area greater than 50% of the wall or the surface to which it is tangent.

Sink marks are a problem that has benefited from recent improvements. Adding a slight amount of gasing or foaming agent to a resin will reduce sink marks where there is a large mass. With proper molding technology, if the amount of expansion material is minimal, the surface need not give any indication that a blowing agent has been added. Greater understanding of the relative wall-thickness requirements of ribs, bosses, and other features has sub-
CHAPTER SUMMARY

There is no reason to believe that the pressure for speed-to-market, increased quality, increased customer satisfaction and reduced product cost, will subside in the foreseeable future. Whenever a development team brings a new product design to market in record time, that time becomes the new standard to be beat. Many companies continue to cut market introduction time in half on a variety of products. The good news is that there is still room for improvement. The potential benefits offered by technology, DFM, and CE have yet to be fully exploited.

There are still too many companies that believe speed-to-market means throwing people at the problem and working weekends. For those companies, bringing a product to market faster means spending more money and compromising on design issues. For companies that have pursued optimizing the entire process, the overall costs have actually gone down and the final product is better than originally planned.

The technology and management system issues that should occur are summarized as follows:

TECHNOLOGY ISSUES

- Use of a 3D CAD model for concurrent manufacturing events.
- Use of multiple software packages to overcome weaknesses of individual systems and provide flexibility for individuals.
- Software compatibility with major customer base (robust IGES conversions).
- Use of solid modeling and rapid prototyping as quick visualization tools.
- Use of simulation software to increase comfort levels of part and tool design.
- Use of modelmaking to confirm accuracy of database, industrial design intent, and verify form, fit, and function.

- Functional models after completion of the part design for manufacturing input.
- Use of technology tools throughout the design-to-production process.

MANAGEMENT AND SYSTEM ISSUES

- Early involvement by the molder in part design.
- CAD personnel with materials, tooling, and processing aptitude—not CAD specialists!
- Need for a coordinated 24-hour mold building operation.
- Multifunctional work teams where each member brings something unique to the process.
- Quick transition from design on paper to design on CAD.

References

REFERENCES

CHAPTER 1

For more detailed information on plastic part design, consult these sources:

- General Electric Company, One Plastics Avenue, Pittsfield, MA 01201, phone (413) 448-7110.
- Engineering Plastics Division, Advanced Materials Group, Hoechst Celanese Corporation, 26 Main St., Chatham, NJ 07928, phone (201) 635-2600, fax (201) 635-4330.
- Mobay Corporation, Plastics and Rubber Division, Mobay Rd., Pittsburgh, PA 15205-9741, phone (412) 777-2000

Bibliography

Abler, Robert; Albert, Stephen; and Barry, Sr., Michael, “Time-Based Product Development,” Appliance Manufacturer (September 1991).

Beall, Glenn, Plastic Part Design for Injection Molding (Chester, CT: Paulson Training Programs, Inc.)


Goldsbury, Clare, “Firms Demand Short Lead Times For Molds,” Plastics News (February 8, 1993).


MATERIAL SELECTION

INTRODUCTION

The consumption of plastics in a variety of industries, ranging from electronics to transportation, will continue to rise through the end of the decade and beyond.1 Plastics in electronic applications are expected to experience the largest growth rate, while the transportation and construction industries, which are largely dependent on economic climates, are expected to experience a decline. Although the state of the economy is believed to have a strong influence on the growth rate of certain industries, and thus their consumption of plastic, some industries, such as appliances and toys, which are usually tied closely to economic liquidity of assets, are displaying moderate increases in expected growth rates.2,3

WHY USE PLASTIC?

The major advantages of choosing plastics as alternatives to metals are:

1. Performance and ease of manufacturing.
2. More cost-effectiveness than metal alternatives due to:
   • Less energy consumption because of lower weight.
   • Lower cost of tooling, especially for complex shapes and styling.
   • Faster tooling time.
3. Inherent corrosion resistance.
4. Styling latitude.

These advantages have led to the increased use of plastics, particularly in the transportation industry, for both interior and exterior applications. A variety of plastics are utilized in the transportation industry, ranging from thermoplastics to thermosets (these terms are discussed later).4,5,6,7

Recyclability, a key issue in many industries because of stricter governmental regulations in Europe, the United States, Canada, and many other countries, is a key determinant in the selection of plastics, particularly thermoplastics, because of the difficulty of disposing of solid waste.8,9 The cost of dumping is rising.

As a result of recycling mandates, the U.S. demand for recycled plastics such as polyethylene terephthalate, high- and low-density polyethylenes, polypropylene, polyvinyl chloride, and polystyrene, continues to rise.10

CONSIDERATIONS

The reasons for choosing a plastic are varied. Surface finish, paint curing latitude (related directly to the heat distortion temperature of the plastic), chemical resistance, impact resistance, ease of design and flexibility of processing, and material and part cost (including labor content, tonnage requirements, and scrap recyclability) are just a few of the typical considerations.

Especially in applications exposed to ultraviolet (UV) light, photodegradation behavior can be a major driving force behind the selection of a particular plastic. The photodegradation process in plastics is synonymous with the photodegradation of any polymer. The chromophores (usually any double bond containing moiety) in the plastic absorb UV light energy to generate excited states of radicals and inter- or intramolecular reactions. These chemical changes manifest themselves as appearance and physical property changes within the plastic material.

Photo-oxidation occurs in the presence of oxygen. The radicals generated by exposure to UV light react with oxygen in the atmosphere to generate the same appearance and physical property changes.

The correct selection of a photostabilizer for a given plastic is predicated on the wavelength sensitivity of the plastic to UV light. Table 2-1 lists the wavelengths of maximum energy absorption (given as activation spectra maxima) of selected plastics that result in the plastic’s photodegradation. Light stabilizers must be selected to preferentially absorb
light at the maximum wavelength sensitivity of the plastic. Light stabilizers sacrificially degrade instead of the plastic. More often than not, a blend of UV stabilizers is chosen to mask the range of wavelengths to which the plastic material is sensitive. The substrate is thus protected by choosing a UV absorber that has a high absorptivity at the wavelength of maximum absorbance of the plastic.

A plastic material is often selected for its relative stability in a variety of environmental conditions, such as humidity, light, and heat. Table 2-2 lists the relative stability of selected unstabilized (no UV stabilizer or antioxidant added) plastics to these environmental factors. For example, if maximum performance from a plastic material in a hot, humid, sunny environment is desired, the choice of polytetrafluoroethylene for the application would be optimum. If one could not afford the cost associated with this plastic, however, good performance is achieved through selection of a plastic such as polycarbonate. Don’t forget, however, that environmental considerations are not the only prerequisites that must be met in any selection. Factors such as solvent sensitivity, flexural modulus, and paintability, if desired, are only a few of the other properties that must be balanced to yield a material that will suit the application.

### SELECTION CRITERIA

Selection of engineering materials is a function of end-use application, environmental conditions, mechanical loading, cost, and recyclability. The suppliers’ technical support, teamed with material databases and selection work sheets, promote effective material selection decisions.

### Identify Functions

When selecting a polymer, a designer must first identify the principal function of the material. Functions might be: provide a support structure, protect from the environment, insulate thermally or electrically, seal in vapor, seal out liquid, transfer torque, absorb energy, or attract attention to a design element.

Once the primary function is identified, the application environment is categorized. Environmental conditions of concern are: temperature, light exposure (UV), humidity, chemical exposure, electrical voltage, and biological agents such as molds, insects, and rodents. Additives are available to enhance plastic part performance in selected environments.

### Types and Applications

While the magnitude of a load is critical, just as important is the type of load and how it is applied. Many plastic materials are viscoelastic and creep over time even with relatively low loading. As previously mentioned, plastics can be strengthened in several manners ranging from chemical means to glass reinforcing. The type of load (that is, tension, compression, flexural, impact, shear) must be considered, since plastics and plastic matrix composites are anisotropic (vary in the direction measured). Polymer chains align when stretched or while forced to flow through constrained channels, causing unequal strength in various axes. Reinforcing fibers and woven fabrics in composites are much stronger than the plastic matrix bonding them together and have different strengths in different directions, and thus are also anisotropic. Impact modifiers, often rubber polymers (elastomers), are incorporated into plastics to improve impact strength and toughness.

### Grades and Reinforcers

Plastics are available in various grades with various additives and reinforcers from several chemical companies and distributors. Weekly price comparisons by generic families are contained in Plastics News.

Recycling or permanent end use is now a key issue in material selection. Manufacturers must plan for life cycle costs including recycling or effectively disposing of products that they produce. With landfill costs at a premium and questions about energy recovery by incinerating, recycling options must be considered during the initial product design and material selection phase of a product.

### Varied Input

Chemical companies, plastics distributors, additive manufacturers, and reinforcement producers provide technical data and
support for plastic part producers. Sales representatives can provide recommendations based on technical laboratory data. Material selection decisions should be finalized only after lengthy discussions with sales representatives and their support staff.

Material databases and selection work sheets promote the objective analysis of various materials. Databases are available in handbooks and on software. Figure 2-1 illustrates a selection work sheet. Knowledge of materials, product application, and environment can be focused for effective decision making when material selection work sheets are used.

MANUFACTURING CRITERIA

Cost

Assuming the polymer is already synthesized, the costs associated with producing a particular device can be divided into raw material costs and processing costs. The cost for the polymer is mostly due to monomer costs, which in turn are proportional to the price of oil, since the starting point for most monomers currently is petroleum. Many monomers can be made from other naturally occurring feedstocks such as natural gas or even from renewable resources such as methanol or ethanol; the predominance of petroleum-based materials is attributable to economics.

As oil reserves become depleted in the next century, one would expect the cost of plastics to rise, unless more cost-efficient technology is invented to produce polymers from the other sources. Other raw material costs come from additives and can be a substantial part of the overall cost. However, fillers are often added to a product for reducing costs.

Processing costs typically are not large, but the initial capital expense can be. Other chapters discuss costs for the processing operations in detail, but some guidelines can be given here. Usually cycle times are short, therefore large numbers of parts can be manufactured in a short time. Often the limiting step is the cooling time, so complicated cooling mechanisms are often required. Unfortunately, faster cooling generally results in more frozen-in stresses. Most operations produce some unusable material as part of the process, so a method of recycling already processed material is important. Loss of temperature control is usually disastrous, since an intractable solid polymer mass may result.

Material Safety Concerns

Generally, polymers are extremely inert although monomers can be dangerous. Therefore, polymer handling issues are not usually crucial, with one major exception. Since polymers are electrical insulators, static charge can build up on a surface, so proper grounding procedures are important. Dust is also a concern, but is not difficult to control.

When synthesizing polymers, the producers must understand the health risks associated with monomers. Typical monomers are low-molecular-weight, highly reactive organic compounds; these represent some of the worst chemical hazards normally encountered in the chemical industry. Also, many polymerizations are highly exothermic so one must be sure adequate temperature control is available. An adequate safety program must be in place before any polymerization is attempted.

Characterization of Raw Materials and Final Product

As with all processes, the raw material must be of consistent quality to produce a consistent product. Visual inspections of the product are crucial; is the polymer off color or does it have an odor? Similarly, visual inspection of the final product is necessary to identify any problems such as bubbles. More sophisticated characterization is determined by the important parameters of a finished part. This section will briefly review commercially available instruments used for raw material and product evaluation. More details are provided in the general texts appearing in the Bibliography.

Molecular Weight

One important characteristic of a polymer is its molecular weight. A number of techniques are sensitive to the molecular weight of a polymer; this section will focus on two of the most popular characterization techniques. Both of these methods measure relative rather than absolute molecular weight; the reader is cautioned that absolute molecular weight methods are difficult, time-consuming, and subject to contaminants. Even in academic settings, only very rarely is absolute molecular weight measured.

The molecular weight of a polymer has a substantial effect on melt viscosity. The viscosity for polymers above a certain molecular weight (most products are well above this value) increases as the molecular weight to the 3.4 power. Therefore a simple viscosity measurement at a single shear rate can be used as a sensitive measure of relative molecular weight. A very rough measure of molecular weight historically has been the melt flow index, which is defined as the amount of polymer (in grams) extruded under a 4.8 lb (2.17 kg) load at 374˚ F (190˚ C) in 10 minutes. This set of conditions was originally developed for polyethylene. Other conditions have been developed for other polymers. With the development of personal computers, linear viscoelastic rheological testers are commercially available and provide a highly sensitive measure of polymer rheology.

With simple viscosity measurements, it is impossible to be sure whether viscosity changes are due to molecular weight variations; since compositional changes, different branching levels, or additive levels can all affect the rheological behavior. If the polymer can be dissolved, then size exclusion chromatography (SEC) (also known as gel permeation chromatography [GPC]) can be used to separate molecules on the basis of molecular weight. In SEC, a column is filled with a highly cross-linked polystyrene gel having pore sizes of the same dimensions as the polymer molecules being investigated. Small molecules can diffuse into the pores more readily than larger ones, hence if a solution of polymer is introduced into one end of the column, large molecules will pass through faster than small ones. By measuring the concentration of polymer effluent as a function of time and comparing it to a series of standards with known molecular weight, the entire molecular weight distribution can be determined.

One necessarily assumes the size distribution is the same as the molecular weight distribution and usually this assumption is reason-
ably accurate. To measure molecular weight for a particular polymer accurately, the column is calibrated with known molecular weight standards of that polymer in the same solvent. Sometimes this is not possible, therefore a common practice is to state a molecular weight relative to some standard, with polystyrene being the most common. The measurement is typically very quick and requires only a small amount of polymer. There are only two common problems with this technique. The additives commonly found in polymers may stick to the beads in the column, clogging the pores and destroying the columns. Also, it may not be possible to find a solvent for the polymer that is also compatible with the beads. If these two issues are resolved, then SEC is the easiest and, all things considered, the best method to characterize molecular weight.

**Measuring Crystallinity**

The fractional crystallinity will have a large effect on polymer properties. It may also be useful to know the rough composition of a composite or a polymer with a large number of additives. Thermal testing is useful for these problems. In differential scanning calorimetry (DSC), the heat capacity of a polymer is measured as a function of temperature; the melting transition appears as a peak in the DSC spectrum. By measuring the enthalpy involved in the transition, the percent crystallinity can be determined since the enthalpy for 100% crystallinity can usually be found in the literature. In thermogravimetric analysis (TGA), the weight of a polymer is measured as a function of temperature. Knowing the weight loss at the decomposition temperature of a component, one can determine the amount of the component in the material.

Another common method exists to measure the percent crystallinity of a polymer. For all polymers, the crystalline material is more dense than the amorphous material. The percent crystallinity can be determined by measuring the density, knowing the 100% amorphous and 100% crystalline densities. The simplest way to measure density is with a density gradient column. In this method, two (or more) somewhat miscible solvents having different densities are mixed. If mixing is done carefully, a column with a continuously varying density gradient is produced. A series of balls that have different known densities are placed in the column and used for calibration. The polymer is then placed in the column and its density determined by its final settling position relative to the balls. The only restriction on this measurement is that the polymer does not dissolve in either solvent.

**Processibility**

Polymers can be difficult to process because of their high viscosity and unique rheological behavior. Almost all polymers are processed as melts because of the prohibitive cost and safety problems associated with solvents. Typically polymers are received as pellets, so the first step is to melt the pellets. Actually, polymers must be treated carefully since many polymers are melted close to the degradation temperature. Proper mixing must be provided because additives can separate from the polymer without mixing. Obviously, high-torque mixers are required because of the high viscosity. Almost all polymers are shear thinning and the power law relationship below is usually an excellent description of the relationship between stress and viscosity:

\[
\tau = m(y)^n
\]

where \(\tau\) is the stress, \(m\) is a constant, \(y\) is the shear rate, and \(n\) is the power law index. Typical power law indexes for most polymers are between 0.2 and 0.8. The power law parameters for many polymers are found in the book by Tadmor and Gogos (see Bibliography). Polymers are generally shear-thinning because the polymer molecules tend to align in the flow direction. Hence even before entering the final processing step, polymers typically already have some preferential orientation.

Adsorbed water must be removed before the final processing step, since steam will cause voids in the final product. Often the original product is stored in nitrogen-blanketed dryers to remove any water that might have been introduced during transport. Obviously, the procedure may need to be adjusted for higher humidity conditions during the summer. Also, polymers that are not normally hygroscopic may have additives that do adsorb water. Finally, the processing temperature must be strictly controlled since some polymers may depolymerize to monomers; this can cause bubbles in the final product and may also be a serious safety hazard.

Polymers shrink when cooled. Generally, the thermal expansion coefficient of a polymer is larger than metal. Also, polymer crystals are more dense than the amorphous melts, so crystallization also leads to shrinkage. Finally, for reactive processes like reaction injection molding, the product typically has a lower total volume than the reactants. Predicting shrinkage of a part is difficult, which is another reason to manufacture a prototype before beginning commercial production. If cooling is done only on the outside shell of a part, internal voids can form since the outside forms a hard rigid shell while the inside is still molten.

**Die Swell**

As a polymer under pressure passes through a hole into a larger opening, the polymer will swell so that the diameter of the polymer exiting the hole is larger than the hole diameter. Typically, die swell decreases with an increase in temperature and decreases with molecular weight. Die swell also increases with shear ratio until, at a certain point, it remains constant or even decreases. Operating in this high shear rate region will cause flow instabilities and probably should be avoided.

**Color**

Physical properties of the finished molding or extrusion are affected by the colorants used and the methods of using them. Carbon black is a good conductor of electricity, but properly dispersed in resin, becomes a good cable insulator. There is a story in the field about a molder of trash cans who added a yellow to an established line of green, gray, and black cans. Same density of polyethylene, same mold, same cycle—but the yellow cans had a great deal of environmental stress cracking. There are many stories of color bleeding, oxidation of resin by colorants at high temperatures, and flame retardants that tend to yellow with age. Color is used for appearance, but colorants and the methods of selection and use affect the properties of a product as well (see “Color in Plastics” in this chapter).

**Properties**

A good way to examine differences between materials, in addition to chemistry, is to look at mechanical and physical properties. Mechanical properties tell how a material reacts to an applied force and physical properties tell how a material reacts to heat, electricity, light, magnetism, and chemicals (see “Measuring Properties,” in this chapter). Mechanical properties relate to the strength, hardness, and toughness of engineering materials. If a material is to be used to support a load, transmit a force, hold components in an assembly, or resist wear, it must be strong enough; that is, it does not break, does not bend, holds its shape, or is hard. Com-
mon descriptions like these are expressed quantitatively by measurements of mechanical properties.

**SUMMARY OF MATERIAL SELECTION GUIDELINES**

Choosing a type of polymer for a certain application is difficult. This is not only because of the large number of polymers available, but also because other types of substances such as metals and ceramics are often considered as well. As a general rule, polymers have the following advantages and disadvantages with respect to other types of materials:

1. Polymers can be rubbery. For an application where a rubbery material is necessary, polymers are essentially the only option.
2. Polymers are resistant to normal atmospheric conditions as well as to very acid or basic environments. This resistivity means that polymers can be used in many environments where metals and ceramics cannot, but this also means polymer waste products degrade extremely slowly or not at all. However, organic solvents will swell or dissolve many polymers.
3. Although polymers may not show visible signs, aging is a problem. Typically, polymers may warp, shrink, creep, or become brittle over a period of years. Many of the additives in polymers are used to reduce problems associated with aging.
4. Most polymers do not have the high-temperature stability of metals or ceramics. The basis of polymers is the carbon-carbon bond which is stable to only about 700˚F (370˚C). Most other organic bonds are stable to temperatures far below this value.
5. Polymers are electrical insulators. The thermal conductivity of polymers is also low.
6. The cost of polymers varies widely. Some polymers are extremely inexpensive, and these polymers have replaced more expensive materials in our daily lives. For example, it is easy to recognize where lower-cost polymers have replaced other materials in common kitchenware. Polymers that can replace structural or load-bearing materials generally cost more than the metal counterpart, but the weight of material is usually much lower.

To make an informed choice about a material, the properties that are important for a particular application must be determined. Then, these properties are translated into material characterization measurements available in product literature. The remainder of this Chapter discusses some general concepts associated with polymer properties. Further information is found in the Bibliography.

**Mechanical Properties**

The distinctive mechanical properties of polymers have been the most important reason for the widespread use of these materials in everyday life. Polymers can be both rigid and flexible, and models used to describe mechanical properties contain both types of terms. A general rule of thumb is that polymers at short times or low temperatures will have properties associated with a glass, while polymers at long times or high temperatures will have properties associated with viscous liquids. However, polymers also have many properties not normally associated with viscous liquids, such as die swell and second normal stresses. (See Chapter 2 of Dynamics of Polymeric Liquids, listed in the Bibliography, for an excellent description of a number of unique phenomena.) Also, solid polymers can gradually change shape over many years in response to stresses frozen in during the manufacturing process.

There are many measures of mechanical properties, such as tensile strength, impact resistance, tear resistance, and hardness. In polymers, as in most materials, sample failure generally starts around some inhomogeneity within the sample, such as a microscopic crack or a dust particle. To improve the reproducibility of measurements, tests are designed so that the stress is concentrated in one area and sample failure occurs at this point. Therefore, tests should be used only as relative measures and should not be treated as absolute measures of performance. Unfortunately, predictions of mechanical properties for a given shape are not very accurate, which means that usually a prototype part must be built. Scaling up the results of smaller prototypes is also extremely difficult.

**UNIQUE QUALITIES**

Polymers are extremely unusual materials, in both structure and properties. Fundamentally, this distinctiveness arises from the large molecular weights. In fact, a single polymer sample will probably have molecules with many different molecular weights, in stark contrast to other materials where the structure and molecular weight uniquely determine the compound. Instead of listing the entire molecular weight distribution for a polymer sample, average measures aid the selection of materials. The three most common are:

\[
M_w = \frac{\sum x_i(Nm)}{\sum x_i} \quad \text{or} \quad M_x = \frac{\sum x_i(Nm)^2}{\sum x_i(Nm)} \quad \text{or} \quad M_f = \frac{\sum x_i(Nm)^2}{\sum x_i(Nm)}
\]

where:

- \(x_i\) = number of molecules with \(n\) repeat units
- \(M\) = molecular weight of the repeat unit

Qualitatively, higher molecular weight species are more important in determining the average as one moves from left to right.
above, and $M_\text{w} > M_\text{n} > M_\text{z}$. A very common single parameter that measures the breadth of the molecular weight distribution is the polydispersity index, defined as the ratio $M_\text{w}/M_\text{n}$. The polydispersity index (as well as the molecular weight) depends on polymerization conditions, but most commercial polymers have polydispersity indexes between 1.5 and 5 and $M_\text{n}$ between 10,000 and 100,000.

**MELT VISCOSITY**

The effect of molecular weight on polymer properties can be significant. Of extreme importance is the melt viscosity. The melt viscosity rises as the first power of the average molecular weight below some critical molecular weight (typically near a molecular weight of 10,000) and as the 3.4 power above this weight. Mechanical properties are usually not as severely affected, as long as the degree of polymerization is above this critical value. The melt viscosity is also affected by the polydispersity since the presence of just a small amount of low-molecular-weight material will decrease the melt viscosity dramatically. In fact, small molecules called plasticizers are purposely added to a polymer to improve the processibility. Plasticizers, along with other polymer additives, will be discussed later in this chapter.

The structure of a polymer cannot always be written as $(A)_n$. Materials that have this type of structure are termed linear polymers. There are two other types of polymers, branched polymers and network polymers. If one envisions a single molecule of a linear polymer as a long metal chain with each link representing a repeat unit, then a branched polymer has other smaller chains hanging off the long chain. Network polymers are those where a series of long chains are connected by these short branches. The process of forming a network polymer is termed cross-linking. Therefore, the molecular weight of a network polymer is essentially infinite, that is, a sample of a network polymer is just one extremely large molecule.

**COPOLYMERS**

Polymers with more than one repeat unit, that is, $A$ and $B$ units, are termed copolymers. Linear copolymers come in two different types: random and block. In random copolymers, the distribution of the $A$ and $B$ units has no recognizable structure: $\text{AAAABBBBAAAABBBB}$... while in block copolymers, the units are grouped in $A$-rich blocks and $B$-rich blocks: $\text{AAAAAAABBBBAAAABBBBAAAABBBB}$... In branched systems a graft copolymer signifies that the main chain consists of $A$ units and branches consist of $B$ units. Clearly classifying structures on this basis can quickly become troublesome because nothing prevents a third monomer being added.

**THERMOPLASTICS AND THERMOSETS**

Polymers are usually classified in terms of their properties rather than their structure. Polymers are divided into the thermoplastic and thermosetting categories. Thermoplastics can be made to flow by heat and pressure, while thermosets cannot. This fundamental processing difference is caused by a fundamental structural difference, since thermosets are network polymers while thermoplastics are not. The synthesis of thermosets requires the end product to be in the form of the final part. The most common application of thermosetting polymers is automobile tires. Thermoplastic polymers can be shaped and formed into nearly any shape.

**BULK PROPERTIES**

Polymers can also be categorized according to bulk properties. Table 2-3 presents a classification scheme that conveniently divides polymers into six classes. The rigidity or flexibility of a polymer is determined by its thermodynamic state. Polymers, even thermosets, have a glass transition temperature $T_g$, which is a temperature at which local thermal motions are greatly reduced. Below this temperature, both thermoplastic and thermosetting polymers have the characteristics associated with inorganic glasses such as brittleness, hardness, and inflexibility. Above $T_g$, thermoplastic polymers behave as very viscous liquids, while thermosetting polymers are rubbery, unless crystallization occurs.

**CRYSTAL STRUCTURES**

As with small-molecule compounds, crystallinity implies that the atoms lie in a well-defined pattern over large distances. Amorphous polymers do not have atoms lying in such patterns. A highly crystalline synthetic polymer is one in which the number of chains in crystalline regions is 80% or greater and the number of chains in amorphous regions is 20% or less (synthetic crystalline polymer is never 100% crystalline). The melting temperature $T_m$ is always greater than the glass transition temperature. Thermoplastic polymers that can crystallize typically have three regimes of mechanical properties: a rigid regime below $T_g$, a flexible regime between $T_g$ and $T_m$, and a viscous regime above $T_m$. Thermosetting polymers are rigid below the glass transition temperature and rubbery above it. The stiffness of the rubber is controlled by the fractional crystallinity and the number density of cross-links.

Polymer sales in the United States during 1993 are shown in Table 2-4. This table lists the amounts for each type of polymer and is separated into three general categories: thermoplastics, thermosets, and fibers. Fibers and thermoplastics are treated in the same manner within this chapter since the differences between them are only in processing.
The selection of plastic materials depends, like all engineering materials, on the application and the loads encountered over the product life span. Plastics have some special environmental limitations, especially temperature, which must be kept in mind. Many plastics are viscous materials, meaning they are semisolid and tend to creep or deform over time when loaded. Creep rate increases as temperature increases. Other polymer materials are elastic and have the ability to store energy by deforming, then snap back when forces are removed.

DIFFERENCES

The terms plastic and polymer are often used interchangeably, and both need to be understood. Plastic may be used as a noun or as an adjective describing a condition. Plastic as an adjective refers to the ability of a material to be shaped and formed by inelastic deformation. Plastic as a noun refers to a group of engineering materials consisting of large macromolecules that exhibit plastic characteristics while being processed. Polymer, a more general term, describes macromolecules often used in engineering applications, but also existing in nature. Polymers may exhibit plastic and elastic mechanical characteristics. Polymers include rubber materials and other elastomers that can stretch to twice their original length and return with little deformation. It should be realized that much of the fundamental chemistry and many of the processing techniques are similar for plastics and rubber compounds.

POLYETHYLENE

The most common plastic is polyethylene (PE) which consists of a long backbone of carbon (C) atoms with two hydrogen (H) atoms attached to each of the carbons. A complete chain of several hundred carbons and hydrogens is an example of a macromolecule. Figure 2-2 illustrates the chemical structure of polyethylene and shows that PE chains are long and slender, with a physical arrangement much like spaghetti on a plate.

Polyethylene has no atoms that link one chain to another. Chains are held to one another by weak forces that are easily overcome by heat, allowing easy melting. Thermoplastic is the term applied to materials like polyethylene that can be repeatedly heated, shaped, then cooled to maintain a new shape.

POLYESTER

Thermoset plastic materials have atoms that link one chain to another. This chemical link or bond is much stronger than the weak forces of a thermoplastic and, in fact, when a thermoset is cured, it cannot be remelted and reformed. Figure 2-3 illustrates a
common thermoset plastic material, polyester, which is used as the adhesive matrix in fiberglass auto body parts. The backbone of the plastic is different from the simple PE chain, and, more important, the chains are chemically bonded to one another by cross-links.

**Butadiene**

Figure 2-4 shows a polymer called butadiene. Butadiene is an elastic material, or rubber, often used in industry. Note that uncured or raw butadiene has a chemical structure much like polyethylene. This suggests that it can be heated and formed like a thermoplastic. After curing (vulcanizing), however, butadiene has cross-linked and become a thermoset, unable to be remelted and reformed.

Manufacturing engineers are increasingly called on to process polymer materials and understand their selection and application. This chapter reviews applications of plastics to products, introduces polymer chemistry, outlines methods of strengthening and enhancing polymers, illustrates common tests for mechanical and physical properties, and provides a format for making material selection.

**APPLICATIONS OF PLASTICS TO PRODUCT TYPES**

With the exception of a few natural polymers like pitch, natural rubber, and wax, few plastic materials existed prior to the late 1800s and early 1900s, when cellulose nitrate and phenolics were developed. These materials, though limited in mechanical and physical attributes, opened up new markets in areas like moving pictures and molded electrical components. In the late 1930s and the 1940s, a war-focused economy advanced technology to develop numerous new plastic materials, in an attempt to substitute these new materials for traditional materials that had been made scarce by military action and blocked trade routes.

**POLYMERS**

From World War II through the 1980s, hundreds of new polymer compounds were formulated for the plastics market. Common materials were categorized as commodity items and included materials like polyethylene, polypropylene, and polystyrene. Chemical companies often hold trade names for various formulations of these plastics. Engineered plastics like nylon and polycarbonate are a second category of plastics with improved physical and mechanical properties. In addition to commodity and engineered plastics, special-purpose plastics also have been developed for unique applications in extreme thermal, load, and environmental applications.

The environmental movement, stressing sorting and recycling, has forced plastic manufacturers and processors to rethink the concept of using a unique plastic for a unique application. A directed movement has shifted manufacturers toward fewer types of plastics with more universal applications. This has promoted easier sorting of recycled plastics with less commingling of dissimilar material. Streams of pure used plastic are far more valuable and reusable than streams of commingled junk plastic.

**MARKETS**

The plastics market can be segregated into packaging, construction, transportation, consumer products, electricity/electronics, and textiles. Within the market, some ten types of plastics make up the bulk of U.S. consumption. Figure 2-5 illustrates the typical annual production of various polymers in the United States. Polyethylene is the most commonly used material and is known for applications from film to milk jugs to chemical barrels.
Polyvinyl chloride (PVC) is known for construction applications in vinyl siding, window cladding, and electrical wire insulation, as well as flexible clothing and upholstering. It should be noted that, on a tonnage basis, the thermoset plastics are not used as frequently as thermoplastics. Thermosetting urethanes, phenolics, amines, epoxy, and polyesters are less common than thermoplastic polyethylene, PVC, polystyrene, polypropylene, thermoplastic polyester, acrylic, and nylon.

**Packaging**

Packaging is the fastest growing and largest market for plastic material. Food packaging, chemical containers, shipping insulation, shrink wrap, and plastic-coated papers represent this important area. Table 2-5 lists several common packaging applications and the plastics typically used in those applications.12

<table>
<thead>
<tr>
<th>Packaging Resin</th>
<th>Applications</th>
<th>Percent of Total Plastic Packaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-density polyethylene (HDPE)</td>
<td>Film, bottles</td>
<td>30</td>
</tr>
<tr>
<td>Low-density polyethylene (LDPE)</td>
<td>Film, bottles</td>
<td>25</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td>Bottles, film</td>
<td>12</td>
</tr>
<tr>
<td>Linear low-density polyethylene (LLDPE)</td>
<td>Film</td>
<td>8</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>Closures, EPS</td>
<td>8</td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>Film, closures</td>
<td>8</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>Bottles, film</td>
<td>6</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Total percent</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

**Construction**

Building construction is the second-ranked market for plastic material. Foamed insulation board, extruded vinyl siding, extruded piping, vapor barrier film, underlayment for shingles, bath/shower units, and countertops are but a few of the building applications seen today.13

**Transportation**

Transportation systems see wide application of plastic and rubber parts and are often ranked number three in the total U.S. market. Plastics compete effectively for applications in transportation because of their low weight, low cost, and ease of manufacture. Common areas of use include upholstery, trim, body panels, air ducts, filters, carpets, fuel tanks, and engineered components such as intake manifolds. Table 2-6 shows typical plastic material applications in the automotive industry.14

**Electrical/Electronic**

Electrical/electronic products have traditionally used large quantities of polymer material. The most basic application is wire coating and insulation. Other fundamental uses are circuit boards, computer and entertainment center housings, and computer and electronic storage mediums. Table 2-7 shows consumption of plastics in electrical and electronic applications by type of plastic.15

**Consumer Products**

Consumer and institutional products, while using far less plastic than other category areas, are important to the part producer. Included in this category are housewares, small appliances and tools, sports and recreation equipment, toys, footwear, baby pants, and medical supplies.
### TABLE 2-6
Automotive Materials and Issues Affecting Them

<table>
<thead>
<tr>
<th>Material</th>
<th>Applications</th>
<th>Key Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>Most interior components, heating and air conditioning ducts and modules, under-the-hood covers, bottles, battery housings, emission components, bumper fascia, side-body molding, rocker covers, air dams, radiator grilles</td>
<td>Interior: problems with scratching and adhesion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Under-the-hood: insufficient high-temperature resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exterior: lack of paintability</td>
</tr>
<tr>
<td>High-density polyethylene</td>
<td>Fuel tanks, bottles</td>
<td>Permeation of gasoline through fuel tank walls</td>
</tr>
<tr>
<td>PVC</td>
<td>Instrument and door panel skins, seats, headliners, hoses, side-body molding</td>
<td>Recycling concerns are reducing use</td>
</tr>
<tr>
<td>ABS</td>
<td>Instrument and door panels, other interior trim</td>
<td>Competition from polypropylene</td>
</tr>
<tr>
<td>Nylon</td>
<td>Intake manifolds, electrical and electronic components, under-the-hood covers, fuel and brake lines, permeation barrier materials, connectors, emission components, wheel covers, mirror housings</td>
<td>Consolidation of grades, especially nylon 6/6; need for high-temperature resistant grades, moisture absorption</td>
</tr>
<tr>
<td>Thermoplastic polyesters</td>
<td>Motor housings, electrical and electronic components, connectors, covers</td>
<td>Competition with nylon</td>
</tr>
<tr>
<td>(PBT and PET)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Foam for seats, carpeting and headliners</td>
<td>Recyclability</td>
</tr>
<tr>
<td>Polyester thermosets</td>
<td>Exterior panels, valve covers</td>
<td>Recyclability</td>
</tr>
</tbody>
</table>

(Courtesy ITB Group and McGraw-Hill Modern Plastics Encyclopedia ’94)

### TABLE 2-7
Worldwide Consumption of Plastics in Electrical and Electronic Applications, by Resin, 1992 (million lb)

<table>
<thead>
<tr>
<th>Resin/Application</th>
<th>U.S.</th>
<th>Non-U.S. a</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>225 (E)</td>
<td></td>
</tr>
<tr>
<td>Consumer electronics</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Electronics</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Telecommunications</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Epoxy</td>
<td>50</td>
<td>123 (J)</td>
</tr>
<tr>
<td>Electrical laminates</td>
<td>51</td>
<td>168 (E)</td>
</tr>
<tr>
<td>Wire and cable</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>HDPE</td>
<td>147</td>
<td>66 (E)</td>
</tr>
<tr>
<td>Wire and cable</td>
<td>390</td>
<td>432 (E), 179 (J)</td>
</tr>
<tr>
<td>LDPE/LLDPE</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Phenolic</td>
<td>51</td>
<td>168 (E)</td>
</tr>
<tr>
<td>Wire and cable</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Electrical/electronic</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Electrical laminates</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Polyacetal</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Electrical/electronic</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Enclosures</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Polyester (unsaturated)</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2,166</td>
<td>2,150 (E), 1,500 (J), 1,500 (R)</td>
</tr>
</tbody>
</table>

(Courtesy Plastics Custom Research Services and McGraw-Hill Modern Plastics Encyclopedia ’94)

a. E - Europe; J - Japan; R - Rest of world
c. Includes both additional end-use applications for the resins cited above and other resins for all electronic applications.
This section will briefly look at atomic structure, review concepts of the periodic table, discuss types of primary and secondary chemical bonds, then illustrate crystal and amorphous structures as seen in polymers.

**ATOMIC STRUCTURE**

The basic unit of matter is the atom. Figure 2-6 shows the common graphical model for an atom. An atom is composed of a positively charged nucleus that attracts negatively charged orbiting electrons.

Negative electrons orbit the positive nucleus at certain distance intervals, or shells. These shells can accommodate a limited number of electrons. Only two electrons can exist in the first shell. Other atomic shells are subdivided into levels, and each level within a shell can possess a maximum of eight electrons.

**PERIODIC TABLE**

The periodic table (Table 2-8) shows more than 100 different elements with hydrogen (H) on the top left and Lawrencium (Lw) on the bottom right. Notice that as you move from left to right, a number in the top left of each box is incremented by one. Hydrogen (H) has one proton and one electron. Helium (He) has two protons and two electrons. Lithium (Li) has three protons and three electrons. It becomes obvious that each of the different elements has a different number of protons and electrons from all the other elements. Carbon has an atomic number of 6 and a weight of 12 and is located in the IVA column.

Each box containing an element abbreviation has a second number in addition to the atomic number. This second number is the atomic weight. The protons and neutrons are the principal components of the atomic weight. It should be noted that all atoms of an element do not necessarily have the same number of neutrons. An element may have atoms with different numbers of neutrons. The number of protons in an atom determines what element it is. A nucleus contains protons and neutrons, and their sum is called the atomic weight. Isotope is a term for an atom of an element whose atoms have different numbers of neutrons, that is, the same atomic number but different atomic weight. If an atom has the same number of orbiting electrons as protons, it is electrically neutral. For example, copper (Cu) has an atomic number of 29 and normally has 29 electrons. If an atom loses or gains an electron it is no longer electrically neutral. An extra electron makes it negative while a missing electron leaves it with more positive than negative charges, so it is positive. A charged atom is called an ion. Ions may conduct electricity or react with other appropriately charged ions to form chemical compounds.

As stated earlier, atomic shells are divided into levels with the maximum number of electrons in each level being eight. As a matter of fact, atoms desire a filled outer electron level. Except for hydrogen (H), helium (He), and other low atomic number elements, atoms desire to have eight electrons in the outer level. To achieve eight electrons in the outer level, atoms may give up electrons, acquire electrons, share electrons, or float positive nuclei in a sea of electrons. The methods used by atoms to achieve a full outer electron level dictate the chemical nature of elements.

The periodic table, in addition to atomic numbers and weights, shows important relationships between elements. Each column has a Roman numeral at the top showing the number of electrons in the outer level of elements in the column.

Looking to the right of the table, one finds VIIA, with fluorine (F), chlorine (Cl), bromine (Br), and iodine (I) underneath. Each of these elements has atoms with seven valence electrons and could be expected to accept one electron, becoming a negative ion. Column IVA, with carbon (C), silicon (Si), and germanium (Ge), contains elements with atoms possessing four valence electrons. Column IVA atoms can be expected to share electrons with other atoms to achieve a full valence level. Note that column IVA materials form the basis for organic materials and most polymers and semiconductors.

In addition to atomic numbers, atomic weights, and valence numbers, the periodic table shows other kinds of relationships between elements. Since all the elements in a column have the same valence number, they have similar chemical properties and tend to react with other elements in similar ways. Elements farther down the columns have greater weight, higher melting temperatures, and higher boiling temperatures than those above them.

Three types of primary chemical bonds have been identified by chemists: ionic, covalent, and metallic. When atoms of elements are chemically bonded together, they form molecules of new compounds that have properties different from those atoms from which they were formed. A good example is the chemical combination of hydrogen (H) and oxygen (O) to form water (H₂O). Hydrogen and oxygen are both gases but when combined in the right proportions under certain conditions, they form a molecule of water.

**IONIC BONDS**

Ionic bonds, as suggested by the name, involve the loss and acquisition of electrons by atoms to create ions. A common example of this bond is table salt, NaCl (sodium chloride). Sodium is a metallic element with a valence of one. Chlorine is from the halogen family and possesses seven electrons. As stated earlier, atoms desire to have filled outer electron shells. In this case, sodium atoms give up their valence electrons to chlorine atoms. As illus-
in Fig. 2-7, the sodium atoms are now positive in charge and attract the negative chlorine atoms. Ionic bonds yield materials that are often solids with a high melting temperature, possessing strength, but brittle. Some ceramic materials are made up of atoms ionically bonded to other atoms and held in a crystalline structure.

**COVALENT BONDS**

Covalent bonds are formed when atoms share electrons to satisfy the desire for eight electrons in the outer level. Covalent bonds range from water (H₂O) to polyethylene (1000[(C₂H₄)₆]).

Polyethylene has a long carbon chain, perhaps 1,000 carbons long. Figure 2-8 shows a polyethylene chain 2,000 carbons long or 2,000 mer (repeat units). The dashed lines represent a shared electron and the angle between the carbons of 109˚ illustrates the three dimensional angle that exists in nature. The brackets with the subscript 2,000 show that the chain is 2,000 units long. As shown, carbon shares its four valence electrons with adjacent atoms and covalently meets the need for eight valence electrons. Hydrogen shares its one electron with one electron from an adjacent atom to form a shared pair, thus satisfying its need to have a complete valence shell of two electrons. Covalent bonds are strong chemical bonds yielding a variety of mechanical and chemical properties.

Organic compounds are based on the carbon (C) atom, as are most polymers (plastics and rubbers). It should be noted that even though polymer chains like polyethylene are bound by strong covalent bonds, bonds may swivel in three dimensions as long as the 109˚ angle is maintained.

**METALLIC BONDS**

The metallic bond exists when nuclei of metals float in a sea of relatively free electrons. Copper and iron (Fe), two commonly used engineering materials, can be seen from the periodic table to be rather complex atoms. With several filled electron shells between the positive nucleus and the distant valence electrons, little force attracts the valence electrons to the parent nuclei. As a result, valence electrons in these and other metals are somewhat free to drift from one atom to the next. The negative charges tend to hold the atoms in a structure and give strength as well as ductility (formability).

**RULES OF BONDING**

Elements to the left side of the periodic table are metal-like in character. In general they are solids, have a shiny appearance, are ductile (formable), often dissolve in water, and conduct electricity. Elements to the right are nonmetals often forming compounds

---

**TABLE 2-8**

**Periodic Table of Elements**

<table>
<thead>
<tr>
<th>Group IIA</th>
<th>Group IIB</th>
<th>Group IIIA</th>
<th>Group II</th>
<th>Group III</th>
<th>Group IV</th>
<th>Group V</th>
<th>Group VI</th>
<th>Group VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Be</td>
<td>Mg</td>
<td>Al</td>
<td>Si</td>
<td>P</td>
<td>S</td>
<td>Cl</td>
<td>Br</td>
</tr>
<tr>
<td>Li</td>
<td>Na</td>
<td>K</td>
<td>Rb</td>
<td>Cs</td>
<td>Ba</td>
<td>La</td>
<td>Ce</td>
<td>Pr</td>
</tr>
<tr>
<td>Be</td>
<td>Mg</td>
<td>Ca</td>
<td>Sr</td>
<td>Ba</td>
<td>Lu</td>
<td>Ac</td>
<td>Th</td>
<td>Pa</td>
</tr>
<tr>
<td>Mg</td>
<td>Ca</td>
<td>Sr</td>
<td>Ba</td>
<td>La</td>
<td>Lu</td>
<td>Ac</td>
<td>Th</td>
<td>Pa</td>
</tr>
</tbody>
</table>

---

Lanthanide series

Actinide series
with (C) called organic compounds. Organic materials may be solid, liquid, or gas; they do not readily conduct electricity or dissolve in water. There are three general rules of chemical bonding. While the rules are not absolute, they give a guide for the non-chemist: 

1. Metals bond to nonmetals usually by ionic bonds.
2. Nonmetals bond to nonmetals usually by covalent bonds.
3. Metals do not usually bond to different metals but form alloys, which are mixtures, not chemical compounds.

SECONDARY BONDS

In addition to the strong primary chemical bonds, weaker secondary bonds exist. These bonds are often electrical in nature but result more from slight charge imbalances in molecules, due to the geometry of the molecule, than from sharing or trading electrons. The secondary bond of concern in thermoplastics is the van der Waals bond that holds polymer chains (like polyethylene) in a structure, one chain to another. Thermoplastics may be melted, formed, then cooled to hold the desired form. The melting does not break the covalent bonds that hold the -C- chains together, but overcomes the weak van der Waals bonds allowing the chains to slip across one another and take the shape of a pattern or mold cavity. When the thermoplastic is cooled, the van der Waals forces once again hold the chains in a spatial relationship.

AMORPHOUS OR CRYSTALLINE

Solids exist as amorphous or crystalline substances or combinations of the two. Amorphous materials such as glass, paraffin, and pine pitch, and plastics like polyvinyl chloride, polystyrene, and polycarbonate, have no definite melting temperature and possess little internal long-range order. Crystalline materials like table salt, iron, copper, polyethylene, polypropylene, and nylon have definite melting temperatures and possess a stable internal order. Amorphous materials in an uncolored state are relatively transparent since crystals are not present to diffuse the passage of light.

Plastics do not crystallize as metals and salts do; rather, they achieve long-range order and crystallize through close packing of long chains, as seen in Fig. 2-9. Amorphous plastic chains, though long, are not able to pack closely together, and thus have little long-range order, or crystallinity. While crystallization in plastics is somewhat dependent on temperature, only plastic chains like polyethylene and nylon crystallize to any significant amount and even they are not 100% crystalline, ranging upward to 90% crystal and 10% amorphous (HDPE).

MOLECULAR WEIGHT

The molecular weight of a polymer is equal to the sum of the atomic weights of the atoms in the chain. One mer of polyethylene consists of two carbons and four hydrogens. The periodic table shows the atomic weight of carbon as 12 and the atomic weight of hydrogen as 1; therefore, the weight of one mer is 12 + 12 + 1 + 1 + 1 + 1 = 28. A polyethylene chain 1000 mers long would have a molecular weight of 1000 \times 28 = 28,000. As the molecular weight of a polymer increases, the melt temperature increases, the mechanical strength increases, processing energy requirements increase, and creep resistance increases.

Molecular weight is given as an average with a standard deviation, since all chains cannot be produced with exactly the same chain length. Batches of a polymer with the same average molecular weight with little deviation from the mean could be expected to process uniformly and exhibit consistent mechanical properties. Batches of a polymer with different molecular weight averages and/or a wide deviation from the mean would have differing and unpredictable characteristics (see page 2-5, “Unique Qualities”).

POLYMER REACTIONS

Polymer reactions are classified as addition or condensation. Addition reactions occur when a monomer is converted into mers, then allowed to polymerize into a long chain of repeating mers. Figure 2-10 shows how ethylene gas, a monomer with double covalent bonds, is broken into mers that recombine with single
covalent bonds to form polyethylene. Most of the common thermoplastics are formed by addition reactions and exhibit a carbon backbone with predominantly hydrogen atoms attached. Chlorine, carbon, benzene rings, and carbon with cyanide may replace hydrogen atoms at specific locations in the polymer structure and form a different polymer material. Condensation reactions occur when molecules, often complex, react to form a polymer and a by-product such as water or alcohol. Condensation reactions may form thermoplastics like nylon or thermosets like phenolic and epoxy.

THERMOSETS

The sales of thermosetting polymers make up a large portion of total polymer sales in the United States as indicated in Table 2-4. Many types of thermosets are manufactured in a two-stage process. First, the uncross-linked polymer is processed by methods similar to those for thermoplastic polymers into the final shape and then the polymer is cross-linked. The amount of cure is usually controlled since the cross-link density affects polymer properties. Generally, the production of thermosetting polymers is complicated and very application-dependent. In particular, thermosetting polymers contain a large number of additives; for example, the rubber content of automobile tires is less than 60% of the total mass.

The other general manufacturing method for thermosetting polymers is one in which the network is formed as part of the reaction. A general mechanism to form thermosetting polymers is to use multifunctional (more than bifunctional) reagents in stepwise polymerizations. However, very few commercially important thermosetting resins begin with multifunctional monomers because of the high costs associated with the production of these monomers. A much more common occurrence is for a reaction intermediate to have multiple reaction sites. Often the precursor is available and consists of partially reacted, partially cross-linked material and can be processed using methods normally associated with ceramics. The phenolic and amino resins are thermosetting polymers of this type.

CROSS-LINKING METHODS

The many methods to cross-link a polymer can be separated into two broad categories: radiation-induced cross-linking and chemically induced cross-linking. The latter is commercially more important while the former can offer the precise control required for certain applications such as integrated circuit technology.

The most important of the latter type has been termed vulcanization and is used to cross-link automobile tires. The typical vulcanization components for a tire consist of sulfur, a vulcanization accelerator, a vulcanization activator, and a vulcanization inhibitor. The sulfur atoms become part of the cross-link, while the remaining compounds are added to control the kinetics of vulcanization. Accelerators are added to increase the speed of the vulcanization by orders of magnitude, and also to significantly reduce the amount of sulfur needed. An activator, usually a metal oxide with a fatty acid such as stearic acid, is added to help initiate the cross-linking. An inhibitor is added to help prevent this undesired reaction. Fortunately, an inhibitor such as n-cyclohexylthiophthalimide will help prevent reaction at lower temperature without affecting the rate at higher temperature.

Radiative methods are also used to initiate cross-linking. If high-energy radiation such as gamma rays and/or electron beam is used, a material with only saturated bonds will cross-link. UV light can be used to cross-link materials with double bonds, but the limited penetration depth of UV light limits this technique to thin films. Electron beam penetrates much deeper and is therefore suitable for thicker films, sheets, and coatings. Electromagnetic radiation initiates cross-linking by creating free radicals through a photochemical reaction.

Other types of thermosetting polymers that cure in a secondary reaction do not have double bonds but have other reactive functional groups remaining after the initial polymerization. For the urea-formaldehyde and phenolic resins, cross-linking may be initiated by increasing the temperature and pressure. Also, the polymer may be lacking one critical reagent that will cause network forma-
tion. For example, silicone room-temperature-vulcanizing (RTV) cement cures on exposure to water vapor in the air. Finally, some materials form a network structure as part of the synthetic procedure, such as polyurethane foams.

DIFFERENT TYPES OF THERMOSETS

The thermosets can be divided into two categories. Thermo-setting polymers above the glass transition temperature are classic rubbers while materials below the glass transition temperature are hard and brittle. Rigid thermosets are extremely important as the continuous phase in composites, which are a blend of a polymer with inorganic fibers.

Rubbery Materials

Diene rubbers are the most important rubbery thermosets. These polymers are produced from free-radical polymerization of monomers having two double bonds. Most synthetic rubbers are copolymers of a diene monomer with another monomer such as styrene or acrylonitrile. Styrene-butadiene rubbers (SBR) are typically made from free-radical polymerizations of 25% styrene with butadiene. The temperature of polymerization is usually low, about 40˚F (4˚C), to reduce branching. The development of this material was driven by the instability of natural rubber supplies beginning in World War II and extending for the next 20–30 years. Historically, SBR and natural rubbers have roughly split the automobile tire business, although this fluctuated with political conditions in southeast Asia. Now, however, the advent of radial tires has reduced the SBR market share. Vulcanized SBR rubbers do not have the abrasion resistance necessary to function as tires, hence 10–30% carbon black must be added.

Natural rubber comes from the tree Hevea brasiliensis, which is found primarily in southeast Asia. This material consists of extremely high-molecular-weight cis-1,4 polyisoprene. This material and styrene-butadiene represent the major rubbers used in tire manufacture. Natural rubber in its native state is mixed with a number of contaminants, most of which must be removed. The high molecular weight means that processing of the native material is nearly impossible, hence the molecular weight is reduced mechanically by a process called mastication. Even in stable political times, natural rubber is more expensive than synthetic SBR. In some respects, such as abrasion resistance, filled SBR products are superior to natural rubber. However, in key areas the natural rubber products are superior. In particular, SBR tires have poorer resilience and tend to have higher heat build-up. For heavy-duty applications such as truck tires, the natural rubber product is more widely used than SBR.

Hard Materials

Phenolic resins. The phenolic resins were the first commercial polymers synthesized from low-molecular-weight materials and date from the turn of the century. Phenolic polymers are manufactured from the reaction of a phenolic compound (phenol and cresol are the most widely used) with an aldehyde (generally formaldehyde). The exact structure of the polymer is still unknown, since a large number of reactions occur. The properties of the final product depend on the synthetic conditions and the phenol/aldehyde ratio. This polymer is produced in a two-stage process so that at the end of the first stage, a tractable polymer can be shipped to a destination for processing into its final form. Once again, commercial resins typically contain large numbers of additives, including accelerators, fillers, and coloring agents. Phenolics are hard and heat-resistant materials, but susceptible to attack from strong acids or bases. Phenolic resins are used in cookware, knobs, and handles, as well as in many other applications. As late as 1950, phenolics had the highest sales of any synthetic polymer; however, they have been replaced in many applications by other polymers. Still, the phenolic resins are commercially important.

Urea-formaldehyde resins. Urea-formaldehyde (UF) thermosetting resins, like the phenolics, are manufactured in a two-step process. The first step yields a low-molecular-weight tractable polymer and the second step results in the hard cross-linked product. As with the phenolic resins, typical UF resins are shipped as powders and then compression-molded at high temperatures (around 300˚F [150˚C]) and moderate pressures (around 5000 psi [35 MPA]) to produce the final product. Both the phenolics and the UF powders can be processed via a screw injection molder. UF materials are generally cheaper and lighter in color and have superior insulating properties relative to the phenolic resins. However, the phenolic resins have better heat resistance and absorb less water. UF resins are used primarily as bottle caps and electrical fittings. Once again, a commercial UF resin contains a number of additives. Melamine-formaldehyde resins are based on the same general chemistry, but are more expensive, absorb less water, and have better heat resistance than UF resins. Epoxide resins. Epoxide thermosetting resins are typically manufactured from bisphenol A and epichlorohydrin. Depending on the synthesis conditions, hydroxyl groups are located along the backbone and/or epoxide groups are located at the ends, either of which can serve as cross-linking sites. A catalyst is used to cause hydroxide and/or epoxide groups to react with each other, or a bridging molecule is used. Typical bridging molecules are amine and anhydrides. As the reader might gather, the number of epoxide systems is truly staggering and these systems can have a wide variety of properties. Generally epoxide resins are prized for their toughness and high adhesion properties. Approximately half of the production of these resins is used for surface coating applications, with most of the remainder in composites and electrical applications.

Polyester resins. Polyester resins have achieved great commercial success as composite materials. Composites are blends of polymers with another component, usually an inorganic fiber such as glass or carbon. Composites are extremely stiff and this stiffness, coupled with their low density, has led to a virtual explosion in applications to replace wood or metal. The inorganic filler in
polyester composites is typically glass, and the fibers can be manufac-
tured in many different forms including cloths and mats.

Thermosetting polyesters differ from thermoplastic polyesters in that one of the monomers has a double bond. Maleic anhydride is usually used to introduce unsaturation into the chain and supplies only roughly half of the acid functional groups. The material is cross-linked by adding another monomer that can be polymer-
ized via a free-radical mechanism. The most common monomer used in this application is styrene. Lamination is the most com-
mon processing method. Laminating consists of coating separate layers of the fibers with resin and then pressing the separate layers together and adding heat until a single reinforced sheet is pro-
duced. Other techniques used with the UF and phenolic resins such as compression molding can be used, but these processes are usually restricted to polyesters with short fibers.

Polyurethane foams. The urethane linkage, like the ester, is contained in products that are commercially important as both thermosets and thermoplastics. Thermosetting polyurethanes are not rubbery, but they are not nearly as stiff as the UF or phenolic resins. Foams are the most common commercial form for a ther-
mosetting polyurethane. Water is added to the reaction mixture to promote cross-linking; multifunctional polyols can also be used. The reaction of water with an isocyanate produces carbon dioxide which is usually augmented with fluorocarbons to produce the desired foam density. Both rigid and flexible polyurethane foams are commercially important. The rigidity is usually controlled by the number of hydroxyl groups per molecule, which in turn con-
trols the cross-link density.

Rubbers that are essentially copolymers of a noncross-linkable monomer with a cross-linkable monomer are also important com-
mercially. Generally, it is desired to have the properties of the for-
mer, so usually the latter monomer is present in small amounts and its purpose is to create cross-link sites. As an example, copoly-
mers of vinylidene fluoride with hexafluoropropylene have become commercially important. The rigidity is usually controlled by the number of hydroxyl groups per molecule, which in turn con-
trols the cross-link density.

SILICONES
Silicones are the only large-volume commercially important synthetic polymers not carbon-based. Silicone thermosets can be separated into flexible silicone rubbers and stiff silicone resins. The stiffness of the chain is a function of the glass transition tem-
perature, which is a function of the organic constituent of the polymer chain. The higher the organic content, the more flexible the chain; hence polydimethylsiloxane rubbers are very flexible materials. The primary advantage of silicone materials over the previously discussed thermosets is their high-temperature stability and low-temperature flexibility, since the range of useful tempera-
tures for these materials is −110 to +500°F (−79 to +260°C). Thermosetting materials can be produced by a number of mecha-
nisms including free-radical cross-linking, trifunctional reagents, and terminal reactive functional groups. Besides the use of sili-
cone rubber as a caulking agent, thermosetting silicone com-
pounds and reinforced composites have been used in applications where electrical insulators stable at high temperatures are required.

THERMOSETS AS FILLERS AND COPOLYMERS
The introduction of small rubber domains in a continuous matrix of glassy polymer is a commercially important method to increase impact strength. Thermoplastics that have been modified in this manner include polystyrene, polyvinyl chloride, and poly-
methyl methacrylate. The most common mechanism of introduc-
ing small rubber domains is to polymerize the rubber in an emul-
sion polymerization and then use the latex as a medium for the ther-
mosetting polymerization. This procedure forms small rubber domains in a continuous matrix of thermoplastic polymer, and hence this material can be processed as a thermoplastic. Another mechanism is to dissolve the rubber particles in the monomer and then polymerize the monomer.

Particle Size
The size of the rubber particles can be controlled by the concentra-
tion of the surfactant. Rubber particle size is a key param-
eter since the improvement in impact strength and other properties is a function of the particle size. The optimal particle size is typi-
cally between 1 and 10 μ. Larger particles are used when stress cracking resistance is required, and smaller particles are used when toughness and stiffness are required. Usually in these rubber-
filled systems, some reaction occurs between the rubber and the ther-
moset so that the rubber domains are covalently bonded to the continuous matrix. This bonding is extremely important because the improved polymer-rubber adhesion that results is key to improving the mechanical properties of the polymer.

ABS Polymers
Acrylonitrile-butadiene-styrene (ABS) polymers are the most important polymers of this type. Butadiene is the rubber phase while styrene and acrylonitrile compose the continuous phase. Acrylonitrile improves bonding between the continuous phase and the dispersed phase. These polymers are stiff, tough, and have good chemical and temperature resistance. The only major disadvan-
tage is their poor flame retardancy. These polymers are consid-
ered the classical high-performance engineering plastic. The sur-
f面 properties are exceptional and this material can be easily painted, electroplated, etc. Applications include housings for many common household appliances as well as plumbing and other fix-
tures. The percent of the three components in ABS varies widely, but typical compositions might be 15% butadiene, 60% styrene, and 25% acrylonitrile. A cheaper version of ABS uses polystyrene homopolymer as the continuous phase and has been termed high-
impact polystyrene. The most common choice for the rubber parti-
cles is a cis 1,4-polybutadiene. Graft or block copolymers can be used to help bond the rubber particles to the polymer matrix.

Improving Impact Properties
Other nonstyrene-based systems have been modified by using rubber particles to improve impact properties. Polymethyl meth-
acrylate blended with a rubbery acrylate such as polybutyl acry-
late has been commercially successful. Polyvinyl chloride has also been toughened through blending with a variety of compounds, the most important being ABS and methacrylate-butadiene-sty-
rene copolymers.
THERMOPLASTICS

THERMOPLASTIC TYPES
Thermoplastic material can be subdivided according to its end-use:
1. Commodity.
2. Intermediate.
3. Engineering.
4. Advanced.
5. Key engineering and specialty plastics.

Commodity
In the commodity classification lie such plastics as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC).

Intermediate
Poly(methyl methacrylate) (PMMA), acrylonitrile-butadiene-styrene terpolymer (ABS), high-heat cellulose acetate butyrate (CAB), and thermoplastic olefin elastomer (TPO) are all classified as intermediate thermoplastics.

Engineering
Engineering thermoplastics include such plastics as acetal polyoxyymethylene, nylon-6/6, polycarbonate (PC), and polyphenylene sulfide (PPS).

Key Engineering and Specialty Plastics
Among thermoplastics there are also key specialty plastics that are frequently utilized. The key engineering and specialty plastics are usually categorized as:
1. Low-end performance polymers:
   - ABS.
   - Styrene acrylonitrile (SAN).
2. Engineering plastics
   - Polyamide (PA) (nylon).
   - Polycarbonate (PC).
   - Polycetals (POM).
   - Polyphenylene oxide/ether (PPO/E).
   - Polyethylene terephthalate (PET).
   - Polybutylene terephthalate (PBT).
   - Polyphenylene sulfide (PPS).
   - Polysulfone (PSU).
   - Polyacrylate (PAR).
   - Polyester sulfone (PES).
   - Polyimide/polyamide imide (PI/PAI).
   - Polyester imide (PEI).

Advanced Thermoplastics
Advanced thermoplastics, such as liquid-crystal polymer, polytetrafluoroethylene (PTFE), polyetheretherketone (PEEK), and polyethersulfone (PES), are higher-priced plastics for specialized applications. These applications include linings for pipe and chemical processing equipment, aircraft hookup wires and interior panels and seating, fire alarm cables, cookware components, prostheses and medical instruments, automotive bearing and piston components, high-temperature electrical multipin connectors, and printed circuit boards.

OVERVIEW OF COMMODITY PLASTICS
The big four—polyethylene, polypropylene, polystyrene, and polyvinyl chloride—comprise approximately two-thirds of all polymers produced synthetically. The common thread linking these commodity polymers is that the monomers are inexpensive. This fact illustrates that the driving force behind the ascendancy of these polymers is not their superior properties relative to other polymers, but economics. Also, the monomer comprises most of the polymer's cost; reaction costs are typically minimal. The large production volumes also allow these four polymers to benefit from the economy of scale.

Comparing these polymers to each other in any detail, or listing the many applications of these materials, is almost impossible. Rather, a general overview of each will be given to provide the reader with some insight into their similarities and differences. To start with, polyethylene and polypropylene are always semicrystalline, while polystyrene and polyvinyl chloride are not.

POLYETHYLENE
Polyethylene should actually be thought of as three polymers: low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), and high-density polyethylene (HDPE). The first is produced from a normal free-radical polymerization and contains a large number of aliphatic side chains. These side chains reduce the crystallinity and hence this material is a less rigid polymer. The second is produced by using a transition metal oxide catalyst and does not have any of the long branches found in the first material. After the discovery of the process leading to this material, LLDPE has taken significant amounts of market share from LDPE, since the manufacturing costs are lower and the product has better mechanical properties. HDPE is produced from a Ziegler-Natta polymerization, (described in the section “Synthetic Procedures”) contains essentially no branches, and hence has a higher crystallinity and is more rigid. HDPE usually competes directly with polypropylene.

Polyethylene is the number one selling plastic material and has been since the 1950s. To a first approximation, the properties of polyethylene are proportional to the crystallinity. As the crystallinity increases, the material becomes tougher and more rigid, the solvent resistance improves, and the material is less permeable to gases. The number of long chain branches is the second most important structural variable. An increase in long chain branching typically reduces mechanical and weathering properties, but improves the processibility considerably. Compared to other polymers, polyethylene has good solvent resistance, is an extremely good insulator, and tends to be very flexible. One extremely important practical problem with polyethylene is its susceptibility to environmentally induced damage. Most television and telephone lines are shielded by polyethylene, so the possible scope of this problem is immediately obvious. The low softening point can also be a significant drawback. Unfortunately, it is difficult to find compatible additives for polyethylene so this method of reducing oxidation or environmental effects may not be possible, although carbon black does improve weathering resistance.
CHAPTER 2
THERMOPLASTICS

Approximately 75% of the production of LDPE and LLDPE is used as film, and HDPE is used primarily in injection- and blow-molding processes. As a film, polyethylene is clear, permeable to some gases, flexible, and tear resistant. HDPE still maintains the flexibility of the lower crystallinity versions, but has higher strength and much better impermeability.

Unlike most other polymers, polyethylene has important markets in different molecular weights. In most polymers, properties other than melt viscosity do not change significantly as molecular weight increases; once a certain molecular weight is attained (around $M_w = 10,000$ for most polymers). Therefore, usually the lowest molecular weight above this threshold value is used. Polyethylene, however, does not conform to this generalization because of its extremely strong tendency to crystallize; the fractional crystallinity increases with molecular weight because of the reduced number of chain ends. Even though these materials are difficult to process, high ($M_w = 3 \times 10^5$ to $6 \times 10^6$) and ultrahigh ($M_w = 3 \times 10^8$ to $6 \times 10^{10}$) molecular weight polyethylene are important because of their high abrasion and impact resistance as well as better resistance to environmental stress cracking. The crystallinity in these materials is greater than 90%, which is extremely high for a polymer.

**POLYPROPYLENE**

Polypropylene is very similar to HDPE since both are produced from Ziegler-Natta polymerizations. Polypropylene has a melting point of about 80˚ F (45˚ C) higher than HDPE, with a corresponding increase in softening point. The molecular weight effect on mechanical properties is opposite to that experienced by polyethylene and other crystallizable polymers; an increase in molecular weight leads to a reduction of crystallinity because of the high kinetic barrier to crystallization. Polypropylene is about 5% less dense than polyethylene and does not environmentally stress-crack. Polypropylene is more susceptible to oxidation and UV degradation than HDPE, but also more amenable to additives to reduce this tendency. Finally, polypropylene is a little tougher and more rigid than HDPE. Besides the normal injection- and blow-molding applications, propylene has become important in the polymer fiber market.

**POLYVINYL CHLORIDE**

PVC is a testament to the importance and power of additives in commercial polymer production. Without additives, PVC would not be a commercial product, since the pure polymer would degrade at the lowest processing temperatures. Two ways to circumvent this problem have been found, adding heat stabilizers and adding plasticizers. The popularity of the latter approach means that PVC should really be thought of as two products, plasticized and unplasticized PVC. The former is a flexible, almost rubbery, type of polymer and is used extensively as wire insulation. The latter is a rigid plastic that is used for piping and building materials. Perhaps the most significant advantage of PVC relative to the other three major thermoplastics is that PVC will not burn, although the large amount of additives can cause serious fire safety problems. Inherent disadvantages include its relative instability and the political consequences of its chlorine content. PVC is typically produced from a suspension polymerization, which is similar to an emulsion polymerization except a surfactant is not used to stabilize the monomer droplets; rather, mechanical agitation and a nonionic stabilizer are used. The large number of additives in PVC means that it can be made with an extremely wide variety of properties. The chemical identity of the additives usually determines the chemical resistivity, since pure PVC has excellent solvent stability. Because it reduces the inherent instability of PVC and the additive content, copolymerization with vinyl acetate has also become commercially important.

**POLYSTYRENE**

Polystyrene is the most glassy of the big four, with the corresponding stiffness and brittleness normally associated with a glass. The solvent stability of polystyrene is not very good. Polystyrene is the only commodity polymer translucent at greater than film thicknesses. Since the attraction of polystyrene is often due to its translucency, yellowing or hazing cannot be tolerated. The latter usually can be eliminated through processing procedures while the former is usually due to the presence of impurities or oxidation and can be eliminated through the use of antioxidants. Polystyrene is the only commodity polymer having significant applications as a foam.

Because of polystyrene’s extreme brittleness, a large portion of styrene monomer production is used in copolymers; the SBR rubbers, ABS, and high-impact polystyrenes are discussed in the section Thermosets as Fillers and Copolymers. Another important styrene derivative is styrene-acrylonitrile copolymers. At the commercial acrylonitrile content of 20%, the last material has significantly better resistance to impact and stress cracking than the homopolymer, but is still transparent. Because of their high cost relative to pure polystyrene, only a very small fraction of the polystyrene market is occupied by styrene-acrylonitrile copolymers.

**OTHER TYPES OF THERMOPLASTICS**

At this point, one questions why other thermoplastics are necessary. For economic reasons, the commodity polymers are always preferred. Although some of the current applications of other polymers are based on historical reasons rather than performance, there are important properties that the four commodity polymers do not have. Some of these are:

1. Extreme high-temperature stability.
2. Hydrolytic stability at high temperatures.
3. Transparency coupled with good weathering resistance.
4. Low adhesion.
5. High abrasion resistance.
7. Extreme rigidity coupled with impact resistance.

In the discussion to follow, the unique characteristics of other types of polymers relative to the commodity polymers and to each other will be identified to help the reader determine which polymers to investigate further for a particular application.

**Polytetrafluoroethylene**

Polytetrafluoroethylene (PTFE or Teflon®) is a unique material. Classifying it as a thermoplastic is not accurate, since it cannot be processed as a conventional thermoplastic; nevertheless, this material cannot be classified as a thermoset because no cross-links are present. PTFE has no solvents at room temperature and only a very few at extremely high temperature. This polymer is stable to well over 600˚ F (315˚ C), has a low coefficient of friction, and is nonadhesive. The material is an excellent insulator and does not change its properties on weathering. The only drawbacks are the difficulty of processing it, and its tendency to creep under load. Both of these problems can be reduced or eliminated in most polymers through the use of additives, but, as the reader might have guessed, there are very few additives compatible with PTFE. Some success in reducing these problems has been achieved via...
copolymerization, but the properties that make PTFE unique are usually substantially reduced.

**Nylons**

Nylons (or chemically, polyamides) were the first commercially important condensation polymer. Nylons are important as adhesives, films, and engineering plastics, but the largest amount of material is used as fibers in the textile industry. As engineering plastics, nylons have excellent abrasion resistance and are marketed as gears, bearings, etc. Nylons typically have adequate weather resistance, although the resistance to direct sunlight is worse than that of other polymers competing against the nylons. Many different kinds of nylons are marketed, so it is difficult to generalize about mechanical properties.

**Cellulosics**

Cellulosics are all derivatives of cellulose, which is the major constituent of the cell wall in most plant matter. This compound is a series of saturated six-membered carbon rings connected via an ether linkage. Each of the rings has three hydroxyl groups and the chemical modification of these groups leads to different products. By far the most common use of cellulosics has been in the textile industry, although cellophane still has some market share as a transparent thin film, especially in packaging applications. As thermoplastics, cellulosics typically have very poor properties including poor heat and solvent resistance as well as high water absorption. There are many different types of textile fibers based on cellulose. Cotton is a cellulose and its importance to the textile industry is obvious. Two synthetic cellulosic textile fibers are viscose rayon and cellulose acetate.

**Polyesters**

Polyesters, like the nylons, are important commercially in many different forms. Polyester fibers, so popular in garments during the 1970s, seem to be making a comeback due to better processing methods. Typically, polyesters are blended with other fibers such as cotton. A major success story during the last 20 years has been the use of polyethylene terephthalate in the beverage bottling market, especially for colas. PET is also very important as a film and is used in small electrical components as well as drawing media for overhead projectors. The stiffness and flexure resistance of PET are much higher than those of the cellophanes.

**Polymethyl Methacrylate**

Polymethyl methacrylate is a brittle clear polymer that has replaced glass in many applications. PMMA has excellent weather resistance compared to the commodity plastics. Besides its improved impact resistance relative to glass, when PMMA shatters, the fragments are not as sharp as those from normal glass and hence not as dangerous. The scratch resistance of PMMA could be improved for many applications, that is, eyeglass lenses. Other acrylates are commercially important, including alkyl 2-cyanoacrylates (Superglue™) and hydroxy ethyl methacrylate, used in contact lenses. In general, the acrylates are amorphous, clear, and brittle materials, with a tendency to absorb water.

**Polycarbonates**

Polycarbonates are unusual in that the only commercial products of any value come from the same monomer, bisphenol A. The polycarbonates are relatively expensive, but have found uses where an extremely rigid and transparent material is required. These materials also are flame-retardant and have good electrical insulating capabilities. The advantage of polycarbonates versus the acrylates is their extreme rigidity coupled with even better impact resistance. These materials also are rigid until approximately 300°F (149°C), whereas the methacrylates lose rigidity near the boiling point of water.

**Acetal Polymers**

Acetal polymers are polymers containing an ether linkage, of which polyoxymethylene is the most important commercially. Acetal polymers compete primarily with thermoplastic nylon in engineering plastic applications. Compared to the nylons, acetal polymers are stiffer, have better fatigue resistance, and absorb less water. The nylons have better impact resistance and abrasion resistance. The applications for the acetal resins are similar to the nylons, that is, gears, valve stems, and other small engineering parts.

**BLOCK COPOLYMERS**

One important type of thermoplastics is not composed of one repeat structure in the polymer backbone, but rather alternates between two different types. These materials are termed block copolymers (each polymer segment containing one type of repeat unit is called a block). Typically, block lengths are approximately 10–20 monomer units, with one block above its glass transition and the other below its glass transition. Block copolymers have the flexibility and toughness associated with filled rubbers, hence these materials have been termed thermoplastic elastomers. Examples of commercially important block copolymers are the styrene-butadiene-styrene block copolymers, thermoplastic polyurethanes, and polyether esters. This type of material is used when a tough elastomer is required. Another characteristic of thermoplastic elastomers is their extremely high fatigue resistance.

**RIGID-ROD POLYMERS**

Another very special class of thermoplastics is rigid-rod polymers. These materials, similar to PTFE, usually cannot be processed like normal thermoplastics. These materials all have aromatic groups in the main chain. If the concentration of aromatic groups is high enough, the molecules will spontaneously align in one direction. This spontaneous alignment leads to an incredibly rigid, stiff material. Also, these types of polymers typically have extremely high temperature resistance. The only commercially important rigid-rod polymer is poly-(p-phenylene terephthalamide [trade name Kevlar®]). Other specialty polymers that have aromatic rings in the main chain but not at a high enough concentration to spontaneously align include polyphenylene oxide, polyetheretherketone and the polysulfones. These polymers are usually expensive but have superior heat resistance, hydrolytic stability, and toughness.

**BLENDS**

Blends are mixtures of polymers without chemical reaction. Almost all blended polymers are subject to macrophase separation which leads to inferior properties. However, there are two overriding reasons for overcoming this problem. First, it is very difficult to molecularly engineer a polymer with a desired set of properties; conceptually it is much easier to find two polymers where the desired properties lie between those of the two and then mix the two polymers. Second, environmental concerns demand that polymers be recycled and reused, but the number of different types of polymers is enormous; to expect the public to separate plastics by type is probably impractical, and separating after collection is expensive. Further, the same polymer species may have widely differing additive contents. To develop recycling and reuse as a
viable commercial alternative, the ability to blend different products must be developed.

There are very few commercially available blends. The rubber-modified blends (discussed in the section Thermosets as Fillers and Copolymers) represent by far the most important commercially available blends. PVC is blended with other polymers such as PMMA to improve processibility. Polycarbonate has also been blended with a number of other materials, primarily to reduce cost. Blending polycarbonate with PET actually leads to better chemical resistance. Another way to force miscibility is to polymerize two networks simultaneously so that the networks are all tangled. Usually, some cross-bonding occurs between the networks. Thermosetting polyesters with styrene linkages, discussed in the aforementioned section, are blends of this type.

It is expected that the market for polymer blends will grow rapidly in the future, driven primarily by environmental concerns. Blend compatibilizers are an active area of research. Historically, the development of polymer additives has solved problems that otherwise would have prevented the development of many very important commercial polymers. Perhaps compatibilizers will be found that perform exactly the same function with polymer blends.

### STRENGTHENING AND ENHANCING PLASTICS AND POLYMERS

Polymers may be strengthened and enhanced in a number of ways ranging from increasing the molecular weight through adding modifiers, to reinforcing with strengthening fibers like carbon or Kevlar. This section will discuss the effects of molecular weight, chemical structure, copolymerization, crystallization, cross-linking, fiber reinforcement and composites, additives, blending, and chain alignment.

#### CHAIN LENGTH

Polymer chain length (molecular weight) has a direct correlation with the mechanical properties of polymer materials. Increased molecular weight increases strength and creep resistance. If polymer chains are compared to pasta, long chains are like spaghetti and short chains are like macaroni. Long chains tend to intertwangle and hold together while short chains pull apart easily and transfer little if any force to adjacent chains.

Thermoplastic parts processors have no control of molecular weight, since it is determined at the chemical process plant where monomers are broken into mers and then polymerized. Chemical processors can alter molecular weight by varying the amount of initiator/terminator added to reactants in the polymerization process. More initiator/terminator yields shorter polymer chains, thus lower average molecular weight. Above a critical molecular weight, polymer properties (except viscosity) are almost independent of molecular weight.

As molecular weight increases, so do the melt temperature and viscosity of the polymer. Since processibility depends on melt temperature and viscosity, there are practical limits on molecular weight as a means to enhance polymer properties.

If increasing the molecular weight of a polymer does not yield appropriate properties, then changing to another polymer with a different chemical structure becomes an option. Figure 2-11 presents the structural formula for three thermoplastics. Polyethylene has a simple carbon chain with hydrogen side groups. Polystyrene has a simple carbon chain but has benzene rings in addition to hydrogen side groups. Thermoplastic polyester has a much more complex chain structure consisting of carbon, oxygen, and benzene rings with side groups of hydrogen and oxygen. Looking at these three structures one might generalize that polyethylene is an arrangement of long slick polymer chains (no large side groups), with good flexibility (simple carbon chain), and good toughness (ability to deform without brittle failure due to chain movement). Polystyrene with large rigid side groups of benzene rings might be expected to be harder and more brittle with perhaps a bit higher tensile strength. PET, with a more complex chain of benzene rings, carbon, and oxygen might be expected to be more rigid and have a higher tensile strength. Table 2-9 compares several properties of PE, PET, and PS.

Generalizations of properties from structural formulas have limitations; however, as illustrated above, differences in chemical structure cause differences in polymer properties. Processors should consult handbooks such as the Encyclopaedia of Plastics, published yearly by Modern Plastics magazine, to determine mechanical, physical, and processing parameters of various polymers.

#### COPOLYMERIZATION

Copolymerization is a third technique for strengthening or enhancing properties of polymers. ABS plastic is the most com-

---

Fig. 2-11 Polymer structures affect properties.
mon copolymer existing as a chemical bonding of acrylonitrile, butadiene, and styrene. When polymerized in a controlled repeating sequence as illustrated in Fig. 2-12, ABS has properties that exceed those of individual constituent mers. ABS is rigid like styrene, hard like acrylic, and tough like butadiene, a rubber.

CROSS-LINKING

Cross-linking is a fourth chemical technique for strengthening or enhancing polymers. As stated earlier, thermoplastics may be heated, formed, then cooled repeatedly. This processibility results from the ability of heat to overcome weak forces that hold polymer chains in relation to one another. These weak forces are much less than the strong chemical forces that hold mers in chains of the polymer. Chains in thermoset polymers are tied together by strong chemical bonds that do not release when heated; therefore, thermoset polymers cannot be reprocessed as can thermoplastics. This thermosetting action is called cross-linking where atoms or small molecules chemically link adjacent polymer chains to one another.

Many polymers may exist in either a thermoplastic or thermoset state. Raw rubber is a thermoplastic polymer that can be formed and processed by thermoplastic techniques like extrusion and injection; however, the rubber must be vulcanized and cross-linked to become a thermoset with good strength and thermal characteristics. Vulcanizing causes a sulfur atom to link with double bonds that exist in adjacent rubber chains. Urethanes and polystyrols may also exhibit thermoplastic or thermoset characteristics.

Epoxy and phenolic are two common thermoset polymers used in part production and as the adhesive/matrix that bonds reinforcing material together in composites. All thermosetting polymers have strong cross-linked bonds that hold chains in fixed relation to one another. Cross-linked polymers have good strength, environmental resistance, thermal resistance, and low creep. They are, however, often brittle.

FIBER REINFORCEMENT

Fiber reinforcement is the predominant method for strengthening and enhancing polymers in a nonchemical manner. Actually, adding reinforcement to a polymer creates a composite of two distinct materials, a binding matrix and a strengthener. Glass is the most common fiber for reinforcement, but carbon, Kevlar, and metals are also used. Fiber-reinforced plastic (FRP) refers to plastics filled with short fibers, approximately 0.1 in. (2.5 mm), whereas composite refers to a matrix reinforced with longer length fibers, possibly woven into a fabric.

As the percentage of reinforcer becomes greater, the strength and physical properties of the FRP or composite become more like the reinforcer and less like the polymer. In addition, the coefficient of thermal expansion is reduced and creep becomes less significant. In effect, the polymer serves only to protect and to transfer forces into the reinforcer.

Fiber-reinforced plastics may be processed by many of the common thermoplastic techniques such as injection molding and extrusion.
extrusion. Composites may have thermoplastic or thermoset matrices, but thermosets like polyester and epoxy are most common.

OTHER ADDITIVES

Additives and even fillers can enhance polymer properties. Additives include colorants, lubricants, plasticizers, light inhibitors, fungicides, pesticides, odorants, impact modifiers, and foaming agents. Fillers include wood paste, minerals, and other materials that are less expensive than the polymer and can be added without appreciably degrading the polymer. Fillers can improve thermal and mechanical properties and alter electrical characteristics.

Colorants add color and opaqueness to polymer parts, but may also modify other properties such as processibility and strength. Lubricants enhance polymer processibility by promoting flow through and removal from process tooling. Plasticizers make polymers more plastic, formable, and flexible. They give auto dashboards soft toughness and allow overshoes to stretch. Inhibitors protect polymers from high-energy light and oxygen that, over time, can break long polymer chains into weaker, more brittle short chains. Carbon black additive can alter the effect of sunlight on a clear, short-lived plastic film, making the film black and long-lived. Fungicides and pesticides are added to polymers to control degradation from living organisms like molds and mice. Odorants are added to polymers to give a long-term pleasant smell or to mask unwanted odors. This additive is common in polymers used for trash and recycling containers. Impact modifiers are typically rubber materials added to brittle plastics to improve their toughness. Polystyrene, an inexpensive, relatively strong but brittle plastic, is often impact-modified and used in toys and furniture products. Foaming agents are chemical additives added to a polymer to cause the formation of bubbles inside a plastic part. Foaming agents are also responsible for foamed hot beverage cups, structural foamed computer housings, and furniture components.

ALLOYS AND BLENDS

As noted, blends are physical mixtures of various polymers in which no chemical reactions are involved and copolymers are not formed. This mixture of polymers, however, may be superior to the original individual components. One such mixture involves ABS (a copolymer), and polycarbonate (a strong, tough, amorphous polymer). Mixing the two yields a stronger, tougher material than ABS, yet less expensive than pure polycarbonate. Some polymers are not compatible, however, and delaminate when mixed together.

It is most common in the plastic industry to work with alloys or blends of varying polymers. The alloys are chosen for particular applications based on the thermal, chemical, and mechanical properties of the blend. Table 2-10 includes a compendium of the most commonly utilized alloys by supplier, trade name, and key properties. As can be seen in the table, one can choose a particular

<table>
<thead>
<tr>
<th>Alloy or Blend</th>
<th>Trade Name</th>
<th>Supplier</th>
<th>Key Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPO/PS</td>
<td>Noryl</td>
<td>GE Plastics</td>
<td>Heat resistance, toughness, improved processing, low cost, low moisture absorption</td>
</tr>
<tr>
<td>Nylon/ABS</td>
<td>Triax 1000</td>
<td>Monsanto</td>
<td>Heat and chemical resistance, good flow, low cost, low temperature impact</td>
</tr>
<tr>
<td>Nylon/elastomers</td>
<td>Zytel</td>
<td>DuPont</td>
<td>Improved toughness and fatigue resistance, chemical and heat resistance</td>
</tr>
<tr>
<td>Nylon/ABS</td>
<td>Triax 1000</td>
<td>Monsanto</td>
<td>Heat and chemical resistance, good flow, low cost, low temperature impact</td>
</tr>
<tr>
<td>Nylon/ABS</td>
<td>Triax 1000</td>
<td>Monsanto</td>
<td>Heat and chemical resistance, good flow, low cost, low temperature impact</td>
</tr>
<tr>
<td>PC/PBT</td>
<td>Xenoy</td>
<td>GE Plastics</td>
<td>High impact and modulus over wide temperature range, chemical resistance</td>
</tr>
<tr>
<td>ASA*/PC</td>
<td>GX200</td>
<td>GE Plastics</td>
<td>Impact, thermal stability, weatherability</td>
</tr>
<tr>
<td>Thermoplastic elastomer (TPE)</td>
<td>Bexloy V</td>
<td>DuPont</td>
<td>Can tailor stiffness, impact strength, control shrinkage</td>
</tr>
<tr>
<td>PET/PBT</td>
<td>Valox</td>
<td>GE Plastics</td>
<td>Heat resistance, fast molding, low cost, improved gloss</td>
</tr>
<tr>
<td>Acetal/elastomer</td>
<td>Delrin</td>
<td>DuPont</td>
<td>Stiffness, toughness, fatigue, wear</td>
</tr>
<tr>
<td>PC/PET</td>
<td>Makroblend</td>
<td>Miles</td>
<td>Low temperature impact, chemical and UV resistance</td>
</tr>
<tr>
<td>SMA/ABS</td>
<td>Caden</td>
<td>Monsanto</td>
<td>Heat resistance, impact, low cost</td>
</tr>
<tr>
<td>Polysulfone/ABS</td>
<td>Mindel</td>
<td>Amoco</td>
<td>Processibility, low cost, heat resistance, can be plated</td>
</tr>
<tr>
<td>PEEK/PES</td>
<td>Victrex</td>
<td>ICI</td>
<td>High heat distortion temperature (HDT), easy processing, low cost</td>
</tr>
<tr>
<td>PC/TPU</td>
<td>Texin</td>
<td>Miles</td>
<td>Stiffness, wear, low temperature impact</td>
</tr>
<tr>
<td>Nylon/PE</td>
<td>Sellar RB</td>
<td>DuPont</td>
<td>Heat/chemical resistance, barrier properties, wear</td>
</tr>
</tbody>
</table>

*ASA=acrylonitrile-styrene-acrylic copolymer
alloy to have a balance of virtually any property, including price, to meet the application.

The growing demands for alloys and blends are given in Table 2-11. The table lists the most widely utilized plastics in total amount consumed, and further subdivides the total consumption into percentages of modified and unmodified plastics. Modification consists of a filler addition, such as talc, glass, or mica, to increase the stiffness or modulus of the material. Where appropriate, the molding conditions are noted, such as injection molding grades only, to differentiate from possible sources of production, that is, compression molding, injection molding, etc. The demand for engineering and specialty plastics worldwide varies in plastic types consumed by country.

Crystallization

Crystallization of polymers is brought about by the close packing of polymer chains allowing rope-like bundles to form. Close-packed bundles deflect and deform in unison. Figure 2-9 illustrates crystalline structure in polyethylene. Note that the polymer is not 100% crystal, but is about 60% crystal and 40% amorphous. Crystals tend to enhance the properties of polymers. The amorphous section loses strength and viscosity at higher temperatures, whereas the crystal section retains strength and rigidity and has a definite melt temperature and heat of fusion. Polymers such as polystyrene, with its large benzene ring side group, cannot pack close together to form crystals and, therefore, are amorphous. Polyethylene, polypropylene, and nylon are common crystalline polymers. Thermoplastic polyester forms crystals in a somewhat temperature-dependent mode and may necessitate preprocessing prior to blow molding.

<table>
<thead>
<tr>
<th>Resin</th>
<th>Total</th>
<th>Modified</th>
<th>% Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP (1)</td>
<td>817</td>
<td>278</td>
<td>34</td>
</tr>
<tr>
<td>ABS</td>
<td>544</td>
<td>42</td>
<td>8</td>
</tr>
<tr>
<td>PC</td>
<td>204</td>
<td>62</td>
<td>30</td>
</tr>
<tr>
<td>PA</td>
<td>817</td>
<td>278</td>
<td>34</td>
</tr>
<tr>
<td>PC/ABS</td>
<td>204</td>
<td>62</td>
<td>30</td>
</tr>
<tr>
<td>PA(1)</td>
<td>168</td>
<td>113</td>
<td>67</td>
</tr>
<tr>
<td>Styrenics (2)</td>
<td>109</td>
<td>32</td>
<td>29</td>
</tr>
<tr>
<td>PET/PBT</td>
<td>91</td>
<td>70</td>
<td>78</td>
</tr>
<tr>
<td>PPO/E</td>
<td>84</td>
<td>84</td>
<td>100</td>
</tr>
<tr>
<td>POM</td>
<td>64</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

1. Includes injection molding grades only.
2. Includes SAN, SMA, and ASA.

Chain Alignment

Chain alignment orients polymer chains along a common axis from forces encountered during processing, as shown in Fig. 2-13. Chain alignment may be an asset or, in some cases, a liability. Textile fibers are drawn or stretched after extrusion to align chains and increase strength. Alignment pulls chains into a parallel structure that greatly improves strength in the direction of alignment. Parts made by injection molding have polymer chains aligned near the tool surface. Friction forces act on the moving chains and tend to line them up parallel to the melt flow in the tool cavities.

However, one region of high friction in injection molds is the gate where plastic first enters the mold cavity. The gate has a small cross-section and aligns polymer chains passing through it. In many cases this alignment at the gate is at right angles to the direction of loading that the part will encounter in final use. This misalignment in relation to forces applied often results in failure parallel to the axis of alignment.
Although the history of polymer penetration in medicine and biomedical sciences is relatively short, they surely are moving into most areas of this field of science and practice. Such polymers (particularly those in contact with living tissues) are generally referred to as biomaterials. Despite the vigorous expansion of this field, only a few new polymers have been successfully designed and applied to a specific medical use. Other polymeric biomaterials are adaptations and modifications of traditional polymers. Table 2-12\(^2\) shows some of the areas where traditional polymers have been found useful. Table 2-13\(^3\) shows the volume of some of these polymers used in 1989, constituting an $11 billion market.

These polymers may come in direct contact with living tissues (intact or compromised) or be used peripherally. The polymeric materials with no contact with biological systems may qualify as industrial polymers and be subject to similar performance require-

ments and testing. However, implantable polymers or those coming in contact with blood ex vivo, for example, will require a significantly different set of qualifications. At the present time, there are less than adequate standards for suppliers of medical polymers. Standards for classification of the commercial polymers in terms of end use are on a voluntary basis and therefore these polymers should be examined individually and case by case. An example of such classification is shown in Table 2-14.\(^4\)

To provide a better picture of the biological environment where biomedical polymers may be used, some physicochemical and mechanical conditions in different parts of the human body are listed in Table 2-15.\(^5\) The components of blood are listed in Table 2-16.\(^6\)

### CLASSIFICATIONS

It is wise to have two approaches toward qualification of a medical polymer. One is meeting U.S. Food and Drug Administration (FDA) suggested or required standards, and the second is an internal set of standards that may supersede or complement the FDA’s. This will bring extra assurance of successful performance. The FDA has categorized all medical devices into three groups.

**Class I**

This class requires general control methods for labeling and good manufacturing practices. These products are not life supporting and do not pose a potential risk of injury.

**Class II**

Class II must conform to performance standards for materials, testing methods, specifications, and design.

**Class III**

This class requires premarket notification and FDA consent, predicated on the safety and effectiveness of the device, which is life-sustaining.

### TABLE 2-12

<table>
<thead>
<tr>
<th>Resin</th>
<th>Primary Features</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>Processing ease</td>
<td>Caps, needle hubs, medical packaging, and waste bags</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Autoclavability and contact clarity</td>
<td>Syringes and specimen collection cups</td>
</tr>
<tr>
<td>General-purpose styrene</td>
<td>Transparency</td>
<td>Petri dishes, labware, and test tubes</td>
</tr>
<tr>
<td>High-impact styrene</td>
<td>Toughness, opaque</td>
<td>Home test kits, diagnostic equipment, housings</td>
</tr>
<tr>
<td>Styrene acrylonitrile</td>
<td>Chemical resistance and toughness</td>
<td>Diagnostic components, fluid handling devices, and flat plate dialyzers</td>
</tr>
<tr>
<td>Acrylic</td>
<td>High light transmission rates and chemical resistance</td>
<td>IV components and specimen collection containers</td>
</tr>
<tr>
<td>Acrilonitrile-butadiene-styrene</td>
<td>Toughness, low-and high-gloss, good processibility</td>
<td>Housings, surgical staplers, home test kits, IV connectors</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>Chemical and heat resistance, toughness, transparent</td>
<td>Cardiomy reservoirs, blood centrifuge bowls, perfusion devices, and hemodialyzers</td>
</tr>
<tr>
<td>Polyester</td>
<td>Chemical resistance</td>
<td>IV components, catheters, surgical instruments, housings</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>Improved chemical resistance, toughness, and processibility</td>
<td>IV connectors, catheters, tubing, and drug delivery systems</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>High heat resistance</td>
<td>Sterilization trays</td>
</tr>
</tbody>
</table>

### TABLE 2-13

<table>
<thead>
<tr>
<th>Polymer Family</th>
<th>Usage, lb*, 1989</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>480</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>340</td>
</tr>
<tr>
<td>Low-density polyethylene (LDPE)</td>
<td>320</td>
</tr>
<tr>
<td>High-density polyethylene (HDPE)</td>
<td>250</td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>175</td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>60</td>
</tr>
<tr>
<td>Thermoplastic polyesters</td>
<td>45</td>
</tr>
<tr>
<td>Acrylics</td>
<td>40</td>
</tr>
<tr>
<td>Silicones</td>
<td>25</td>
</tr>
<tr>
<td>Nylon</td>
<td>20</td>
</tr>
<tr>
<td>Acrilonitrile-butadiene-styrene (ABS)</td>
<td>15</td>
</tr>
<tr>
<td>Thermoplastic urethanes (TPU)</td>
<td>10</td>
</tr>
<tr>
<td>All others</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>1830</td>
</tr>
</tbody>
</table>

*Million
The extent of preclinical and clinical studies required by FDA and manufacturers’ internal standards depends on how critical the performance of the device is to the patient.

The major concerns about biomaterials are as follows:

1. Biocompatibility. Biocompatibility is a very complicated area and not yet well understood and established. There are, however, a number of tests used to assess some biocompatibility aspects of a material’s performance. Surface analysis for proteins and platelet adhesion and morphology is used to predict the hemocompatibility; soft tissue cell adhesion and its morphology shed light on soft tissue compatibility; and, for immunogenicity, complement activation is tested. These are among the most popular examples practiced in vitro.

2. Toxicity (including genotoxicity).

3. Carcinogenicity (chemical and physical). The concerns over items two and three go beyond the original polymers. Adequate care should be taken in the processing, as some low-molecular-weight compounds can be generated in this step by thermal/hydrothermal decomposition or depolymerization. Residual solvents in solution casting/coating are another cause for concern.

4. Sterilizability. For sterile products, the material must stand the sterilization conditions with minimum deterioration in its physicochemical and biological properties. There are four well practiced sterilization methods: (a) solution, using formaldehyde or glutaraldehyde at room temperature; (b) autoclave, moist or dry at temperatures ranging from 250–350˚ F (121–177˚ C) for a few minutes to a few hours; (c) gas, using 100% ethylene oxide (EtO) with its residues in the final product of less than two ppm; (d) radiation, using Co gamma rays at 2.5–4 Mrad.

5. Biodurability/biodegradability. A biostable biomaterial must not undergo any degradations or decompositions that might compromise the above-mentioned properties. Conversely, a

---

**TABLE 2-14**

Definitions of Biomaterials (Implant/Medical Grades) Versus Clean/Commercial Grades

<table>
<thead>
<tr>
<th>Bio-testing</th>
<th>Implant Grade</th>
<th>Medical Grade</th>
<th>Clean Grade</th>
<th>Commercial Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-year implant data available</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meet or exceed USP XX, class VI plastics test</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrogen</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin sensitization</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tissue cell culture</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90-day implant with histopathology on all major organs</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Quality controls                                |               |               |             |                  |
| Lot testing for 24 trace metals                 | x             | x             |             |                  |
| FDA registered plant using GMPs                 |               |               |             |                  |
| Lot quality control                             | x             | x             | x           |                  |
| Lot traceability                                |               |               |             |                  |
| Product certification                           | x             | x             |             |                  |
| Physical properties audited on a regular basis   | x             | x             |             |                  |
| Four-year sample retention                      | x             |               |             |                  |
| 90-day sample retention                         |               |               |             | x                |
| All multi-component materials are lot matched   | x             |               |             |                  |

| Packaging                                        |               |               |             |                  |
| Units separately wrapped, sealed and labeled     | x             | x             | x           |                  |
| Each 25 lb unit wrapped separately              |               |               |             |                  |
| Strained through 200 mesh                       | x             | x             |             |                  |
| 50 lb boxes strained through 120 mesh           |               |               |             | x                |
| 1,000 lb boxes screened through 120 mesh        |               |               |             | x                |

| Tech service and samples                         |               |               |             |                  |
| Free samples                                     | x             | x             | x           | x                |
| Test results on request                          | x             | x             | x           | x                |
biodegradable material should follow the designed degradation course.

Three major factors govern the success of a biomaterial to achieve its goals: properties and biocompatibility of the material, health conditions of the recipient, and competency of the operating surgeon. Polymer/material scientists and processing engineers can only influence the first factor and have no control over the other two.

### TABLE 2-15

<table>
<thead>
<tr>
<th>Physicochemical and Mechanical Conditions in Humans</th>
<th>Value</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>1.0</td>
<td>Gastric contents</td>
</tr>
<tr>
<td>4.5-6.0</td>
<td>Urine</td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>Intracellular</td>
<td></td>
</tr>
<tr>
<td>7.0</td>
<td>Interstitial</td>
<td></td>
</tr>
<tr>
<td>7.15-7.35</td>
<td>Blood</td>
<td></td>
</tr>
<tr>
<td>( pO_2 ) (mm Hg)</td>
<td>2-40</td>
<td>Intermédiary</td>
</tr>
<tr>
<td>12</td>
<td>Venous</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Arterial</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Venous</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>Atmospheric</td>
<td></td>
</tr>
<tr>
<td>( pCO_2 ) (mm Hg)</td>
<td>40</td>
<td>Alveolar</td>
</tr>
<tr>
<td>2</td>
<td>Atmospheric</td>
<td></td>
</tr>
<tr>
<td>Temperature °F (°C)</td>
<td>98.6 (37)</td>
<td>Normal core</td>
</tr>
<tr>
<td>68-108 (20-42.5)</td>
<td>Deviations in disease</td>
<td></td>
</tr>
<tr>
<td>82 (28)</td>
<td>Normal skin</td>
<td></td>
</tr>
<tr>
<td>0-113 (0-45)</td>
<td>Skin at extremities</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical Stress psi (MPa)</th>
<th>Tissues</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-58 (0-0.4)</td>
<td>Cancellous bone</td>
</tr>
<tr>
<td>0-580 (0-4)</td>
<td>Cortical bone</td>
</tr>
<tr>
<td>580 (4)</td>
<td>Muscle (peak stress)</td>
</tr>
<tr>
<td>5800 (40)</td>
<td>Tendon (peak stress)</td>
</tr>
<tr>
<td>11,603 (80)</td>
<td>Ligament (peak stress)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stress cycles (per year)</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 ( \times 10^4 )</td>
<td>Peristalsis</td>
</tr>
<tr>
<td>3 ( \times 10^6 )</td>
<td>Swallowing</td>
</tr>
<tr>
<td>0.5-4 ( \times 10^7 )</td>
<td>Heart contraction</td>
</tr>
<tr>
<td>0.1-1 ( \times 10^6 )</td>
<td>Finger joint motion</td>
</tr>
<tr>
<td>2 ( \times 10^8 )</td>
<td>Walking</td>
</tr>
</tbody>
</table>

### TABLE 2-16

| Components and Composition of Human Blood |
|------------------------------------------|--------|
| Blood                                    |        |
| Packed cell volume                       | 38.5%  |
| Serum volume                             | 61.5%  |

| Serum composition (mean values)          |        |
| Cations                                  | meq/L  |
| Anions                                   | meq/L  |
| Sodium                                   | 142    |
| Chlorine                                 | 101    |
| Potassium                                | 4      |
| Bicarbonate                              |        |
| Calcium                                  | 5      |
| Phosphate                                | 2      |
| Magnesium                                | 2      |
| Sulfate                                  | 1      |
| Total                                    | 153    |
| Organic acids                            | 6      |
| Proteins                                 | 16     |

| OTHER ELEMENTS                           |        |
| Iron                                     | 0.75-1.75 mg/L (ppm) |
| Nickel                                   | 1.0-5.0 µg/L (ppb)   |
| Titanium                                 | 3.3 µg/L            |
| Aluminum                                 | 2.0 µg/L            |
| Copper                                   | 0.8-1.4 µg/L        |
| Chromium                                 | 0.3 µg/L            |
| Manganese                                | 0.4-10 µg/L         |
| Vanadium                                 | < 0.2 µg/L          |
| Cobalt                                   | 0.15 µg/L           |
| Serum proteins                           |        |
| Total                                    | 65-80 g/L           |

| Distribution (%)                         |        |
| Albumin                                  | 6.15   |
| Globulins                                | 34.5   |
| α                                         | 8.2    |
| β                                         | 10.3   |
| δ                                         | 12.6   |
| Fibrinogen                               | 4.0    |

| Cellular distribution                     |        |
| Type                                      |        |
| Typical dimension (µm or 0.001 m)         |        |
| Erythrocyte                               | 4-5.6 \( \times 10^6 \)µL |
| Platelet                                  | 1.5-3 \( \times 10^6 \)µL |
| Leucocyte                                 | 2.8-11.2 \( \times 10^6 \)µL |

| Leucocyte distribution (%)                |        |
| Neutrophils                               | 59     |
| Eosinophils                               | 2.4    |
| Basophils                                 | 0.6    |
| Monocytes                                 | 6.5    |
| Lymphocytes                               | 31     |
| 7-18                                      |        |
SYNTHETIC PROCEDURES

Even though the number of different polymers is large, there exist only a few basic methods to synthesize these materials. The synthetic procedure represents still another way to classify polymer materials. The treatment given in this chapter will be brief and is meant to introduce the reader to these different techniques; for further information the reader should consult the references listed in the Bibliography. A knowledge of the synthetic technique can be important when selecting a material. Of primary importance to material selection is that different synthetic techniques can produce polymers with the same repeat unit but with different properties. In particular, the polydispersity, crystallinity, and branching frequency are greatly affected by the synthetic method. Also, polymers made by different synthetic techniques can have differences in their response to environmental factors such as ultraviolet light or moisture.

ADDITION POLYMERIZATION

Certainly the synthesis route that produces the highest tonnage of commercial material is free radical or vinyl polymerization, which is one type of addition polymerization. Polyethylene, poly-vinyl chloride, and polystyrene are normally synthesized via free radical polymerization. An initiator, typically a peroxide or an azo compound, decomposes to form two molecules, each with an unpaired electron. This radical then reacts with a monomer molecule to form a radical compound that contains one monomer unit. Then this radical compound reacts with another monomer to form a radical compound with two monomers. This cycle continues until something happens to deactivate the radical. This procedure is shown schematically below:

\[
\begin{align*}
\text{Initiation} & : & I & \rightarrow 2R^* \\
\text{Propagation} & : & R^* + A & \rightarrow RA^* \\
\text{Termination by disproportionation} & : & RA_m^* + A & \rightarrow RA_m^* + A \\
\text{Termination by combination} & : & RA_m^* + RA_n^* & \rightarrow RA_{m+n}^*
\end{align*}
\]

where I represents the initiator, R represents the radical and • represents an unpaired electron. Typically the rate-limiting step is the formation of radical molecules, which means the final molecular weight will depend on the concentration ratio \((A)/(I)^{1/2}\). The polydispersity index is two for termination by disproportionation and 1.5 for termination by combination.

The polydispersity index is likely to be greater than two for many reasons. The first is that another possibility besides initiation, propagation, and termination can occur. If a suitable material is available, the free radical can transfer from one molecule to another:

\[RA_m^* + B \rightarrow RA_{m+B}\]

Table 2-17 shows the structures of monomers commonly used in addition polymerizations.

Chain Transfer

The chain transfer molecule can be a third species, or an initiator, an unreacted monomer, or even another polymer chain. If chain transfer occurs to one of the first three species, the number average molecular weight decreases, while the polydispersity index typically increases. Chain transfer to a polymer can either increase or decrease the number average molecular weight, while the polydispersity index typically increases.

Increased Polydispersity Index

Perhaps the most common cause of a high polydispersity index is that monomer concentration decreases as the fractional conversion increases. The decrease in monomer concentration leads to a decrease in both the number average and weight average molecular weight compared to the polymer that was formed earlier in the reaction. This leads to an increase in the polydispersity index since the high molecular weight polymer formed earlier is weighted more heavily in the calculation of \(M_w\) for the whole sample. Extremely broad molecular weight distributions are often not desirable, hence commercial processes often use multiple additions of initiator and/or monomer. A final cause of high polydispersity indexes is autoacceleration, which is a decrease in coupling termination rate due to an increase in reaction mixture viscosity.

Emulsion Polymerization

A special type of free-radical polymerization is called emulsion polymerization. Instead of polymerizing in a solution, as it would for normal free radical polymerization, the monomer polymerizes in a solvent in which it is essentially insoluble. An emulsifier, which traps the monomer inside micelles, does not allow the monomer and solvent to macroscopically phase-separate. The polymerization occurs inside these micelles. Emulsion polymerizations are usually much easier to control than free radical polymerizations. For cost-effectiveness, the solvent for nearly all emulsion polymerizations is water. The term latex refers to the water-emulsifier-polymer mixture that remains at the end of an emulsion polymerization. A coating of normal housepaint is the end result of an emulsion polymerization; when the water dries, a thin layer of polymer is left coated to the surface.

Other reactive species besides free radicals are important in addition polymerizations. In cationic polymerizations, monomers add to cationic ions, while in anionic polymerization, monomers add to carbon ions. Finally, in coordinated polymerizations, monomers add to an organic–transition metal complex. The last represents the mechanism for commercial polypropylene synthesis. All of the addition polymerizations are kinetically similar; however, the termination mechanisms can be quite different. For example, only free radical polymerizations can terminate via a bimolecular mechanism. The cation and anionic procedures are generally carried out at very low temperature, below 32˚F (0˚C), while the free radical polymerizations take place above 120˚F (49˚C). Often polymers can be synthesized from the same monomer by using more than one technique. Cationic and anionic polymerizations are not generally commercially important because of the low temperatures required and the sensitivity of the reaction to small amounts of water.

Anionic polymerizations create molecular weight standards found in process control laboratories. Anionic polymerizations can have no termination mechanism. This fact, coupled with the kinetic nature of the polymerization, means that an extremely narrow molecular weight distribution polymer can be synthesized.
Also, it is very simple to predict the molecular weight from a given set of reaction conditions. These polymers are extremely important for theoretical studies of the effects of molecular weight on polymer properties.

**Ziegler-Natta Polymerization**

The addition polymerizations in which a monomer joins a polymer–transition metal complex are termed Ziegler–Natta polymerizations, named after the two principal architects of this technique. One of them, Giulio Natta, is still the only chemical engineer to have won a Nobel Prize. The Ziegler-Natta initiators consist of a Group I-III organometallic and a transition metal compound. These initiators are the only compounds that will cause the polymerization of propylene and other -olefins. The beauty of these compounds is not only their ability to cause the polymerization of otherwise unreactive monomers, but the linearity and stereoregularity of their products. Linearity is extremely important, as discussed with respect to polyethylene. Stereoregularity refers to carbon chirality. If a polymer has a backbone chiral carbon (four chemically distinct species are attached to one carbon atom), then the material will not crystallize unless the four groups are arranged in the same manner for each carbon. All monosubstituted -olefin monomers will produce polymers with chiral carbons. In polymer science, one speaks of the tacticity of a polymer in regard to this phenomenon. Isotactic and syndiotactic polymers will crystallize, while atactic polymers will not. Commercial polypropylene is almost exclusively the isotactic stereoisomer. For more information about stereoisomerism, see Bibliography.

**Ring-opening Polymerization**

The monomers used in addition polymerizations have at least one double bond. The only major exception to this rule is addition polymerization in which the covalent bonds of the monomer all form a closed geometric object, that is, ring-opening polymerization. In fact, some authors classify this kind of polymerization as a separate class from addition and condensation polymerization; however, the fundamental polymerization steps are identical to the other addition polymerizations. Polypropylene oxide is an example of a commercially important polymer produced via a ring-opening polymerization. The suitability of a ring compound for polymerization into a linear polymer is governed almost entirely by the thermodynamic stability of the ring. Hence, six-member rings very rarely polymerize, while three- and four-member rings will usually polymerize.

**CONденSATION OR STEPWISE POLYMERIZATION**

In this method of polymerization, one bifunctional monomer (a bifunctional monomer is a molecule having two reactive function groups) reacts with another bifunctional monomer to produce a dimer. Because bifunctional monomers are used, the dimer will still have two unreacted functional groups available for further reaction. A third molecule, which can be monomer, dimer, trimer, etc., which also has two reactive functional groups, can react with the dimer and form a polymer. Note that, unlike addition polymerizations, propagations do not occur only with monomers. The general reaction step for stepwise polymerizations can be written as:

\[ x\text{-mer} + y\text{-mer} \rightarrow (x+y)\text{-mer} \]

An example of a condensation polymerization is the reaction of a diacid with a dialcohol (diol) to form an ester:

\[ \text{HO-R-OH + HOOC-R'-COOH} \rightarrow \text{HO-R-OOC-R'-COOH + H}_2\text{O} \]
Stepwise polymerizations are distinguished from addition polymerizations by the following:

1. In addition polymerizations, the polymer grows by adding monomer, while in stepwise polymerizations, the polymer can grow by adding monomer or other oligomers.

2. In addition polymerizations, high-molecular-weight polymer is formed at low monomer conversions, while in stepwise polymerizations, high-molecular-weight polymer is formed only at very high monomer conversions. This behavior is often used to differentiate addition and stepwise polymers. However, ionic polymerizations, which are addition polymerizations, will often not have high-molecular-weight polymers at low conversions. The desire to assign ring-opening polymerizations to a separate category arises from the fact that most ring-opening polymerizations also produce high-molecular-weight materials only at high conversions. The failure of an addition polymerization to produce high-molecular-weight material at low monomer conversions arises when the rate of initiation is not the rate-determining step; that is, the rate of initiation is faster than or equal to the rate of propagation.

3. Achieving molecular weights over 100,000 g/mol for stepwise polymerizations is extremely difficult because of the kinetics of these reactions.

**Reaction Injection Molding**

Parts can be made directly from the monomer with stepwise polymerization, that is, synthesis and manufacturing can be combined in one step. Usually this combination is not possible with addition polymerizations because these reactions are highly exothermic. Perhaps the most common example of this type of operation is reaction injection molding (RIM). Some foams are also produced in a one-step process. The primary advantage of producing parts in this manner (besides the inherent simplification advantage of reducing a two-step process to a one-step process) is that the monomers usually have orders-of-magnitude lower viscosities. Therefore, some knowledge of stepwise polymerization chemistry is important for the manufacturing engineer.

**Small-molecule By-product**

Stepwise polymerizations often result in the production of a small-molecule by-product, as in the ester example discussed previously. This fact has a number of ramifications. Perhaps most important, the small-molecule by-product must be removed to drive the polymerization to high conversion. Often this is done by performing these reactions under vacuum and/or at higher temperatures to evaporate the by-products. Also, the polymer may not be stable when exposed to some solvents because the polymerization reaction is typically reversible, and reversal is catalyzed by certain conditions. This type of problem should be distinguished from physical aging, which is more of a long-term effect. Further discussion of these types of properties will be found in the next section of this chapter.

Stepwise polymers are usually classified on the basis of the functional group that is formed as a result of combining the two reactive functional groups. Not included in Table 2-17 are the interchange reactions that can result in the formation of polymer. Table 2-18 gives the chemical reactions that result in common stepwise polymers. Interchange polymerizations start with a small molecule having the desired functional group linkage and, through successive interchanges, high polymers are created. An excellent example is the production of polycarbonate:

\[
\text{nR}_1-\text{OCOO-R}_2 + \text{nHO-R}_3-\text{OH} \rightarrow (\text{R}_2-\text{OCOO})_n+n\text{R}_1\text{OH} + n\text{R}_2\text{OH}
\]

Also, the ends of the monomer can contain reactive functional groups that react with each other; that is, instead of A-R-A and B-R-B monomers, one can have only A-R-B monomers. The molecular weight can be easily controlled through stoichiometric imbalances. Therefore producing oligomers of condensation polymers is very straightforward. These oligomers can then be used to build block copolymers.

**COLOR IN PLASTICS**

Physical properties of the finished molding or extrusion are affected by the colorants used and the methods of using them. Carbon black is a good conductor of electricity, but properly dispersed in resin, becomes a good cable insulator. Color is used for appearance, but colorants and the methods of selection and use affect the properties of a product as well.

**Color Glossary**

- **Hue** is the basic color of an object, determined by dominant wavelength. Violet has the shortest wavelength in the visible spectrum, red the longest.
- **Tint** is hue with white added.
- **Shade** is hue plus black.
- **Value** refers to the degree of brightness or cleanness of a color.
- **Chroma** relates to the purity of the color based on the various amounts of other colors that are mixed into it.

**Cost Factors**

A final problem is the cost of color in plastics. Involved are the pigments and dyes themselves, the cost of making dispersions, the equipment to do the work, the labor involved, the vehicles necessary to carry the color, the opacifiers in some cases, the downtime for purging to change colors, and the cost of obsolescent colored resin.

While the problems of color in plastics are many, and growing in number daily due to new materials and new colorants, a great deal of progress has been made in standardization through the use of modern color evaluation equipment. That standardization in large-quantity operations is bringing some lower costs. These matters will be discussed on the following pages.

**Coloring Methods**

You can cut costs, upgrade quality, and speed up production—if you know which system of coloring plastics is most suitable for your needs.

Colorants can find their way into a finished product by any of several routes, each of which is circumscribed by considerations of cost, service, quality, inventory, and even physical characteristics of the plastic or colorant.

Basically, the key figures in the industry—colorant suppliers, materials manufacturers, compounders, and processors—function as follows:

1. The colorant supplier can sell direct to the resin supplier who then makes precolored resins and compounds for sale to plastics fabricators.

2. Compounders (who in some instances can be the resin supplier or the colorant supplier) make color concentrates or master batches by incorporating colorant into resins. These, in turn, are sold to the plastics materials supplier, molder, processor, or reprocessor, who adds unpigmented resin, mixes,
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Result</th>
<th>Example</th>
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</thead>
<tbody>
<tr>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>~ C – OH + H – O ~</td>
<td>~ C – O ~</td>
<td>Polyester</td>
</tr>
<tr>
<td>Carboxylic Acid + Alcohol</td>
<td></td>
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<tr>
<td>O</td>
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<td>HO</td>
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<tr>
<td>~ C – OH + H₂N ~</td>
<td>~ C – N ~</td>
<td>Polyamide</td>
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<tr>
<td>Carboxylic Acid + Primary Amine</td>
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<tr>
<td>Acid Chloride + Primary Amine</td>
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<td>O</td>
<td>~ C – OH + Cl – C – Cl</td>
<td>Polycarbonate</td>
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<td>Alcohol + Phosgene</td>
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<td>R₁ Cl – Si– Cl + H₂O</td>
<td>R₂ ~ Si ~ O ~</td>
<td>Polysiloxane</td>
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<td>Chlorosilane + Water</td>
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<td>~ NCO + HO ~</td>
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<td>Polyurethane</td>
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<td>Isocyanate + Alcohol</td>
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<td>O</td>
<td>~ CH₃ O – C – O – O – C – O ~</td>
<td>Bisphenol A polycarbonate</td>
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<td>Alcohol + Phosgene</td>
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<td>~ NCO + H₂O ~</td>
<td>~ N – C – N – CH₂ O – N C – O – CH₂ CH₂ CH₂ CH₂ O – C – N –</td>
<td>MDI/BD/PTMO polyurethane</td>
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<tr>
<td>Isocyanate + Primary Amine</td>
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<tr>
<td>~ CHO + 2 ~ NH₂</td>
<td>~ N – C – N ~</td>
<td>Polyurea</td>
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<td>Aldehyde + 2 Primary Amines</td>
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</table>

*This material is a cross-linked polymer in its commercial form. Hydrogen abstraction from the nitrogen and subsequent reaction forms the basis for cross-linking in these systems.*
and molds or processes. For resins such as polyesters and epoxies, which are supplied uncolored, the compounder makes a liquid paste concentrate compatible with the resin system. Molders can then add these pastes to the liquid thermosetting resin along with the catalysts and fillers.

3. The colorant supplier can sell dry powdered colorants direct to plastics processors to be used for dry coloring resins.

Within this framework, there are various coloring methods available for handling thermoplastics or thermosets. Obviously, one of the big differences between techniques used for either involves the question of heating. Most of the methods of internally coloring thermoplastic resins and compounds require heat. Conversely, methods of coloring thermosets cannot use much heat or the entire batch will be precured and spoiled.

**Dry Coloring**

Dry coloring is one of the basic methods for coloring thermoplastics. The system consists of tumble-mixing dry powdered colorant with the resin or compound and passing the mix through an injection molding machine, calender, or extruder. This is probably the simplest system for coloring thermoplastics. At the same time, it is often not the best method when high quality and uniform color are required, but a satisfactory coloring job can be produced in most cases.

Dry coloring offers several advantages to the processor:

1. The processor can produce an almost unlimited color range and can match nearly any specified color without maintaining a large inventory of colored plastic material.
2. Plastic material is not wasted since the processor colors only the exact amount needed.
3. The process permits a considerable savings in inventory space for the processor, who has to stock only the colorants for immediate requirements.
4. The dry coloring process offers extreme flexibility in that the molder can switch from one color to another in a short time. Delivery time for dry color shipments is normally less than that required for colored resin.

There are, however, two main disadvantages to the dry coloring method:

1. Dispersion is usually not as complete as with precolored materials.
2. In handling the mixed color and plastic material, colorant dust sometimes is generated. When this occurs, color contamination of other plastics in the area can result.

With polystyrene and low-density polyethylene, the mixing operation performed by the injection-molding machine or extruder is sufficient to provide good colorant dispersion with dry colors. To achieve uniform dispersion of dry colors in polypropylene and high-density and high-melt-index polyethylene, it is often necessary to install a special inexpensive breaker plate in the heat cylinder or nozzle.

The dry coloring procedure for all granular thermoplastic resins is essentially the same. It is as follows:

1. A measured amount of resin is charged into the tumbling drum. For good tumbling action, the resin charge should be 50–60% of drum capacity. Liquid wetting agents can be added to improve the adherence of the colorant to the resin granules. If wetting agents are used, they should be tumbled briefly (5 minutes) to coat the resin before the pigment is added. Colorant suppliers will recommend when and in what proportions wetting agents should be used.
2. The powdered colorant is then added to the resin in the drum. An ordinary household flour sifter can be used. This aids colorant distribution and helps break up lumps of pigment that may have formed.
3. The method of tumbling is important. Experience has shown that end-over-end tumbling provides the best dry color and resin mix. The operator must not exceed about 90% of the speed that would cause the mix to centrifuge and not tumble in the drum. Critical speed normally falls between 30–45 rpm. The processor should experiment with the length of tumbling time to determine the best cycle for the operation.
4. Some resins will require drying (for example, nylon, ABS, acetal) to remove trace moisture picked up during tumbling. This is not necessary with polystyrene, polyethylene, etc.
5. After mixing (and drying, if needed), the resin is ready for the hopper of the molding machine, calender, or extruder. The colored resin should be transferred carefully from the drum to the hopper to minimize separation of the pigment from the resin particles.

Although dry coloring is a simple process, certain precautions must be taken:

- Tumbling time must be uniform from batch to batch of a given colorant and plastic.
- Colorants must be weighed accurately. Dry colors are available in preweighed packages from colorant suppliers.
- The tumbling and color addition operations should be handled in a plant location apart from other processing operations to avoid color contamination. A different tumbling drum should be used for mixing each color, or the drum should be thoroughly cleaned before reuse. It is very easy to contaminate other batches.
- The resin must be dry. Addition of moisture-laden resin can cause marked deterioration in the quality of the finished part. Even if dry resins are used, it is normally necessary to dry moisture-sensitive resins after the addition of the colorants and before molding.

**Extrusion Coloring**

The primary use of extrusion coloring for thermoplastics is to make precolored compound resin. It is an intermediate coloring step that provides better color dispersion and produces a more uniform color.

The colorant (or colorant blend) is first thoroughly mixed with the resin in a dry blender, using methods similar to those described for dry coloring. This dry mix is then charged into the extruder. As the mix passes through the heated extruder, the feed screw mixes the fused resin and colorant mixture.

The colored material is extruded in continuous strands, approximately 0.12 in. (3.2 mm) in diameter, which are air-cooled or cooled by passing through water and then chopped into pellets. Some polyolefin resin suppliers cut the pellets before the strand is cooled. The pellets, which are then air-cooled, are called hot cut and are more spherical than the cylindrical cold cut pellets.

Extrusion coloring is usually done by resin suppliers, compounders, and large plastics fabricators. These companies do their own color matching and blending.
Color Concentrates

Color concentrates are concentrated mixtures of resin and colorant. They are used by molders and extruders to make colored thermoplastic parts. A color concentrate may contain 10 times the proportion of colorant needed in the finished part. The term usually refers to a solid that is supplied in chip or pellet form for use in polyolefins and epoxies. Liquid and paste color concentrates also are used extensively to color vinyl compounds.

The percentage of colorant used in a color concentrate is determined by the use the concentrate is put to, including the method of fabrication—molding, extrusion, blowing, etc. Each of these processes acts as a mixer, but to different degrees. An extruder is considered to be a good mixer, whereas the injection molding machines are not. If the concentrate will be mixed well with the uncolored resin during processing, a larger percentage of colorant can be used in the particle of concentrate. This means that a proportionately smaller amount of concentrate to resin is needed. A formula for specifying proportion of color to resin can be found in the section Calculating for Colorant Ratios.

If a resin manufacturer does not have intensive mixing equipment, it is usually more economical to use a commercial color concentrate than to set up a color laboratory to control the making of a precolored resin by the extrusion method.

Before there were high-density polyethylenes, color concentrates for low-density materials were made with high-flow resins and worked very well. But when attempts were made to use a low-density color concentrate to color a natural high-density resin for injection molding, impact strength of the molded product was less than satisfactory. Today, material makers recommend concentrate with the same melt index and density as the resin being molded.

Special equipment is required to make a color concentrate, since a higher percentage of colorant is being added to natural resin than is usually done by other coloring methods. In some instances, an extruder can be used to make a concentrate, but it is difficult to add the 10–15% of colorant needed to make a concentrate to the fused resin with the mixing action provided by an extruder. A better way of adding high percentages of colorant is through intensive grinding. If an extruder must be used, the mixture can sometimes be achieved by repeated passes through the extruder, but each pass adds to the cost of the process.

Two-roll rubber mills can be used to grind the colorant into the resin. However, intensive mixers such as the Banbury mixer have been found satisfactory and economical for volume production. However, intensive mixers such as the Banbury mixer have been found satisfactory and economical for volume production. Yet intensive mixers are used extensively to color vinyl compounds.

Attrition grinders. An alternative mixing method is attrition milling, which is designed to grind and mix the resin and colorant powders with a high-speed attrition, or wearing, action. Although this method does not produce the quality grind that is possible with a ball mill, it is considerably less expensive for small batches. A molder who is coloring melamine or urea ordinarily uses an attrition mill.

Coloring Liquid Thermosets

Thermosetting resins that are supplied in a liquid state (for example, polyesters and epoxies) cannot be colored uniformly simply by adding the colorant in a dry powder form.

Mixing dry powdered colorant into a liquid thermoset is like mixing flour and water—lumps of powdered pigment form in the liquid resin. Also, colorants tend to settle, and some colorants that are promoters and oxidizing agents cause certain thermosets to cure and harden. As a result, liquid thermosets are supplied in a natural state for the user to color.

The method of fabrication determines how a liquid thermoset should be colored. If, for example, a liquid thermoset is to be used in a molding operation, it is best to add the colorant in a liquid or paste concentrate form. The paste concentrate corresponds to the color concentrates used in coloring thermoplastic resins, and it is used in essentially the same way. A highly concentrated mixture of colorant and resin is made by grinding colorant into the liquid resin. The concentrate can then be added to the uncolored liquid resin by the molder with a simple stirring-in-operation.

Gel coats. The gel coat is becoming a popular method for coloring the outer surfaces of some thermoset reinforced plastics parts. A gel coat is a pigmented polyester resin mixture that can be applied by simple brush or spray techniques to hot or cold surfaces prior to molding or laminating operations. The gel coat layer reacts with the molding resin during the curing cycle to become an integral part of the molded product. The gel coating process provides a continuous color surface over large or small areas without subsequent finishing operations.

Gel coats do an excellent job of suppressing surface fiber patterns. The gel coats also serve as vapor barriers.

Paste concentrates. Paste color concentrates are used almost exclusively in coloring liquid thermoset resins such as polyester and epoxy resins. They are also widely used in coloring vinyl compounds. These concentrates are usually made on a grinding mill similar to the three-roll mill used in the paint industry, but ball mills and other wet grinding mills can also be used.

Selection of the grinding vehicle or carrier is important. The colorant carrier usually uses a carrier of the same chemical type as the resin to be colored, so that, being completely compatible with the resin, it will not adversely affect the properties of the molded part.

The dispersions vary in viscosity from a pourable syrup to a heavy paste, depending on the vehicle used, the pigment, and the proportion of solids.

Sometimes, to achieve a specific color match, the color supplier must use several different types of pigments in a single paste color concentrate. In such instances, a separation of the different pigment types occasionally will occur when the concentrate is stored over long periods. The pigment supplier can minimize this
Dispersions and Agglomerates

A continuing problem with finely ground particles of pigment is that they have a tendency to form agglomerates. One reason for this is that being of different sizes and shapes, the pigment particles tend to lock together. The usual reason for formation of agglomerates in inorganic pigments is the presence of an impurity or a soluble salt. Although it is almost impossible to eliminate these impurities, pigment manufacturers are continually refining their production methods to produce finer, easier-dispersing colorants.

Organic pigments and dyes, being softer than the inorganics, form agglomerates more easily. As with the inorganics, agglomerates are also caused by residual soluble salt content. This is not too important with dyes, which go into solution in the molten resin. However, as a rule, the organic pigments, are hard to disperse.

The varying flow characteristics of plastic materials also affect dispersion of the colorant. The low-melt-index polyethylene resins, for example, are easy to color, and colorant dispersion presents no problems. But high-melt-index resins cannot be satisfactorily colored with the same pigments or dispersing methods used for the low-melting resins.

Improvements in colorant formulations have not been the entire answer. Better dispersion aids and molding techniques have improved the dispersion of colorants in polyethylene. In the search for a technique that would enable an injection molder to dry-color any polyethylene resin with good results, the Venturi breaker plate, an advanced, simplified version of the ordinary breaker plate, was developed. It has a single orifice of very short land length and is easy to install. Quality of dispersion is very high.

The size and shape of the part also affect dispersion characteristics. It is more difficult to disperse colorant in a flat part, such as a plastic tile, dish, or item with mostly regular contour, than in a part that is irregular in shape. For example, when molding a plastic dish where the gate is in the middle, if proper dispersion methods are not used, the result is often a bull’s-eye effect.

Knowing the resin, color, and shape of the product, the colorant supplier usually can predict the type of dispersion that will be necessary. A simple breakdown would perhaps list dry coloring as the least expensive coloring method. Next would come precoloring by the manufacturer. Color concentrates would be considered the most expensive. However, competitive situations can change this breakdown.

In addition to the cost of the coloring operation, other cost-related factors must be considered:

1. Inventory cost. Which coloring method will permit lowest inventories of raw materials?
2. Rework and scrap costs. Will these costs increase with the use of either dry coloring or concentrate coloring even when the most improved dispersion aids are used? If a continuous standard color is to be maintained, color continuity and quality control call for the use of the highest quality dry colorant or precolored resin.
3. Improved service. Which method will enable the molder to make the initial selection easy when dollars and cents are a factor.

As a rule, the makers of precolored resins and color concentrates do not have the selection and delivery speed of the dry colorant supplier. With dry colors, it is not necessary for the processor to have large inventories. Orders can be smaller and service considerably faster.

FACTORS IN CHOOSING A COLORANT

Resins and Processing

The resin and the processing method are particularly important in choosing a colorant. For example, acid-sensitive colorants (cadmium reds and ultramarine blues) must be used with care in resins, such as polyvinyl chloride and its copolymers, that liberate acids at high temperatures. Some pigments (iron blues) are preferable for coloring resins that use acid rather than alkaline catalysts. Using the wrong resin-colorant combination can sometimes have serious results. To cite another example, a color for application in polystyrene was compounded using a hansa yellow pigment. Several years later the molder used some of the pigment left from the polystyrene application to color a yellow polyethylene cap for a household oil can. Although hansa yellow is suitable for use in polystyrene, it tends to crock in polyethylene. The error in application was not discovered until the oil cans had been filled, sealed, and placed on dealers’ shelves. All the oil cans had to be recalled and replaced at considerable expense.

Colorant Concentration

The ratio of colorant to resin will vary the color effect and the properties of the color produced. The color that results from the use of colorants in high concentrations is usually more lightfast than colors produced by the same pigments in low concentrations (tints). Low pigment concentrations minimize the bleeding and crocking tendencies of a colorant. In general, increasing the colorant concentration promotes bronzing with certain red pigments.

Some dyes and pigments, such as iron oxide and phthalocyanine pigments, have antioxidant effects. When used in high con-
centrations, they can retard or inhibit the cure of some catalyzed polymers. Within this framework there are, of course, certain practical considerations. It is not necessary, for example, to select a colorant with heat resistance capability of 500°F (260°C) for a resin that is never processed above 350°F (177°C) if a less expensive colorant will produce the desired shade and meet all other requirements.

Organic red pigments can be used successfully in most flexible vinyl applications because of the vinyl's lower processing temperatures. Other thermoplastic resins, such as polypropylene, require higher melting temperatures. For these resins, the more expensive, highly heat resistant cadmium pigments are more suitable.

**Product End Use**

End use of the colored plastic part is an equally important consideration. If the product will be in contact with acids, the colorant system obviously must be acid-resistant. Are electrical properties important for the plastic? If so, this fact must be considered when the colorant system is being evaluated. Some colorant systems reduce the dielectric properties and resistance of insulating plastic materials. Others can improve these properties.

**Colorant Characteristics**

There are several key characteristics that users should look for in selecting a colorant. One series, known as the performance characteristics, includes the colorant's brightness, hiding power, tintorial strength, and transparency. A second series, known as the resistance characteristics, includes heat resistance, weather resistance and lightfastness, resistance to migration, and chemical resistance.

Inorganic pigments can be divided into synthetic and natural groups. Synthetic inorganic pigments are made from combinations of metallic oxides, sulfides, etc. Natural inorganic pigments are mined and then refined. The more heat-resistant inorganic pigments are finely ground mixtures of inorganic materials that have been calcined at from 1200–2100°F (649–1149°C). However, some inorganic pigments are calcined (or in some cases dried) at temperatures lower than 1200°F (649°C) and occasionally below 250°F (121°C). These exceptions include the iron blues, chrome yellows, chrome oranges, and molybdates.

Inorganic pigments are insoluble in the common solvents used in plastics, and they are insoluble in the resins themselves. In general, the inorganic color family produces opaque colors, but there are several exceptions. The iron blues, for example, can make translucent shades when used in low concentrations. Some synthetic inorganic pigments produce bright colors at high concentrations, but in general they are not as bright as those that can be made with organic pigments and organic dyes. However, tints made with organic pigments are generally stronger and cleaner than those made with inorganic pigments.

The primary advantages of inorganic colorants are their excellent resistance to heat, light, and migration. Chemical resistance, although generally good, varies within colorant groups. Inorganic colorants have a high specific gravity and a lower oil absorption than organic pigments and dyes. They also have considerably less antioxidant effect and better weather resistance.

Organic pigments are divided into two classes, toners and lakes. There are two types of toners, insoluble organic toners and lake toners. The insoluble organic toners are usually free from salt-forming groups. Lake toners are practically pure, water-insoluble heavy metal salts of dyes without the fillers or substrates of ordinary lakes. Lakes, which are not as strong as lake toners, are water-insoluble heavy-metal salts or other dye complexes precipitated upon or admixed with a base or filler. They are characterized by brightness and brilliance, but the resulting colors usually are not as bright as those obtained from dyes. Their tintorial power is not as high as that obtainable with most dyes, but it is considerably better than that of inorganic pigments. Organic pigments are also characterized by low specific gravity and greater resistance to migration than dyes. Oil absorption is higher with most organic pigments than with most inorganic pigments.

Translucent or nearly transparent colors can be made with organic colorants, but these effects are possible only at low pigment concentrations and with excellent dispersion. Polystyrene, for example, colored with an oil red dye, is transparent. When colored with an organic red pigment, the polystyrene appears hazy. Each organic pigment varies greatly in its resistance characteristics and adaptability to use in specific resins.

Dyes are synthetic or natural organic chemicals that are soluble in most common solvents. They color by going into solution. The color effect produced by a dye is distinctly different from that obtained with inorganic and organic pigments. Dyes yield bright, strong, and transparent colors. Positive characteristics include an almost limitless color range, good transparency, high tintorial strength, and low specific gravity. Most dyes migrate in polyolefins and vinyls. However, the processing temperatures of most thermoplastics are so high that the use of dyes is limited. The suitability of dyes for coloring different resins varies considerably from one dye family to another.

**Resistance Characteristics**

**Heat resistance.** The heat resistance of a color produced in a given plastic is predicated on:

- Exposure time.
- Exposure temperature.
- Exposure conditions.
- Colorant type.
- Pigment concentration.

Most organic pigments can withstand a few minutes at high temperature but not prolonged periods of exposure. Some decompose if held more than 5–10 minutes above 400°F (204°C). Nearly all do so erratically at 500°F (260°C). Dyes break down at any temperature above 350–400°F (177–204°C), even when exposure time is short. Most inorganic pigments are noted for their heat resistance and can withstand temperatures in excess of 550°F (288°C). Some cadmium pigments can withstand temperatures over 1500°F (816°C). A notable exception to this rule is the tendency of molybdate orange to darken at relatively low temperatures in polystyrene (450°F or 232°C).

Normally, an increase in pigment loading improves the heat resistance of a colorant. There are experts, however, who believe that the actual heat resistance of a pigment is not affected by the amount used.

In certain applications, there is action between the resin and the colorant system. If, for example, ultramarine blue is used in a particular polyvinyl chloride compound that liberates hydrochloric acid in trace quantities, the color would lack in heat stability. This would be due entirely to the reaction in this particular resin. This reaction would be accelerated by higher temperature, thus affecting the heat resistance of the colorant or colorant system.

**Weather resistance and lightfastness.** Any discussion of light stability must take into account varying exposure conditions.

Most flexible vinyl film is evaluated for light stability only, since it is normally not used in direct weather. This broadens the colorant selection considerably.
As a rule, dyes are less lightfast than organic pigments, and organic pigments are less lightfast than most inorganic pigments.

Generally, phthalocyanine pigments have excellent light stability. Certain of the red shade phthalocyanine blue pigments, however, change color toward the green shade on exposure.

Some colorants have good light stability, but poor weather resistance. The cadmium yellow family is an example. When used in interior applications (mass tone or tint), these pigments have excellent stability to both sunlight and artificial light. Outdoors in tints or pastels, however, the weathering effect of moisture plus sunlight causes the cadmium yellow pigments to fail.

On exposure to light some colorants fade, others darken, and a few change in hue. For example, under certain conditions lead chromate yellows, cadmium yellows, chromium reds darken, and red lake fades.

All colorants known to be light sensitive fade more severely when used in low pigment concentration and when compounded with white to make tints or pastel shades.

Sometimes a compromise must be made in selecting a colorant. Sometimes when only one colorant is available to produce a desired color, it must be used even if it has less than the desired degree of light stability. If there is a choice between two colorants with inferior light stability, it is best to choose one that darkens rather than fades on exposure. This is not true for white and off-white pigments, however, since any darkening is magnified but fading is not as noticeable.

In matching some darker colors, it may be possible to balance a hue shift with fading by using a two-component colorant system. One colorant is selected that darkens or shifts in hue in a direction that makes up for the fading or hue shift of the other component. A molybdate orange-red lake C mixture is an example.

It must be noted that when colorants are rated as lightfast in mass tone yet have low stability in tint, the mass tone does fade after long exposure.

**Resistance to migration.** There are four types of colorant migration in plastics:

1. **Bleeding** is the migration of the colorant from one plastic into another material with which it is in contact.
2. **Crocking** is evidenced by a migration of the colorant to the surface of the plastic so it can be rubbed off.
3. **Bronzing** usually accompanies crocking and appears as a metallic effect on the surface of the plastic part.
4. **Plate-out** is the migration of a colorant when the plastic is on compounding or calendering rolls. Once at the surface of the plastic the colorant plates, or adheres, to the metal rolls of the calender and is withdrawn from the resin system.

Colorants that do not migrate are susceptible to plate-out in some vinyl resins with certain plasticizers and stabilizers.

Some BON reds will plate out even when used in typical calender formulations.

Bleeding and crocking are the most common forms of migration. It is possible for one to occur without the other.

There are two tests for checking migration. For crocking, rub the colored plastic with a white cloth after a period of aging. If pigment rubs off on the cloth, the colorant has migrated. Commercial devices for testing are also available. To test for bleeding, clamp the colored part to a piece of plastic material of the type that the colored material will touch during use. Separate the parts after a week. Bleeding has occurred if the colorant has migrated.

Most dyes and some organic pigments migrate in vinyls, polyethylene, linear polyethylene, and impact polystyrene. Hansa yellows are often cited as the classic example of an organic pigment that migrates. Another good example would be the pyrazolone red family. Long exposure at high temperature promotes all forms of migration.

**Chemical resistance.** This term applies to chemical attack by the contents or environment of the plastic article and attack by the plastic system itself or the colorant.

The stability or resistance of a colorant system to chemical attack often depends on the permeability of the plastic material to the chemical. If, for example, the plastic absorbs a portion of a solvent, the solvent might react with the colorant in the plastic. But if the plastic is nonpermeable to the chemical, the color would not be attacked.

**Colorants in Food Packaging**

A colorant may be safely used in contact with food when:

1. It does not migrate to the food.
2. It is generally recognized as safe (substances that present no hazard in their intended use because of their long history of safe use and because of test evidence by recognized experts of their unharmful nature).

At present, a manufacturer of a food container who maintains that it and the colorants in it do not migrate to the food is exempt from the food additives amendment laws. Here, the burden of proof rests with the government to prove otherwise. However, a manufacturer who finds that the colorant in a plastic container does migrate into the food must make sure that those components of the container that do migrate (and which thus indirectly become a food additive) are sanctioned to be used. The user of colorants for plastics is expected to be familiar with the government laws pertaining to them.

The manufacturer of colorants has no means of controlling the use of a product sold to a manufacturer of packaging materials. This makes it impossible for the colorant manufacturer to issue a valid guarantee of the safety of the product and eliminates legal obligations and responsibilities.

**COLORANT TYPES**

In selecting a colorant for any specific plastic, it is as important to know the characteristics of the colorant as it is to know the characteristics of the plastic. This section reviews the properties of some of the more commonly used inorganic and organic pigments and dyes.

**Inorganic Violets, Blues, and Greens**

Chrome greens are used extensively in polyester and other catalytic oxidizing resins. They have little effect on the catalytic oxidizing reaction, and their use cost is low. Heat resistance and lightfastness are good. Alkali resistance is low. They are mixtures of chrome yellow and iron blue and, consequently, their properties vary with the proportions of each component. If, for example, a chrome green is on the light yellow side, the properties are closer to those of chrome yellow than to those of iron blue.

Chromium oxide greens are dull, dark greens, vastly different in color from the chrome greens. These pigments have outstanding heat, light, and chemical stability. Tinctorially they are weak and hard to disperse. Normally they make olive drabs and similar low-intensity greens. It is impossible to produce bright green or clean pastel shades with these pigments.

Cobalt aluminates pigments are formed from a crystalline combination of cobalt and aluminum oxides. Heat resistance is very high. The color varies with addition of other inorganic materials. A small addition of chrome to the cobalt aluminates produces a
SYNTHETIC PROCEDURES

Organic Violets, Blues and Greens

The intensity of this colorant restricts its use primarily to toning and has been used most extensively in vinyls, with little application in blue pigments that do have red undertones. Mineral violet has been used as a finished pigment and has the same performance and resistance characteristics as the ultramarine blues. Ultramarine blues are used extensively in plastics. Heat resistance is excellent. Chemical resistance is good except to acids. Ultramarine blues are more difficult to disperse than cobalt aluminates.

Hydrated chromium oxide is a green pigment with high chroma, high transparency, and good outdoor durability. It does, however, have lower temperature resistance than the chromium oxide green. This limits its use in plastics.

Iron blues have physical properties similar to the organic blue pigments. Oil absorption is high, and transparent or slightly translucent colors can be produced at normal pigment concentrations. They do not migrate. Lightfastness is good, especially in mass tone or dark shades. Heat resistance is relatively poor. Chemical resistance is generally good, except to alkalies. Since these pigments usually contain a small percentage of free iron, they can cause degradation in certain plastic materials.

Mineral violet is sometimes called manganese violet, mangansese blue, permanent violet, fast violet, or Nuremberg violet. Normally, it is a mixed crystal of barium sulfate and barium manganate. Lightfastness is good. Since it does not have a red undertone, it is often used as a blue tinting colorant with white pigments. Also, it can be used in combination with other inorganic blue pigments that do have red undertones. Mineral violet has been used most extensively in inks, with little application in other plastics. The low tinting strength and relatively low color intensity of this colorant restricts its use primarily to toning and tinting of white finishes.

Inorganic Yellows and Oranges

Phthalocyanine greens and blues are outstanding for use in pastel turquoise color. A smaller amount of chrome, plus more alumina, makes the color blue. Finally the violet-red-blue color range is reached with small additions of silica.

Cobalt aluminates are used extensively in plastics because they are easy to disperse. Also, they are heat and light stable. They are chemically inert and do not affect the curing of thermosetting resins.

The use cost of these colorants is high. Though relatively inexpensive on a per pound basis, higher percentages of pigment are required in the resin than the other blue pigments such as phthalocyanine blue. Often the cobalt aluminates produce a tint or are used for tinting a white pigment because of their good dispersion and heat resistance.

Cobalt aluminate pigments should not be confused with cobalt blue pigments. Cobalt blue is a mixture of ultramarine blue and a white pigment, such as zinc oxide.

Cobalt blue is often considered a part of the ultramarine blue family; however, the presence of a white pigment such as zinc oxide distinguishes it, and gives it light blue color. Cobalt blue is supplied as a finished pigment and has the same performance and resistance characteristics as the ultramarine blues.

Ultramarine blues are used extensively in plastics. Heat resistance is excellent. Chemical resistance is good except to acids. Ultramarine blues are more difficult to disperse than cobalt aluminates.

Hydrated chromium oxide is a green pigment with high chroma, high transparency, and good outdoor durability. It does, however, have lower temperature resistance than the chromium oxide green. This limits its use in plastics.

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Organic Violets, Blues and Greens

Pigment green B contains an iron complex and for this reason is limited to use mainly in acrylic and styrene resins. Its outdoor durability is poor.

Phthalocyanine green and blue pigments are often called the workhorse colorants of the plastics industry. Their performance and resistance characteristics are very good, and they do not migrate. Lightfastness is excellent in both mass tone and tint. The red-shade phthalocyanine blues are a little weak with respect to lightfastness.

The phthalocyanine greens are more heat stable than are the red-shade blues, since the red-shade blues tend to turn toward the greener shades under extremely long exposure.

Although bright in color, the phthalocyanine pigments are translucent when used at normal pigment concentrations. These pigments may inhibit the cure of the polyester resins. Some resin suppliers suggest that the pigment concentration be kept below 2% in polyesters. Normally this is not a problem because phthalocyanine greens and blues are strong colorants. Currently, phthalocyanine green is the only brilliant green satisfactory for use in plastics. Mass tones of the phthalocyanine greens and blues are very dark, but with the addition of small amounts of a white pigment, such as titanium dioxide, brilliant green and blue colors are possible. The phthalocyanine pigments are generally difficult to disperse. Phthalocyanine blues and greens are outstanding for use in pastel shades where light stability is required.

Phosphotungstic acid and phosphomolybdate acid (PTA and PMA) toners are a class of organic green pigments. Lightfastness, however, is generally poor. In most instances, these pigments have a tendency to bleed. They produce transparent colors at normal concentrations of use. Primarily, PTA/PMA toners are used because they are easier to disperse than some dyes. In most cases, however, the dyes are just as good and less expensive to use.

Inorganic Yellows and Oranges

Cadmium selenide oranges and cadmium mercury oranges are described under cadmium selenide red and maroon and cadmium mercury red and maroon pigments.

Cadmium sulfide yellow pigments are normally supplied in two grades: concentrated and extended. This pigment family includes a complete color range from green, or lemon yellow, to pure orange. Although the natural color of concentrated cadmium sulfide is orange, small amounts of zinc are added to make lemon yellow. The concentrated grade pigment is noted for its clean mass tone and color strength. The extended grade is normally made by extending, or coprecipitating, the concentrated pigments with barium sulfate or diatomaceous earths. The resultant extended pigment costs less to use than the concentrated grade. Extended cadmium sulfide yellow pigments are bright in mass tone but not as bright as the concentrated grade. Also, the extended grade does not have the strength of the concentrated grade.

The resistance characteristics of this family are generally excellent, weathering being the major exception. Exposure tests indicate that the weather resistance of cadmium sulfide colorants is affected by the ability of the vehicle to resist the passage of moisture vapor. Fading may result if the permeability of the vehicle to moisture increases in conjunction with its exposure to sunlight.

Chrome yellows and oranges are types of lead chromates. Some of the chrome orange pigments are being replaced by blends of chrome yellow and molybdate orange.

The chrome orange pigments, being basic in character, are relatively resistant to alkaline attack but have poor resistance to acids. They cannot be used where they might be exposed to attack by sulfur fumes. Sulfur compounds attacking chrome orange can produce lead sulfide (black), destroying the color. The yellow lead chromates tend to darken on exposure.

Titanium pigments form an inorganic yellow pigment family including crystalline combinations of the oxides of titanium and nickel and of titanium and chrome. The color range includes yellow for the nickel titanates, through the orange-to-buff color range for the chrome version. These colorants have extreme stability to weathering and heat when compared with the cadmium yellow pigments. They are not as bright or as strong as the cadmium yellow colorants, but they are less expensive to use.

Molybdate orange is a coprecipitated mixture of lead chromate, lead sulfide, and lead molybdate. It is unique among the inorganic pigments since it possesses brightness in addition to high strength. One of its major uses is with organic and inorganic red pigments to
produce relatively low-cost, bright red colors. It does have poor heat stability in some resins, for example, polystyrene.

Zinc chromate yellow is not a lightfast pigment. Heat resistance is moderate, and resistance to weathering is poor. These pigments have low resistance to alkalies and moderate resistance to acids. Hiding power is good. The zinc chromate yellows can be used to color acrylics, cellulosics, and general-purpose polystyrene.

**Organic Yellows and Oranges**

Benzidine oranges and yellows produce strong, bright yellow and orange shades. They are approximately twice as strong and, as a rule, more bleed-resistant than the hansa yellow pigments. In lightfastness, however, benzidines are inferior to hansa yellows.

The orthoanisidine and the metaxylidide yellows are more expensive than the other benzidine pigment types. They yield more-transparent colors, have better stability, and are slightly more bleed resistant.

Hansa yellows have limited use in most plastics because of a strong tendency to migrate. Lightfastness is good, especially in mass tone applications, but there is a definite tendency for the color to fade as the percentage of pigment is reduced. It is a relatively transparent yellow, having good acid and alkali resistance.

Nickel-azo is an organic yellow pigment with good lightfastness when used in both low and high pigment concentrations. In high pigment concentrations, however, the color tends to be on the green side. Heat stability is good. The main limitation of this pigment is its greenish hue.

**Inorganic Reds**

Cadmium mercury reds and maroons are a relatively new line of cadmium pigments. Mercury is used in place of selenium. The color is controlled by increasing the mercury sulfide content instead of increasing the concentration of cadmium selenide. Physical properties of mercury pigments are similar to those of selenium pigments, except that the latter may show better heat stability.

Cadmium selenide reds and maroons are different in basic composition and properties from cadmium sulfide yellows. The method of manufacture, however, is similar. Cadmium selenide maroons, reds, and oranges can be made in concentrated or extended pigment form. They are coprecipitated, calcined mixtures of cadmium sulfide and cadmium selenide.

Colors range from yellow-orange to maroon. The color is controlled by the cadmium selenide content. Varying percentages of extenders can be coprecipitated and calcined to make extended pigment grades. Barium sulfide or diamonaceous earth can be used as extending materials. When these pigments are extended, their brightness in mass tone is good, though not as good as that of the concentrated grade. Color strength is also reduced.

Use cost of cadmium red pigments is high. Although not as bright as many organic reds and maroons, cadmium red pigments offer excellent heat resistance and good lightfastness, especially in the deep shades. Resistance to chemicals is usually good. There is one limitation to be noted, however. The weather resistance of the colorant decreases when large quantities of moisture are present. Generally, the darker shades of cadmium reds have better weather resistance than do the lighter shades.

Chrome in pink is a ceramic, high-temperature calcined pigment. It has excellent stability and disperses well in all thermoplastic and thermosetting resins. Hiding power is low. It is a weak pigment. It does not have wide use in plastics, except where its heat resistance properties are desired.

**Organic Reds**

Alizarin red has a limited use in plastics. Sometimes known as madderlake, alizarin red is an anthrquinone dyestuff precipitated on either a calcium or aluminum hydrate base. Lightfastness is poor. Tinting strength is relatively low. For this reason it is an expensive colorant to use. Alizarin red can, however, be used in some of the lower-temperature resins such as flexible vinyls and acrylics.

BON stands for β-oxy naphthoic acid. BON reds and maroons are precipitated (with manganese) azo pigments of the betaoxy naphthoic acid type. Mass tone lightfastness is sufficient for use in most of the thermoplastic resins. Colors range in shade from light red to dark maroon. Generally, the dark red shades are more light stable. The manganese BON reds accelerate the degradation of polyethylene. Their use is limited in polyvinyl chloride whenever an oxidizable system is present. Manganese could trigger the oxidation reaction, developing a rancid odor.

Lithol reds (sodium, barium, and calcium salts) are vivid colors. This colorant family includes the pigments referred to as lithol maroon, barium lithol (scarlet), sodium lithol (yellowish red), and calcium lithol (crimson). They are tinctorially strong. Heat resistance is moderate to low, and lightfastness is poor. Dispersibility is usually poor, because the pigment particles form agglomerates that are difficult to break up. The lithol reds are relatively low in cost and can be used in some lower temperature applications where stability is not important.

Lithol rubines are characterized by brilliant deep mass tone and bright blue undertone tint. Lithol rubine is normally used with other pigments such as molybdate orange, since its hiding power is low. Use cost is low. Alkali and acid resistances are poor, as is lightfastness. These pigments would be excluded from almost all molding resins processed above 425°F (218°C).

Naphthol reds are bright red pigments. Normally naphthol pigments bleed in polyethylene and vinyls. While not highly recommended, they can be used, with care, in some of the lower-temperature resins such as acrylics and polystyrene. Heat resistance is moderate to low. Lightfastness, especially in the tint range, is poor, as is weather resistance.

Para red and chlorinated para red pigments produce extremely brightest colors. Heat and light resistance are moderate to poor. These pigments migrate in any plastic containing a plasticizer and in most of the PE resins. The para and chlorinated para pigments are most useful for coloring thermosetting resins such as the phenolics, aminos, and polystyrelacs.

Permanent red 2B pigments are occasionally referred to as rubine reds. They are similar to the BON reds, but instead of being precipitated with manganese, the permanent red 2Bs are precipitated with metals such as calcium, barium, and strontium. Brightness is excellent; color strength is good. Heat resistance, however, is moderate, and lightfastness in tint is poor. They are nonmigrating in vinyls and polyethylene.

Pigment scarlets are organic pigments classified as having good bleed resistance and poor light stability compared with inorganic pigments. They darken on exposure, where most other pigments fade. Combining a pigment scarlet with a fading red pigment may extend the time during which there is no apparent fading.

Several different types of pigment scarlets are available. One is zinc-precipitated and another is lead-precipitated. The lead-precipitated materials present problems in vinyls because of a tendency to cause lead sulfide staining.

Pyrazolone reds are used more often than other organic red pigments in vinyls because they have good lightfastness in mass tone. However, they have a tendency to migrate. Lightfastness of pyrazolone red pigments in low concentrations is poor. Heat resis-
Blacks and Browns

Ceramic blacks and browns are created from a crystalline combination of two or more oxides of chromium, cobalt, iron, and zinc. The color range varies, depending on which oxides are used, going all the way from black to a very light buff or tan. Since these pigments are high temperature calcined products, they have good stability and excellent heat resistance. They are excellent for use in all of the high-temperature resins. High-temperature ceramic pigments are expensive to use, and, for lower molding temperature applications, the iron oxide pigments are satisfactory.

Iron oxide pigments normally have good stability. The red-brown iron oxide pigments were perhaps the first colorants used in plastics. They are, however, not as heat-stable as the ceramic pigments.

The yellow or buff iron oxides are hydrated iron oxide. For this reason, they have limited resistance. They are low in cost, as are the brown and black iron oxides. Hiding power is good, and they do not migrate. Poor heat resistance is a disadvantage.

Natural inorganic pigments are inexpensive colorants to use. They are sometimes called mineral pigments, in that they are mined from the earth and normally are not color-controlled. Their application in plastics is limited because maintaining color continuity is difficult. This colorant family contains the ochres, siennas, umbers, and natural red iron oxides and ranges from yellow-brown to red-brown.

General resistance characteristics of the group are rated as good. It must be noted, however, that these pigments often contain impurities that accelerate degradation of some resins.

Carbon black is the name loosely given to the colorant family that includes channel black, furnace black, and lampblack. Lightfastness, heat stability, and resistance to migration are excellent. These blacks are widely used in resins subject to ultraviolet attack. Producing a nearly perfect black, they absorb all light and inhibit the effect of ultraviolet radiation on the resin. Using 3% of carbon black in polyethylene, for example, provides a material that absorbs almost all ultraviolet rays that strike it and inhibits cracking and failure. These colorants are hard to disperse. This is partly due to their extremely fine particle size. The carbon blacks are very strong antioxidants, more so than the organic phthalocyanine pigment family, and prevent or inhibit oxidation. Therefore, they are difficult to use in polyesters.

Some carbon blacks are electrically conductive. Care should be taken when selecting a black for use in electrical insulating com-
COATINGS FOR PLASTICS

In the mix, the ratio of concentrate to uncolored resin can be as much as 1 to 10:

\[
\frac{C + R'}{R} = \frac{1}{10} \tag{4}
\]

or

\[
R = 10 \left( \frac{C + R'}{R} \right) \tag{5}
\]

The required ratio of \( C \) to \( R' \) in the concentrate may be determined by substituting the value for \( R \) from Eq. (5) in Eq. (3):

\[
\frac{C}{10C + 10R' + R} = \frac{0.5}{100} \tag{6}
\]

or

\[
C = \frac{5.5}{95} R' \tag{7}
\]

Expressing this as parts of color per 100 parts of resin, the color required in the concentrate is 5.79 parts per 100 parts of resin.

The previous calculations are generalized in the following:

\[
\frac{C}{R'} = \frac{B (A + 1)}{100 - AB} \tag{8}
\]

where \( A \) = parts of resin to be colored per 1 part of concentrate to be used; \( B \) = parts of color required in the finished material per 100 parts of resin to be colored.

In the example of the garden hose, the following equation would result:

\[
\frac{C}{R'} = \frac{0.5 (10 + 1)}{100 - 10 \times 0.5} \tag{9}
\]

or

\[
C/R' = 5.79 \text{ parts of color per 100 parts of resin as determined,}
\]

or a proportion of 94.527% resin and 5.473% color in terms of percentage concentrations.

If the same end color is desired in a different part to be made by a different process, such as injection molding, a new resin-to-concentrate ratio would have to be formulated. For example, it might be necessary to use four parts of concentrate to every 10 particles of uncolored resin, instead of the 1 to 10 ratio of concentrate to resin used in the extruded garden hose, since the mixing action possible in a plunger injection machine is not as good as that possible in the extruder.

In this instance, Eq. (8) may be used to determine the revised composition of the concentrate that will be required to still get a 0.5 part per 100 parts ratio of color to resin in the final product. The calculation is as follows:

\[
\frac{C}{R'} = \frac{B (A + 1)}{100 - AB} \tag{10}
\]

\[
A = 10/4 \text{ OR } 2.5
\]

\[
B = 0.5 \text{ (as before)}
\]

then

\[
\frac{C}{R'} = \frac{0.5 (2.5 + 1)}{100 - (2.5 \times 0.5)}
\]

\[
\frac{C}{R'} = \frac{0.5 (2.5 + 1)}{100 - (2.5 	imes 0.5)} = \frac{7}{395}
\]

\[
\frac{C}{R'} = 1.772 \tag{11}
\]

Thus, under the conditions stated for the molding process, a color concentrate should be specified at 1.772 parts of color to 100 parts of resin.29

**CHAPTER 2 COATINGS FOR PLASTICS**

**REASONS FOR COATING PLASTIC SUBSTRATES**

Plastics are coated with thin layers of paint for several reasons:

1. Reproduction of gloss, distinctness of image (DOI), and color.
2. Durability.
3. Improvement of surface quality, that is, filling pits, voids, porosity, etc.
4. Resistant barrier to chemicals.

The color, gloss, and DOI reproduction is important in coating plastics, just as it is in coating metal, wood, or any other substrate, because of the need to match from lot to lot as well as to match adjacent coated substrates, if applicable. For instance, in the coating of automobiles, it is common practice to place a bumper fascia adjacent to the steel hood and fenders. This mandates an exact color match on both plastic and metal. Durability of the coatings on plastic is influenced by the chemistry of the topcoat. Two-component coatings, particularly those cross-linked with isocyanates, have better weathering characteristics than one-component coatings, typically cross-linked melamine-formaldehyde. The durability of the coating, as described previously for plastics, can be enhanced through the proper selection of stabilizers, for example, UV absorbers (UVA) and hindered amine light stabilizers (HALS).

A coating for plastic does not differ much from that utilized on other substrates (primer is applied, followed by a basecoat and a clearcoat). The film thicknesses of the associated coatings are 1.0 mil (25 µ) of primer, 0.5–1.5 mils (13–38 µ) of basecoat (depending on the hiding power of the pigments in the basecoat or color coat), and 1.3–2.0 mils (33–51 µ) of clearcoat. The coatings can be applied wet-on-wet, depending on the chemistry of each respective coat. Most often the primer is applied and baked, and then the subsequent basecoat/clearcoat is applied wet-on-wet. The term wet-on-wet refers to the ability to flash the first coat at ambient conditions for a few minutes (without the need to heat cure the coating to its fully cross-linked state), after which the next coat is applied and flashed, and the two films are baked to promote cross-linking. In the case of waterborne coatings, however, it is neces-
COATINGS FOR PLASTICS

The problems associated with coating SMC are mainly due to the inherent composition of the glass-reinforced composite. The reinforced SMC substrate is a polymeric composite consisting of reinforcing fibers embedded in a polymeric matrix. Other materials such as filler and pigments may also be present. Sheet molding compound is a heterogeneous substrate; it is a filled, glass-reinforced thermoset polyester sheet containing an unsaturated polyester resin solution in conjunction with the styrene monomer, shrinks on polymerization. The low-profile additive, on the other hand, undergoes thermal expansion to compensate for the shrinkage. Surface defects, however, are inherent because of the composition of the substrate stresses induced in the substrate from cutting, drilling, etc., and processing conditions (heat and pressure during molding). Most of the substrate defects that affect painting of SMC originate at or within several hundred micrometers of the surface. Domain stratification of the low-profile additive or mold-release agents can create surface areas of different free energies that affect flow, leveling, and adhesion of paints. Sanding of the substrate to eliminate dirt problems associated with the molding process, for instance, can affect mechanical and chemical adhesion and introduce pits, porosity, voids, and fiber breakthrough that will be evidenced in a cratered or poor DOI topcoated system.

Primers are utilized on SMC for several purposes, such as:
1. Providing adhesion to a nonuniform surface.
2. Improving the surface quality by:
   • Providing uniform surface.
   • Equalizing surface tension.
3. Improving surface smoothness.
4. Eliminating (covering) surface defects, for example:
   • Voids.
   • Cracks.
   • Mold lines.
   • Glass fibers.
5. Eliminating surface porosity.
6. Providing a barrier to solvent penetration.

Solvent penetration. One mode of topcoat failure on SMC is believed to result from migration of topcoat or primer solvents into the microporous substrate. As the substrate heats during the topcoat bake, the solvent expands and is expelled through the partially cured topcoat. The problem occurs with all types of topcoats, both one-component and two-component systems, and often manifests itself in the form of pits, porosity, or craters in the topcoated material.

Fluorescent microscopy. A test method developed at General Motors Research (GMR) laboratories utilizes fluorescent microscopy to study the effects of solvent migration on the properties of primed SMC parts. In this method, a fluorescent dye (7-diethylamino-4-methyl coumarin) is solubilized in a model basecoat formulation. The model basecoat/clearcoat system is applied over the preprimed SMC substrate and cured. The amount of dye that penetrates through the coating system is then calculated by cross-sectioning the painted SMC composite and examining it by fluorescent microscopy. In this manner, the depth of dye penetration can be correlated to topcoat solvent penetration through the primer into the substrate. Hence, this method can predict the solvent penetration barrier of the primer to basecoat solvents and relate results to the physical appearance of topcoated parts (absence or presence of pits or porosity).

A modified solvent permeability test predicts the solvent permeability resistance of selected primers to basecoat solvents. In
this method, the primer to be tested is applied to a piece of filter paper, cured, and exposed to basecoat solvent blends in a Fisher-Payne permeability cup. The filter paper acts as support for the primer film, simulating the porosity of SMC panels (2.5 µ pore size). From the results obtained, the effect of primer thickness, bake temperature, and solvent diffusion times can be correlated to topcoat solvent penetration resistance.

**Predicting Pits and Porosity**

Another test utilizes SMC plaques obtained from headlight openings to predict the manifestations of pits and porosity in topcoated parts. The SMC headlight opening cutouts (obtained from SMC hoods) are subjected to bending stress to expose porosity and glass fibers. The stress is applied by holding both ends of the headlight opening plaque (size of cutout plaque was 2 × 8 in. [5.1 × 20.3 cm]) and pushing down simultaneously on the ends so that the middle of the plaque buckles. The stress is alternately applied and released so that a cracking noise is heard but no cracks are visible. In this manner, porosity and glass fibers are exposed.

The stressed plaques are subsequently primed after wiping with isopropanol and baked. The basecoat/clearcoat is applied over half of the primed panel, and cured, and the incidence of craters is measured in the primer as well as in the primer/basecoat/clearcoat system. In this manner, the solvent penetration of the primer and the primer’s permeation resistance to topcoat solvents are measured. One of the findings of this work is that cross-linked, waterborne baked primers provide the best resistance to pits or porosity (craters) in topcoat-finished parts.

The previously described procedure for measuring solvent penetration into SMC relates to only one of many problems associated with finishing reinforced plastic substrates. In fact, when finishing any plastic material, the major attribute initially required to attain adhesion is wettability. In the following section, the prerequisites and basic principles governing the finishing of plastics are covered.

**ADHESION OF COATINGS**

With the advent of increased plastic use in the coatings industry, and in particular with the increased utilization of thermoplastic olefins, substrates are becoming increasingly difficult to paint because of the lack of adhesion. With adhesion, stress may be transmitted across the boundary topcoat and the plastic. The stress may be of various forms: tension or compression (normal to the interface), shear (parallel to the interface), peel, or a combination of these. To withstand these stresses, and prevent any considerable strain across the interface, there must be forces of attraction between paint and plastic substrate; these are the forces of chemical bonding.

**Basic Principles**

Before discussing the way in which forces of resistance are achieved, we must consider one of the absolute criteria for attaining maximum adhesion (bond strength) between materials (paint and plastic), namely wettability. In surface wetting, even minute traces of contaminants on the order of angstroms (10⁻¹⁰ m) in size will adversely affect the contact angle. The inherently low surface-free energies of plastics such as the olefins also adversely affect adhesion. Therefore, most surfaces must be pretreated prior to application of a surface coating for the attainment of maximum adhesion.

Two major types of attraction forces influence adhesion, namely (1) primary valence forces and (2) secondary van der Waals forces. The primary valence forces are subdivided into (a) ionic or electrostatic bonds, (b) covalent electron pair bonds, and (c) metallic electron gas bonds (generally not relevant in adhesive bonds). The secondary van der Waals forces are subdivided into (a) Debye induction forces and Keesom orientation factors, (b) London dispersion forces, and (c) hydrogen bonding. Some of the properties of the bonds resulting from these forces are illustrated in Table 2-19. In surface wettability the effect of polarity is greater than that of London dispersion forces. The energy of a single dispersion force bond is approximately 1 kcal/mole. On the other hand, a molecule physically absorbed to the surface at, for example, 50 segment sites, can be bonded via London forces with a total energy of about 50 kcal/mole. This total bond energy due to the dispersion forces has the magnitude of a chemical bond.

**Diffusion Theory**

The theories of adhesion, adsorption, mechanical interlocking, and diffusion vary in content but are generally related. The diffusion theory is very popular and assumes that adhesion is directly related to the ability of molecules to diffuse into a substrate. Once molecules are diffused into the substrate, electrical or mechanical interlocking phenomena may occur between the material being diffused, the coating, and the substrate to affect the degree of adhesive strength.

The effective volume expansion required for a rubber molecule to diffuse into a favored packing arrangement of polymer chains has been calculated. It was found that the larger the required volume expansion, the worse the adhesion at a given temperature. For a molecule of natural rubber to diffuse into a favored packing arrangement of natural rubber, a 15% volume expansion of the packed polymer chains was required. On the other hand, for a molecule of ethylene-propylene-diene rubber (EPDM) to diffuse into a favored packing arrangement of EPDM, a 27% volume expansion was required. Therefore, the natural rubber should exhibit better autoadhesion than EPDM under the same conditions.

**NATURE OF SUBSTRATE SURFACE**

In surface wetting, the effect of polarity can be offset by even a thin layer of nonpolar material. Wettability, commonly defined by the contact angle between a drop of liquid and a surface, is the characteristic most relevant to the adherence of paint. A line drawn tangent to the surface of the liquid droplet at the point of contact with the substrate defines the contact angle. A smaller contact angle is indicative of improved wettability by a liquid. Frequently, contact angle measurements with a variety of test liquids are analyzed by a two-parameter surface energy tech-

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**TABLE 2-19**

Properties of Valence Bonds of Various Types

<table>
<thead>
<tr>
<th>Bond Type</th>
<th>Primary</th>
<th>Equilibrium Lengths (Å)</th>
<th>Energy (kJ/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionic</td>
<td>2–4</td>
<td>600–1200</td>
<td></td>
</tr>
<tr>
<td>Covalent</td>
<td>0.8–3</td>
<td>60–800</td>
<td></td>
</tr>
<tr>
<td>Metallic</td>
<td>2–6</td>
<td>100–350</td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Debye Keesom</td>
<td>2–4</td>
<td>ca. 20</td>
<td></td>
</tr>
<tr>
<td>London</td>
<td>4–6</td>
<td>ca. 40</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>ca. 3</td>
<td>ca. 60</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 2
COATINGS FOR PLASTICS

adhesive strength of the coating/plastic composite. Hence the material crystallinity, are inversely proportional to the
Stress Measurements
or through the temperature applied in the coating cure process, through solvent migration and possible degradation of the plastic
flash or gated areas. The coating operation can also induce stress
stress. Stress can be imparted in the molding operation through
part prior to testing, for example, temperature, humidity, and
temperature. Adhesion can also be affected by conditions of the
example, pressure, temperature, time, rate of cooling, and mold
temperature. Adhesion can also be affected by conditions of the
surface region can consist of: (1) spherulites smaller or
ture. While the interior of most crystalline samples are spherulitic,
ter regions, of varying thickness, which can be influenced by the shear
imparted in the molding operation through contours in the part, or in fabrication operations such as trimming or cutting of the part to remove excessive plastic, for example, flash or gated areas. The coating operation can also induce stress
through solvent migration and possible degradation of the plastic,
through the temperature applied in the coating cure process,
leading to distortion or shrinkage in the plastic.

Stress Measurements
Residual stresses imparted in the plastic as a result of either the
molding or painting operation have been studied. Deformation-induced internal stress and the development of residual molding stresses in a number of polymer processing operations have been
described. Titomanlio has proposed a mechanism of cooling-stress
build-up in the injection molding of polymers. The roles of both
pressure history in the melt during sample cooling and interaction
between sample and mold are identified. Bauer and Treuting have
described methods of measuring the stresses and properties of
polymer coatings and sheet film, respectively, through the use of
impulse viscoelasticity and removal of thin surface layers.

Molding Conditions
In the injection molding of thermoplastics, in particular phase-separated thermoplastic alloys such as rubber-modified polyolefins (termed thermoplastic polyolefins or TPO), weak boundary layers exist. The weak boundary layer is a transcrystalline region, of varying thickness, which can be influenced by the shear imparted on the alloy during molding, by the variance in the molding
temperature and the melt temperature, and by the cooling of the part after molding. Figure 2-14 depicts the effect of the WBL on the resultant adhesion of an aluminum/polyethylene/aluminum adhesive joint. Quenching the joint in liquid nitrogen results in the highest adhesion, followed by cold water quenching and cool air quenching. The thickness of the weak boundary layers, and hence the material crystallinity, are inversely proportional to the adhesive strength of the coating/plastic composite.
two are associated with compression molding while the last is found with injection molding where molecular orientation exists in the melt. As an additional consequence, the surface may differ in crystallinity and molecular orientation from the bulk material. The concentration and type of nuclei present at the polymer surface during crystallization is recognized as the principal factor in determining surface structure.60

Optical differential interference contrast microscopy with Nomarski interference filters has been utilized to determine the crystal structure variations throughout the boundary layers in polypropylene.62 The technique determined variations in hexagonal spherulites as a function of depth according to the ability of the polypropylene to undergo selective swelling of less ordered regions. Subsequent reordering of the chains or their segments occurred on recrystallization. It was found in the analysis of the data that, in optical micrographs, hexagonal spherulites formed relatively flat concave boundaries whereas monoclinic spherulites formed conical shapes of approximately 0.5 µ.

Although scanning electron microscopy, x-ray diffraction, and imaging secondary ion mass spectroscopy have been used to characterize the crystallinity variations described above in the boundary layers, a rather simple yet elaborate technique can be utilized to view the boundary layers in selective polymers and polymer blends.

A surface zone of birefringent layers is the characteristic morphology associated with injection-molded polypropylene when viewed under cross-polarized transmission light microscopy. The birefringence between the layers is caused by a variation in the crystallite size and shape throughout the layers as well as by a variation in polypropylene to ethylene-propylene copolymer ratio. In this particular plastic, the top and bottom surface birefringent zones vary in thickness. This is believed to be due to the variation in the roughness or porosity of the top class A surface of the mold versus the back side of the mold which is known to be porous. The porosity variable is cause for variation in the crystallographic growth since porous materials with roughness amplitudes on the order of 3000 Å or less can be sites for nucleation.

Once the nature of the surface morphology of a plastic is understood, it becomes much easier to develop adhesion promoters based on the several theories of adhesion that exist.

**PLASTIC SURFACE PRETREATMENTS**

Surface pretreatment of a plastic is one way to achieve adhesion of a particular coating to a substrate. Several mechanical pretreatments exist, including plasma discharge, cross-linking by activated species of inert gases (CASING), and flaming. Chemical and solvent pretreatments are also widely used for adhesion promotion. The effect of mechanical pretreatment on the substrate surface is to remove potential WBLs and to increase surface roughness. Solvent (liquid or vapor) pretreatments also remove the WBL and increase surface roughness in addition to preparing the surface for diffusion by softening or plasticizing the outermost layer. Chemical pretreatments perform all of the above tasks and also alter the surface chemistry of the substrate, resulting in changes in the rate and degree of surface wetting.

**Mechanical**

**Plasma.** Plasma pretreatment, accomplished in air (corona discharge plasma) or in vacuum (glow discharge plasma) results in formation of excited species (atoms and molecules, ions, free radicals, free electrons, metastables) that react with the polymeric substrate. The modification of the surface, when performed in air, is the most widely accepted method for the pretreatment of thermoplastic olefin, a blend of polypropylene and polyethylene propylene rubber. The treatment of the substrate by corona plasma is accomplished in approximately three seconds but can be affected detrimentally by humidity and temperature. The process consists of passing the substrate (in this case a thin film) over a dielectric-covered roll and pulsing with an ionized air stream produced by a (10–20 kHz) step-up generator attached to the electrode (usually aluminum). The dielectric-covered roll consists of a grounded metal electrode insulated with a material such as epoxy, silicone rubber, chlorinated polyolefin, or polyester. The film is passed through the ionized air gap (air gap spacing is usually 0.004–0.008 in. [0.1–0.2 mm]) at a speed of 39–78 in./s (1–2 m/s). Treatment is affected by the air gap distance to the part as well as the traverse speed of the film.

When plasma treatment is carried out in the presence of a vacuum, usually about 1-torr reduced pressure, and at a much lower frequency than that utilized in corona discharge, the process is referred to as glow discharge.

**CASING.** An acronym for cross-linking by activated species of inert gases, it is a treatment in the presence of an inert gas. The effects of a variety of gases utilized in the plasma treatment of polyether sulfone on the adhesion of an epoxy coating are listed in Table 2-20.63 The CASING process employing argon produces an adhesive joint of about the same integrity as that produced in air (as determined by single lap-shear strength). Ammonia, nitrogen, and oxygen plasmas are less effective pretreatments.

The length of discharge time in air versus surface free energies of treated plastics is depicted in Fig. 2-15.64 It can be seen that, as the crystallinity of the polymer being treated increases (from low-density polyethylene, to medium-density polyethylene-propylene copolymer, to polypropylene), increasing exposure time is required to achieve the same level of surface free energies. This is rationalized by diffusion theory as the time required for a species to penetrate or permeate into a substrate. In this case, the transcristalline WBL is directly proportional to the degree of substrate crystallinity as measured by its surface free energy.

**Flame.** The flaming process uses several burners positioned at various sites around a rotating part. This pretreatment is most often utilized for thicker-section parts such as bottles. The flame treatment mechanism is simply a thermal oxidation of the surface. The post-treatment adhesion depends on several factors, including treatment time, natural gas flow, airflow, air/gas ratio, position of the component relative to the flame, burner-surface separation, and the nature of the natural gas (for example, methane, propane,

<table>
<thead>
<tr>
<th>Plasma Gas</th>
<th>Single Lap-shear Strength</th>
<th>Locus of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (solvent wipe)</td>
<td>1300 psi (9.09 MPa)</td>
<td>Interfacial</td>
</tr>
<tr>
<td>Argon</td>
<td>3150 psi (21.7 MPa)</td>
<td>Substrate</td>
</tr>
<tr>
<td>Air</td>
<td>3100 psi (21.4 MPa)</td>
<td>Substrate</td>
</tr>
<tr>
<td>Ammonia</td>
<td>1870 psi (12.9 MPa)</td>
<td>Substrate</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>2830 psi (19.5 MPa)</td>
<td>Substrate</td>
</tr>
<tr>
<td>Oxygen</td>
<td>2650 psi (18.3 MPa)</td>
<td>Substrate</td>
</tr>
</tbody>
</table>
or butane). Since the flame temperature can exceed 3500˚ F (1927˚ C), the burner-surface separation is usually kept large (0.24–0.35 in. [6–9 mm]), and the exposure time is limited to one second or less to avoid plastic decomposition or deformation. The oxidizing flame is kept rich in oxygen to assure complete combustion. The higher homologues of carbon comprising the gas require a greater excess of oxygen as their carbon content increases. For example, methane requires a 10% excess of oxygen, propane a 15% excess, and butane more than a 15% excess.

Chemical

Chemical pretreatments roughen low-crystallinity substrates and remove the weak boundary layer. Pretreatment can be done at elevated temperatures (140–180˚ F [60–82˚ C]) for several minutes, but, since higher temperatures distort the polymeric substrate, it is best to perform the treatment at lower temperatures for extended times. Several chemical solutions have been utilized, such as aqueous potassium permanganate/sulfuric acid solution, aqueous potassium dichromate/sulfuric acid solution (chromic acid), and aqueous peroxydisulfate solution. Chromic acid oxidation is the most widely used method of chemical pretreatment despite its highly corrosive nature.

Chromic acid. The mechanism of chromic acid oxidation is well understood and is dependent on the amount of water present in the chromic acid solution. The free water combines with the chromic acid to form an active species with the chromium oxidation state of six. The formation of H₂CrO₄ as the active species controls the overall rate of substrate oxidation.

The depth of chromic acid pretreatment on polypropylene was analyzed by laser microprobe mass spectroscopy (LMMS), as shown in Fig. 2-16. When the treated substrate is pulsed with a laser, approximately 0.2 μ of material is etched away, and the nature of the removed material is determined by mass spectroscopy. By repeating this process on the same spot, the treatment depth can be determined from the change in the mass spectrum as related to the number of laser shots. The pattern for chemically pretreated polypropylene after one and seven laser shots is depicted in Fig. 2-17. The spectrum after seven laser shots is identical to that of untreated polypropylene, indicating that a depth of penetration of 0.4–0.6 in. (10–15 mm) is achieved.

Although chromic acid oxidation of low-free-energy surfaces is effective, the toxicity of chromium, a heavy metal, often negates the use of this pretreatment. Other pretreatment methods described herein are more environmentally acceptable.

Solvent. Solvent cleaning, or pretreatment of polypropylene by trichloroethylene vapor (TCE vapor degreasing), also becomes effective through removal of the WBL. Controlling etching time, however, is crucial to successful pretreatment, since under extended treatment times the solvent can also diffuse through the WBL to attack the amorphous region of the substrate. Solvent attack on the amorphous region weakens the cohesive energy of the surface...
layer, thus detrimentally affecting the adhesive strength of the coating-substrate composite.

**Summary of Pretreatment Methods**

The effect of pretreatment type is proportional to the amount of oxidation of the surface to be coated, which is directly related to the surface tension or wettability. The surface energy component of a two-parameter surface energy (consisting of London dispersion and Keesom polar contributions) varies in the polar contribution component of surface energy without any significant change in the dispersion energy component.\(^6\) Such change of character is related to a reaction between surface free radicals and air oxygen. The actual weight percentages of species present were determined by x-ray photoelectron spectroscopy (XPS) and are reported on the basis of total oxidation species present.

Through attenuated total reflectance infrared (AT-IR) analysis, the surface of an object can be analyzed in such a way that a multiple reflection infrared spectrum of the surface is obtained. The depth of penetration depends on the actual wavelength of the measurements. Each species at the object surface can be measured by XPS. The binding energy of each species is determined as the difference between the energy of the incoming photoelectron versus the measured energy of the escaping photoelectron. The energy of these photoelectrons is representative of the atom bombarded. It can be seen from Table 2-21 that the oxygen content of the treated polypropylene substrate depends on the pretreatment method utilized. The oxygen content after flaming, plasma discharge, or chromic/sulfuric acid pretreatments can be partially removed by wiping. However, the decrease after benzophenone/UV treatment followed by wiping is much less. Clearly, the former methods result only in physically bonded oxidized materials. The nature of the oxygen demonstrates that an oxidation of the C-C or C-H bonds on the polypropylene takes place. An exception to this is the nature of the oxygen after chemical pretreatment: despite an oxygen content of 16.5%, no C-O or C=O bonds can be detected, leading to the assumption that in this case the oxygen is bound to the Cr atom of the pretreatment chemicals. Thus, the oxidative species formed from chromic acid pretreatment will be Cr-O analogues.

There are many disadvantages associated with the pretreatment methods just described. For example, the glow discharge method requires a vacuum chamber, the flaming method poses a serious fire hazard in areas of high solvent density (spray booths), the corona discharge process is expensive, and the chemical pretreatment is corrosive. The vapor degreasing pretreatment, currently a very effective pretreatment utilized by Japanese automotive manufacturers, is being regulated by promulgation of the Montreal Treaty restricting use of ozone-depleting chemicals. Trichloroethylen e, the solvent utilized in the vapor degreasing pretreatment, is a known ozone-depleting chemical and as such will be carefully controlled. Research is currently being conducted to find replacements for TCE and trichloroethane.

**ADHESION PROMOTERS**

Other methods have been developed to improve adhesion to polyolefins, one of which involves the use of chlorinated polyolefin (CPO) tie-coats to help topcoats adhere to untreated polyolefin plastics.\(^6\) This method applies a thin layer (micrometer level) of a dilute solution (less than 35 percent of weight) of a CPO to the polypropylene substrate. The thickness of the CPO adhesion promoter layer is crucial: if too thick, cohesive failure will occur, and if too thin, adhesion will not be attained.

### TABLE 2-21

**The Effect of Pretreatment Method on the Amount and Type of Oxygen on the Polypropylene Surface**

<table>
<thead>
<tr>
<th>Pretreatment Method</th>
<th>Percentage Total Oxygen Content</th>
<th>Surface Chemistry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wiping Off</td>
<td>before</td>
</tr>
<tr>
<td>Flaming</td>
<td>16.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Plasma</td>
<td>14.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Benzophenone/UV</td>
<td>21.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Chemical</td>
<td>16.5</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Many addition adhesion promoters exist, although none of them are commercially available. For example, silylated CPO block copolymers,\(^6\) acid or anhydride grafted styrene-butadiene copolymers blended with chlorinated maleic anhydride propylene copolymers,\(^6\) cyclohexylmethacrylate-isodecylacrylate copolymers,\(^6\) waterborne polyester sulfonate metal salts (in which one component of the polyester was polyethylene glycol),\(^7\) and a fluoro polymer of undisclosed composition\(^7\) have all been claimed to promote adhesion to untreated polyolefines.

Until such systems are commercially available, the low cost of polyolefinic materials will be offset somewhat by the higher costs associated with improving the adhesion of topcoat materials and the need for a pretreatment method prior to painting.

### CLEANING PLASTICS

Most plastics (other than the polyolefinic-type materials discussed above), after being cleaned of all soil, are paintable with the right kind of paint. On plastics, one method utilized to predict paintability is to pour alcohol (such as isopropanol) onto the part.\(^7\) If the alcohol beads up, the surface is not adequate for paint adhesion. Water, the old standard utilized in determining the wettability of metals because it sheets over the surface if clean, cannot be used on plastics. This is because the surface tension of most plastics, even when clean, will allow water to spread and sheet (termed the water-break-free condition).

Before any attempt to paint even the easy to paint plastics, the surface must be clean. The types of soil that the pretreatments must remove include:

1. **Substrate components at or near the surface that can interfere with paint performance.** Typical contaminants include plasticizers, antistats, lubricants, flame retardants, heat stabilizers, UV stabilizers, fillers, monomers, and the like.
2. **Processing aids needed in the manufacturing of the plastic article.** Such materials include internal mold release agents such as metallic fatty acid salts, oils, or polymers, and external mold release agents such as waxes, polyvinyl alcohol, vegetable derivatives, and metallic fatty acid salts.
3. **Soils produced from operations after molding but before painting, such as fabricating soils (sand dust, aerosols from air lines, flashing residuals, lint, handling soils).**
4. **Soils from handling or storage.** These contaminants can include marking soils, smoke tar, dust, lubricants/oils for equipment, and handling soils.

Mold release agents (water-soluble metal soap-based molecules, or wax- and oil-type nonsoluble materials), vary in the ease at which they are removed from the plastic surface. Water-soluble
mold release agents, such as zinc stearate, are the easiest to clean. On the other hand, wax- and oil-type mold releases are not water-soluble and thus require higher temperature cleaning with a solvent-aided cleaner. Silicone- or fluoro polymer-based materials are difficult to treat because of their water insolvability, and are the most detrimental to painting processes because of their tremendous surface activity. At very low concentrations, even at parts-per-million levels, these materials can play havoc with topcoat paint adhesion and hence should not be utilized.

Some plastics have built-in mold release agents, such as SMC (usually contains a soap-based material to aid release) and RIM (sometimes contains an internal mold release [IMR] agent). Although these plastics are relatively easy to clean, the migration of the release agent to a precleaned surface must be kept to a minimum. This often necessitates keeping the surface temperature of the parts in the washer dry-off below the surface temperature of the postcure heating used in the molding process.

Types of Cleaning

There are three major types of cleaning processes used to prepare plastics for painting: hand wiping (utilizing a solvent or combination of solvents), solvent cleaning, and aqueous-based power-washing. The hand wiping technique is labor-intensive, and it therefore is used in less than 5% of all plastic cleanings before painting.

Aqueous Cleaning Stages

The aqueous-based pretreatment of plastics is the most widely utilized method for cleaning plastics. Conveyorized spray washers are preferred, being used in over 90% of all current plastic power wash systems. A high-quality spray washer consists of seven separate functions, or stages: precleaning, cleaning, rinsing, conditioning or rinse aid, deionized (DI) rinsing, air blow-off, and oven drying. Minimum requirements for a spray washer, however, include only three stages: cleaning, rinsing, and rinsing with DI water. As the number of stages increases, the cleanliness of the part increases and the maintenance of the spray washer becomes simpler. For instance, if one utilizes a rinse stage prior to the cleaning stage, particles such as sanding dust or plastic flashing splinters can be removed, thus saving replenishment of cleaning chemicals. A stage following the cleaning stage that utilizes a rinse aid or water conditioning chemical can often eliminate water spotting in the dry-off stage.

Precleaning. The precleaning step often uses a tap water rinse of short duration (15–30 seconds) to remove soil and minimize the amount going into the main cleaning stage. Often the water utilized in this stage can be supplied from the first rinse stage, resulting in conservation of water.

Cleaning. The cleaning step can utilize a variety of cleaners (acidic or basic), but most often the cleaner is designed to remove specific soils from the plastic part. This stage is generally 45–120 seconds in duration and operates at 20–30 psi (138–207 kPa) fluid pressure. Operating temperatures range from 120–170˚ F (49–77˚ C). Most cleaners used today are acidic products, with fewer than 3% of the applications in North America being alkaline. Current acidic cleaners are based on phosphoric acid and operate at a pH of 2.5–3.5. Drawbacks of this technology include attack on mild steel equipment and the potential emission of phosphates into the environment. Recently, nonphosphate-based cleaners have been developed to be utilized in existing equipment and reduce the waste disposal expense associated with phosphate containment.

Filtration of the cleaner stage is highly recommended since the cleaner stage is continually recirculated. As the amount of loose material and contaminants increases in concentration in the bath, the possibility for redepositing the soils on the part increases. Alleviation of this problem can be achieved by using a precleaner stage in addition to filtering the cleaner bath.

Rinsing. A variety of water rinses ensure that all of the cleaner surfactant is removed from the part. The fresher the rinse water, the more efficient the rinse. Therefore, the rinse stage is diluted by overflowing the rinse tank to maintain a contaminant level in the rinse stage of less than 1–3% of the concentration of the cleaner chemical. Typical overflow rates of 5–10 gal/min (19–38 L/min) are common in a 2000–5000 gal (7570–18,925 L) capacity system. General exposure time in the rinse is 30 seconds with an operating temperature of 72–120˚ F (22–49˚ C). Filtration is also recommended in this stage.

Rinse aids are replacing the conditioner chemicals in old spray wash systems to assist in the elimination or removal of water spots on the parts after drying. Two major types of rinse aid products are utilized:

- A surfactant that modifies the surface tension of the water and allows the surface of the plastic parts to be wet with water in an even, break-free sheet.
- A surface-modifying polymer that reacts with the surface to change the normal hydrophobic plastic surface into a hydrophilic surface. The advantages of the surface-modifying polymer rinse aid is that unreacted material is easily rinsed away, leaving a uniform thin layer on the plastic surface. With the surfactant-type rinse aid, there is no enhanced wetting of the plastic in following rinse stages, and water remaining on the part will be beaded water droplets that can lead to water spots.

The last rinse stage is a DI water rinse to ensure that all previous treatments are rinsed away. The rinsing in this stage is usually done in two steps—a 20–40 second recirculated-water step followed by a fresh-water step. The fresh DI water should have a conductivity of 5–15 µΩ, while the recirculated DI water should range from 50–100 µΩ.

Air blow-off. An air blow-off follows the last rinse stage to assure that excess water on the parts is removed. The air is usually filtered and cleaned so that no recontamination occurs. Deionizing air and a desiccant and fine filtration system are recommended to eliminate static charge build-up on plastic parts and the recontamination of the parts by the air, respectively.

Dry-off. The dry-off oven is the final stage in the power wash process. The optimum dry-off temperature for the plastic should be determined to ensure that IMR agents do not migrate to the cleaned surface and the material stays well below the heat distortion temperature of the part.

COATING TYPES

The coatings market is being dramatically altered by environmental constraints imposed by local, state, and federal governments. The key concerns of government regulators and consumers include:

1. Treating the earth as one biosphere, having a finite capacity for cleaning itself of toxins.
2. Cleaning air of pollutants that are killing lakes and causing a dramatic increase in respiratory illness.
3. Ensuring that smog-enshrouded cities do not become industrial nightmares.
4. Making the agricultural and livestock products that people eat safe for consumption over the long term.
These concerns have led to legislation over the last several years that causes manufacturers to place a greater emphasis on research to meet and exceed government and consumer demands for clean air.

Environmental Constraints (Selecting Compliant Coatings)

Environmental demands have led to a nationwide program, the revised Clean Air Act of 1990, which limits the volatile organic compounds (VOCs) in a paint. The VOCs of a paint are calculated as pounds of solvent per gallon of paint. Prior to 1970, the VOC content of most paints was well above 5 lb/gal (0.6 kg/L). Current major industrial paints are now limited to approximately 3.5 lb/gal (0.4 kg/L) of VOC because of imposed environmental pressures. Stricter legislation in the future is likely to push the VOC limits even lower.

Regional regulations. The issue of air-quality compliance is complicated by different regulations in various states and regional areas. Although the federal government (through the U.S. Environmental Protection Agency [EPA]) has set minimum national standards, states and designated regional areas can adopt their own compliance rules. The EPA activities for putting the Clean Air Act Amendment (CAAA) of 1990 into effect include:

1. Preparing new control technique guidelines (CTGs).
2. Developing rules to limit emissions of toxic air pollutants through a program referred to by two names, National Emission Standards for Hazardous Air Pollutants (NESHAPs) and Hazardous Air Pollutants (HAPs).

Control technique guidelines. The EPA has scanned the marketplace to find out about available technology in an attempt to put control technique guidelines in place. The CTGs are designed to cut VOC emissions without imposing an unreasonable financial burden on companies required to buy pollution reduction technology. A CTG is a document prepared by the EPA to assist states in defining reasonable achievable control technology (RACT) for major sources of VOC. Many CTGs were prepared in the 1970s for the following industries: can coating, fabric coating, paper coating, automotive and light-duty truck assembly, metal furniture, magnet wire insulation, large appliances, miscellaneous metal parts and products, and wood paneling.

The Plastic Parts Coating CTG will address the coating of plastic parts for automotive/transportation, business machines/ electronic equipment and other miscellaneous issues. The plastic parts CTG proposal is contained in Tables 2-22 through 2-24. It can be seen that for automotive plastic parts, the VOC limits are categorized by low bake (<194°F [90°C]) and high bake (>194°F [90°C]) conditions, as well as interior, exterior, and specialty coatings. Credits toward VOC emissions may be given for red- and black-pigmented coatings because of the thixotropic nature of these paints. Red and black pigments, being highly structured, are difficult to disperse. To achieve and maintain proper dispersion stability, increased levels of resin, dispersant and/or solvent are often required. The resultant increase in solvent level affords higher VOCs in formulated paints. Business machine coatings are classified by prime, color, touch-up or repair, fog coat, or texture type.

Hazardous wastes. Also included in regulatory compliance is the issue of hazardous wastes. On March 29, 1990, the U.S. EPA promulgated a final rule revising the procedure used to determine whether wastes are hazardous because of their potential to leach significant concentrations of toxic constituents into landfills.

The extraction procedure (EP) for measuring toxicity was replaced with the toxicity characteristic (TC) leaching procedure (TCLP). Included in the U.S. EPA list are 25 commonly used organic chemicals in the surface finishing industry such as methyl ethyl ketone, tetrachloroethylene, ethylene glycol ethers, and the like. This law severely restricts the coating formulator in the choice of solvent to fully formulate a VOC compliant material.

Through the years, improved paints have been developed because of pressure from environmental and consumer activists. The objective of improving overall quality and reducing emissions (VOCs) has led to a wider selection of paint types. The user, therefore, must select a coating type that meets the cost of required application, equipment, energy costs for use, pollution and waste collection expenses, and application and cured performance requirements of the coating.

One- and Two-component Systems

Table 2-25 lists types of coatings utilized in industrial and special-purpose end uses by technology. Chemmark-based forecasts show increased usage of all types of materials in 1996 except for conventional noncompliant coatings, lacquers, and nonaqueous dispersions. Overall, consumption of solvent-based materials is expected to decline from the 74% level in 1986 to 63% in 1996. This compares to an 85% level in 1975.

<table>
<thead>
<tr>
<th>TABLE 2-22</th>
<th>Automotive Plastic Parts CTG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Bake</strong></td>
<td><strong>High Bake</strong></td>
</tr>
<tr>
<td>EPA Proposed lb/gal (kg/L)</td>
<td>EPA Proposed lbs/gal (kg/L)</td>
</tr>
<tr>
<td>Interior Color</td>
<td>3.2 (0.38)</td>
</tr>
<tr>
<td>Interior Primer</td>
<td>3.5 (0.42)</td>
</tr>
<tr>
<td>Exterior Flexible Color</td>
<td>5.1 (0.6)</td>
</tr>
<tr>
<td>Exterior Flexible Clear</td>
<td>3.7 (0.44)</td>
</tr>
<tr>
<td>Exterior Flexible Primer</td>
<td>5.5 (0.65)</td>
</tr>
<tr>
<td>Exterior Nonflexible Color</td>
<td>5.1 (0.6)</td>
</tr>
<tr>
<td>Exterior Nonflexible Clear</td>
<td>3.7 (0.44)</td>
</tr>
<tr>
<td>Exterior Nonflexible Primer</td>
<td>5.5 (0.65)</td>
</tr>
</tbody>
</table>

* Cure temperatures of 194°F (90°C) or less

<table>
<thead>
<tr>
<th>TABLE 2-23</th>
<th>Business Machines Plastic Parts CTG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EPA Proposal</strong></td>
<td><strong>lb/gal (kg/L)</strong></td>
</tr>
<tr>
<td>Prime</td>
<td>2.9 (0.34)</td>
</tr>
<tr>
<td>Color Topcoat</td>
<td>2.9 (0.34)</td>
</tr>
<tr>
<td>Texture</td>
<td>2.9 (0.34)</td>
</tr>
<tr>
<td>Fog Coat</td>
<td>2.2 (0.26)</td>
</tr>
<tr>
<td>Touchup and Repair</td>
<td>2.9 (0.34)</td>
</tr>
</tbody>
</table>

Does not include coatings for electromagnetic and radiofrequency shielding.
A solvent-borne coating generally consists of seven major constituents:

1. Resin.
2. Cross-linker.
3. Rheology control agent.
4. Catalyst.
5. Pigments.
6. Flow and leveling additive.
7. Solvent.

The resin (often referred to as the binder) is responsible for the main attributes of the coating when cured with the cross-linker (or cross-linking agent). The curing, or network formation, is often accelerated through the use of a catalyst. Rheology control agents, often referred to as sag control agents, are added to impart shear thinning behavior when the resin is under high shear (that is, spray application) and rheology, or antisagging behavior, when under low shear (applied on a substrate). Pigments are introduced to impart color, gloss control, and/or ultraviolet protection. The amount of pigment depends on the color and the hiding power required of the coating. The flow and leveling additive is often introduced to relieve surface tension variations between the coating and the substrate, to eliminate craters, and prevent pinhole formation. Solvents are added as necessary to achieve flow under application conditions. In coating plastics, it is of particular importance to choose solvents that will not degrade or attack solvent-sensitive materials (that is, poly carbonate). Stress crazing due to solvent attack can dramatically lower the physical properties of the coated part.

To achieve a VOC-compliant coating, one must consider the molecular weight of the main binder utilized in the coating formulation, as well as the effect of the additives on the final paint viscosity. Application viscosity, which is affected by the rheology of the coating constituents, is most often controlled by freely adding solvent to achieve the necessary flow and leveling upon application. This in turn affects the final VOC emission of the paint.

### Primers

The total automotive composite coating on plastics often consists of more than just the basecoat/clearcoat. In difficult-to-paint substrates, such as the thermoplastic olefins described previously, an adhesion-promoting primer or a surface pretreatment is accomplished prior to topcoating. Excluding such materials, one has the option to next apply a primer surfacer. The primer surfacer, composed most often of a polyester cross-linked with a blocked isocyanate or melamine, is applied at a dry film thickness of approximately 1.0 mil (25 µ) by conventional spray application equipment. The primer is often made conductive through the use of conductive carbon black pigment, to increase the transfer efficiency of the electrostatic topcoating procedure. The function of the primer surfacer is to provide filling and leveling properties as well as some chip resistance to the substrate. Cure conditions range from 250–325˚ F (121–163˚ C) for 20 minutes.

### Basecoats

**Solvent borne.** The solvent-borne basecoat, consisting of a polyester or acrylic binder to be cross-linked with melamine or isocyanate, is applied at a dry film thickness between 0.6–1.5 mils (15–38 µ), depending on the color. Poorer-hiding colors, such as red, yellow, and white straight shades, require the higher film builds, whereas metallics and the darker shade colors are applied at the lower film builds. The solvent in the solvent-borne basecoat is allowed to flash off (evaporate) for 3–5 minutes at ambient conditions before the solvent-borne clearcoat is applied. This process of applying one coating over another, where the first coating is not in a cross-linked or cured state, is referred to as the wet-on-wet process.

**Waterborne.** Optionally, a waterborne basecoat can be utilized to achieve better aluminum orientation in metallic films. Several papers have described metallic orientation and the advantages of waterborne basecoats.78,79

The waterborne basecoat consists of a urethane or acrylic dispersion with passivated aluminum flake dispersed for metallic glamour. The aluminum must be passivated to prevent reaction with water and the evolution of hydrogen gas. Passivating agents

---

**TABLE 2-24**

<table>
<thead>
<tr>
<th>Coating</th>
<th>EPA Proposed VOC lb/gal (kg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gloss Reducer</td>
<td>4.0 (0.47)</td>
</tr>
<tr>
<td>Air Bag Cover</td>
<td>5.9 (0.70)</td>
</tr>
<tr>
<td>Black/Argent Reflective Lamp</td>
<td>5.9 (0.70)</td>
</tr>
<tr>
<td>Soft Coatings</td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td>6.8 (0.80)</td>
</tr>
<tr>
<td>Vacuum Metallizing</td>
<td></td>
</tr>
<tr>
<td>Stencil</td>
<td></td>
</tr>
<tr>
<td>Adhesion Promoters</td>
<td></td>
</tr>
<tr>
<td>Ink Pad</td>
<td></td>
</tr>
<tr>
<td>Electrostatic Prep</td>
<td></td>
</tr>
<tr>
<td>Resist</td>
<td></td>
</tr>
<tr>
<td>Head Lamp Lens</td>
<td>7.4 (0.88)</td>
</tr>
</tbody>
</table>

---

**TABLE 2-25**

<table>
<thead>
<tr>
<th>Type of Coating</th>
<th>1986</th>
<th>1996</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solvent-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional low solids*</td>
<td>42</td>
<td>30</td>
<td>Decrease</td>
</tr>
<tr>
<td>Lacquers</td>
<td>9</td>
<td>5</td>
<td>Decrease</td>
</tr>
<tr>
<td>Two-part catalyzed</td>
<td>16</td>
<td>19</td>
<td>Increase</td>
</tr>
<tr>
<td>High solids</td>
<td>6</td>
<td>9</td>
<td>Increase</td>
</tr>
<tr>
<td>Nonaqueous dispersion</td>
<td>1</td>
<td>0</td>
<td>Decrease</td>
</tr>
<tr>
<td>Total</td>
<td>74</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Water-based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emulsions/latex</td>
<td>8</td>
<td>10</td>
<td>Increase</td>
</tr>
<tr>
<td>Water solubles and dispersions**</td>
<td>13</td>
<td>18</td>
<td>Increase</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powder</td>
<td>4</td>
<td>6</td>
<td>Increase</td>
</tr>
<tr>
<td>Radiation curable</td>
<td>1</td>
<td>3</td>
<td>Increase</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

(Courtesy Chemark)
include chromium or phosphate esters. The basecoat may be cross-linked with a blocked isocyanate or melamine curing agent. The basecoat is prebaked (with infrared or thermal convection ovens) to release most of the water (>90%) prior to clearcoat application.

Clearcoats
The solvent-borne clearcoat is spray-applied over the basecoat at a dry film thickness of 1.8–2.0 mils (45.7–50.8 µ). The clearcoat, responsible for UV protection, chemical resistance, chip resistance, and so on, is most often composed of a hydroxy functional acrylic binder with a melamine or isocyanate cross-linker. Ultraviolet light absorbers and hindered amine light stabilizers are added to achieve better resistance to the oxidative degradation which results from exposure to sunlight.

The clearcoat is referred to as a two-component (2K) clearcoat when an isocyanate cross-linking agent is utilized as the cross-linker. The isocyanate must be added to the hydroxy functional acrylic just before spray application to prevent premature gelation (cross-linking). Cure conditions for isocyanate cross-linked systems range from ambient (car refinish technology) to 250˚ F (121˚ C) for 30 minutes.

One-component, or 1K, clearcoats are equivalent to 2K clearcoats with the exception that they are cross-linked with melamines. Cure conditions can be lowered to 230˚ F (110˚ C) by adding acid catalysts, but generally lie in the range of 250˚ F (121˚ C) for 30 minutes. Blocked isocyanate cross-linked versions of 1K clearcoats are also available, but cure requirements necessitate 275˚ F (135˚ C) or higher to deblock the isocyanate and allow it to react. Typical blocking agents on the isocyanate include methyl ethyl ketoxime and malonate esters.

Research is being conducted on waterborne clearcoats in attempts to achieve lowered VOC emissions. Waterborne clearcoat research is limited to water-dispersible acrylics because high gloss and good weatherability can be attained. Removal of water from the film, however, is a problem as coalescence often begins prior to through-cure, resulting in solvent-popping. Much work remains to be performed on optimum formulation parameters (for example, solvent blend, antiscratering surfactants, rheology control) to attain defect-free coatings.

New Cross-linking Technologies
The traditional cross-linking technologies utilized in the coatings market range from hydroxyl functional binders (acrylics or polyesters) cross-linked with melamines (1K) or isocyanates (2K) to drying oils that cure through oxidation of the unsaturated bonds, to epoxy resins cross-linked with amino resins.

New cross-linking technologies, however, are being developed with hopes of achieving more environmentally acceptable coatings. Fluoropolymers, epoxy-anhydride new curing technology (NCT), and siliconized-acrylics new enamel technology (NET) are a few of the coating chemistries being introduced. Increasing demands have necessitated these advances. The need for properties such as chip resistance and resistance to acid rain may result in further technological advances.

Nonpolluting Coatings
If we look at the molecular weight dependency of resins in the various coating types, it is readily evident why VOC compliance is more easily achieved in radiation-curable and powder coatings. The molecular weight of nonaqueous dispersion resins, for example, exceeding 105 g/mole, results in very viscous materials, whereas the typical molecular weight of a radiation-cured oligomer ranges from 102–103 g/mole. The radiation-cured oligomer is a very low viscosity material that requires little, if any, additional solvent to attain application specifications.

If we consider the evolution of coating technology, we can see that by the mid-1950s, waterborne and higher-solids coatings were already under development. Powder coatings, 100% reactive liquid coatings (electron beam and UV cure), and other novel nonpolluting coatings (such as supercritical carbon dioxide) were not necessarily in vogue until later in the decade.

Powder Coatings
Powder coating consumption is the fastest growing finishing technology in North America. There are several types of powder coatings available, classified by resin type. The production of these powders varies by country.

The United States uses mostly polyurethane powder as does Japan, while Europe is heavily tied to the hybrid-type powders. The major impetus for growth can be attributed to the virtually pollution-free finishing system, as well as the dramatic leap forward in materials and equipment technology that makes them essentially 100% transfer efficient (with spent powder recycled). Major powder coating R&D goals include: (1) reduce baking temperature, (2) improve thin-film capability, and (3) provide durable low-gloss exterior systems.

Thermosetting. Thermosetting powder coatings tend to begin cross-linking at or near their melt temperature. This can severely limit the smoothness of a deposited coating. Cure temperatures of these thermosets generally lie in the range of 300–350˚ F (149–177˚ C). Therefore, these coatings can only be applied and cured over thermoset plastics, such as SMC, that have a higher heat distortion temperature than that required for the powder to cross-link. Applications for these high-curing-temperature powders have included chip-resistant primers as well as in-mold primers.

Vinyl ether. Several vinyl ether functional polyurethane powder coatings have been formulated that show a sharp melt temperature at 104 or 140˚ F (40 or 60˚ C) and no cross-linking until 248˚ F (120˚ C). This wide gap between the melt and cross-linking temperatures allows better flow and leveling prior to full cure. The cross-linking temperature is effectively lowered through the use of a latent cationic initiator that decomposes just prior to cross-linking. The lowered cure requirements of these powders allows their use on a wider variety of plastic components.

Flame spraying has been utilized as a technique to increase the flowability of thermoplastic powder coatings. By passing through an air/gas (usually propane) flame, the powder is efficiently melted into a free-flowing composition before impact onto the substrate. Once reaching the substrate, the powder can flow and be subsequently quenched to prevent further degradation of the resin. By quenching the powder, varying degrees of crystallinity can be attained which can afford dramatically different physical properties of the cured coating, for example, impact resistance and elongation.

Electron Beam and Ultraviolet Curing Coatings
Radiation-curable (radcure) coatings technology uses ultraviolet radiation or an energetic electron beam (EB) to cure or harden the coating. Radiation with energy of about 1.7 to 6 electron volts (eV) (representing the UV region) and about 10,000 to one million eV (the electron beam range) is used.

Acceptance of radiation-cured finishes has been slow, and current consumption is low (about $300 million or 3% of the industrial coatings market). It is expected that the radcure technology will reach about 10% of the industrial coatings market by the year 2000.
The major advantages of radcure technology are speed of cure, reduced emissions, 100% solids systems, and elimination of ovens or other sources of thermal energy (less energy consumption). However, there are also disadvantages: it is necessary to formulate clear or transparent coatings to allow UV light penetration; the appearance of these coatings is somewhat lower in quality than that of conventional finishes; UV coatings are generally toxic because of the chemical nature of the monomers that comprise the coating; and uniform, flat substrates are necessary for line-of-sight UV radiation.

The UV coating is usually composed of unsaturated monomers that polymerize with UV light (in the presence of a photoinitiator, which absorbs radiation and begins polymerization). Unsaturated polyesters copolymerized with vinyl monomers or multifunctional acrylates are often utilized. Most recently, however, vinyl ether monomers for cationic curing with epoxies have shown promise due to reduced shrinkage of cured films and improved adhesion to substrates.

MEASURE PROPERTIES

A good way to examine differences between materials, in addition to considering their chemistry, is to look at mechanical and physical properties. Mechanical properties tell how a material reacts to heat, electricity, light, magnetism, and chemicals. There are many measures of mechanical properties, such as tensile strength, impact resistance, tear resistance, and hardness. In polymers, as in most materials, sample failure generally starts around some inhomogeneity within the sample, such as a microscopic crack or a dust particle. To improve the reproducibility of measurements, tests are designed so that the stress is concentrated in one area and sample failure occurs at this point. Therefore, tests should be used only as relative measures and should not be treated as absolute measures of performance. Unfortunately, predictions of mechanical properties for a given shape are not very accurate, which means that usually a prototype part must be built. Scaling up results of smaller prototypes is also extremely difficult.

MECHANICAL PROPERTIES

Mechanical properties relate to the strength, hardness, and toughness of engineering materials. If a material is to be used to support a load, transmit a force, hold components in an assembly, or resist wear, it must be strong enough; that is, it does not break, it does not bend, it holds its shape, or it is hard. Common descriptions like these are expressed quantitatively by measurements of mechanical properties.

Tensile Strength

Tensile strength, as suggested by the name, is a measure of how a material reacts to a tension, or pulling load. A simple illustration of tensile load in a cable is shown in Fig. 2-18. A load of 200 lb (91 kg) is supported by a 1 in. (2.54 cm) diameter cable. To determine tensile strength, an ever-increasing load is applied to a specimen while the elongation of the specimen is monitored and recorded. A specimen of plastic, metal, or other engineering material is prepared according to the American Society for Testing and Materials (ASTM) specifications as shown in Fig. 2-19. A specimen has a dog-bone shape because stress needs to be concentrated in the test region, not in the area where gripping jaws hold the specimen in the test machine. Before a specimen is mounted in a test machine, its width W and thickness T are measured, and the original length, typically 2 in. (5.1 cm), is marked on the specimen.

A standard specimen measuring 0.5 × 0.125 in. (1.3 × 0.32 cm) is mounted in the universal test machine. By hydraulic pressure, a controlled load is applied to the specimen, tending to pull it apart. The load is increased at a controlled rate while data are collected on elongation of the test specimen versus the applied load. The load in pounds is divided by the cross-sectional area of the specimen to yield stress per unit (pounds per square inch or newtons per square meter [pascals]). Data for a test are shown in Fig. 2-20.

The figure shows that the specimen failed when the stress reached 19,000 psi (131,000 kPa). Besides the ultimate tensile strength, the plot shows several other relevant facts. Notice that the abscissa (x axis) shows elongation of the specimen while the ordinate (y axis) shows tensile stress in pounds per square inch. Elongation is not expressed in inches of elongation but is given as a percentage of original length using the formula:

\[
\text{Elongation} = \frac{\text{Final Length} - \text{Original Length}}{\text{Original Length}} \times 100\%
\]

where the final length is the total elongation of the specimen and the original length is the length before the test.

Supercritical Carbon Dioxide-based Coatings

Supercritical carbon dioxide paint application is a means to effectively lower the VOCs of coatings. In this process, supercritical carbon dioxide, at conditions above critical temperature and pressure in the phase diagram (for CO₂, the critical point is 72.8 atm and 88.0°F [31.1°C]) acts as a liquid, and is used as a solvent, making possible a coating that can be applied at increased solids and reduced VOCs. Coating composition can remain essentially the same, except that the solvent is eliminated and replaced with liquid supercritical carbon dioxide. Advantages of this technology include VOC emission reductions, increased atomization of paint, and simplified formulating practices. Disadvantages associated with the technology include the need for carefully controlled temperature/pressure application equipment as well as the need to determine the compatibility of supercritical CO₂ with the paint formulation (the liquid supercritical carbon dioxide has a solubility parameter close to that of hexane and thus is not miscible with a wide range of solvents and/or resins).

![Fig. 2-18 Tension force.](image-url)
strain. The elongation $\Delta l/l_0$ is divided by the original length $l_0$, to allow for differences in specimen length. This rate of elongation, $\Delta l/l_0$, when multiplied by 100, yields percent elongation and is called strain.

The elastic modulus, a measure of stiffness, is equal to the slope of the stress-strain curve in its linear region, as shown in Fig. 2-21. A comparison of two plastics with different moduli, such as glass-filled polyester, modulus 1,159,558 psi (7995 MPa) and non-glass-filled polyester, modulus 312,232 psi (2153 MPa), helps relate modulus to stiffness. A glass-filled polyester is much stiffer than a nonglass-filled polyester (Fig. 2-22). Sports enthusiasts should relate high-modulus fishing rods, golf club shafts, and tennis rackets to greater stiffness. New composite carbon-epoxy materials give high modulus with very low weight and excellent tensile strength per weight.

**Toughness**

Toughness is the ability to support a load with elongation in contrast to supporting a load with little elongation and ensuing catastrophic brittle failure. Figure 2-22 illustrates the toughness of two plastic materials. Material a is a polyester, with short glass fibers embedded throughout. Material b is polyester with no glass. The glass-filled plastic has a tensile strength about three times that of the unfilled plastic; however, it elongates very little before breaking. The unreinforced plastic is not as strong but it is tough. It elongates under load. Toughness may be visualized as the area under the stress-strain curve.

**Impact Strength**

If you were selecting a material to manufacture front air dams for sports cars or shoulder pads for a football team, impact...
strength would be a primary consideration. Total energy absorbed by a specimen being impacted with a concentrated kinetic mass (a moving object) is the definition of impact strength. How much energy delivered to a small area is required to break a specimen?

Two devices are commonly used to measure impact strength. One is illustrated by Fig. 2-23 and is typically used to measure the impact strength of plastic pipe. Often built on site to ASTM specifications, it consists of a cylindrical iron weight, a pulley, a cable, and a pipe large enough for the weight to slide through it. Holes are drilled into the pipe at 1 ft (30.5 cm) intervals so a painted end of the weight can be located visually inside the pipe. The pipe is mounted vertically with the pulley at the top, the cable passing over it having one end attached to the weight inside the pipe. Test specimens of pipe are located directly beneath the pipe, and the weight is raised to a desired height and dropped.

The energy absorbed by the test pipe specimen on impact is the kinetic energy resulting from the release of the potential energy (PE) of height, equal to the product of weight \( w \) and height \( h \). For example, selected PVC pipe did not fail when a 5 lb weight was dropped from a height of 10 ft. How much energy did it absorb?

<table>
<thead>
<tr>
<th>Material</th>
<th>Grade</th>
<th>Rate</th>
<th>Temperature</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valox</td>
<td>420</td>
<td>0.4</td>
<td>73</td>
<td></td>
</tr>
</tbody>
</table>

stress (\( \text{psi} \))

<table>
<thead>
<tr>
<th>percent strain</th>
<th>stress (( \text{psi} ))</th>
<th>stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.000</td>
</tr>
<tr>
<td>0.50</td>
<td>6051.0</td>
<td>41.720</td>
</tr>
<tr>
<td>1.04</td>
<td>11792.0</td>
<td>81.303</td>
</tr>
<tr>
<td>1.58</td>
<td>15759.1</td>
<td>108.655</td>
</tr>
<tr>
<td>2.65</td>
<td>19051.8</td>
<td>131.357</td>
</tr>
<tr>
<td>26.30</td>
<td>19051.8</td>
<td>131.357</td>
</tr>
</tbody>
</table>

Please note that the elastic modulus output is a calculation using a least squares fit of the linear region of the curve. Review of the actual stress-strain graph is recommended.

"Tensile" stress versus percent strain

Fig. 2-20 Tensile test data. (Courtesy GE Plastics)
Another device used to measure impact strength is the Charpy-Izod tester. Charpy and Izod tests are performed on the same machine; however, the specimens are prepared and mounted in different ways. Charpy-Izod machines are instrumented to measure absorbed energy by comparing the angle (energy of height and arc) of a pivoting mass at two positions: position a with maximum potential energy and position b after much of the energy was absorbed by the impact. Energy absorbed may display several units such as inch-pounds, foot-pounds, newton-meters, or dynes.

Charpy tests are made with a notched specimen lying horizontally on the mount. Izod tests are made with the notched specimen mounted vertically in a vise with the notch facing the impact mass. Some materials do not require notches; however, standard procedures should be verified by consulting ASTM or other handbooks before conducting tests.

**Hardness**

Hardness tests measure a material’s resistance to a concentrated penetrating force. Test devices and scales of measurement often are named for the person or company that developed them. Common names are Rockwell, Brinell, and Shore. All involve a standard force created by weights or springs acting on a standard penetrator. Penetrators range from diamond points to hardened steel hemispheres. Hardness is measured on a calibrated scale proportional to depth of penetration or diameter of indentation made in the test specimen. Since scales are specific to types of test machines, penetrators, and load weights, it is difficult to correlate measurements made on different scales.

The Shore durometer measures the hardness of plastics or rubber. It consists of a spring-loaded penetrator of a standard shape that is pressed full against the test specimen surface. A dial reading calibrated from 0–100 is inversely proportional to the depth of penetration. A high reading represents a hard surface with little penetration. When the specimen surface is soft, the spring forces the penetrator deep into the surface, giving a low reading.

**Creep**

Creep is important when engineering materials encounter loads over extended periods of time, especially at elevated temperatures. Creep is measured as elongation or other load-induced deformation over a length of time. An example of creep is found in elastic bands supporting weights. An elastic band might stretch 4 in. (10.2 cm) when initially loaded. After one hour of supporting the load, it could reach 5 in. (12.7 cm). Three hours later it may reach 6 in. (15.2 cm). Eventually the band could be expected to break.
Plastic, glass, and many soft metals tend to creep significantly as time passes. Creep is temperature-dependent. Increasing temperature leads to greater creep. A simple creep test can be conducted by suspending loads on plastic specimens, placing them in a controlled-temperature environment, and measuring elongation versus time at various temperatures. The heat deflection test measures the deflection of a test specimen mounted between supports and loaded in the center. In a heated oil bath with controlled temperature rise, the heat deflection temperature is recorded when the thermoplastic

Fig. 2-22 A comparison of two plastics with different moduli, such as glass-filled polyester, (a) and a nonglass-filled polyester, (b) helps relate modulus to stiffness. A glass-filled polyester is much stiffer than a nonglass-filled polyester. (Courtesy GE Plastics)
deflects 0.010 in. (0.25 mm). Heat deflection temperature is a function of the chemical makeup of the polymer, the degree of polymerization, and additives.89

**OTHER PROPERTIES**

Other thermal properties of importance are the coefficient of linear thermal expansion and flammability. Table 2-26 shows the coefficient of expansion of polyethylene to be about 4 times that of aluminum and about 10 times that of steel.90 Many part assemblies have failed because designers did not take into account the wide range of expansion coefficients of engineering materials.

Flammability tests determine if a polymer melts, burns when ignited, or self-extinguishes when the ignition source is removed. Burning rates and characteristics may be modified by adding flame retardants.

Electrical characteristics are important for many polymer applications. The arc resistance test determines the current necessary to produce an arc through a specimen when two electrodes are positioned on the same surface. Dielectric strength tests measure the voltage necessary to drive an arc through a specimen when the electrodes are on opposite sides of the specimen.

**TESTS AND THEIR SIGNIFICANCE**

The growth of the thermoplastics industry has seen plastic products evolve from the low-performance throwaway dishware and inexpensive toys of the 1940s to today’s sophisticated, high-performance applications in such products as computers, automobiles, and construction materials. Because of the wide range of applications and the large number of materials available today, the process of selecting the correct material can become complex.

The material selected ultimately depends on the performance criteria of the products, aesthetics, and cost effectiveness. However, analyzing how a material is expected to perform with respect to the mechanical, electrical, and chemical requirements is essential to the selection process. It is the job of the design or product engineer to translate the product requirements into material properties. The characteristics and properties of a material that correlate with known performance are referred to as engineering properties. They include such properties as impact resistance, flexural strength, hardness, chemical resistance, flammability, stress crack resistance, and temperature tolerance. Other important properties include optical clarity, gloss, UV stability, and weatherability.

Because of the nature of plastics, small changes, not only in conditions such as temperature and time under load, but in the test conditions themselves, can adversely affect the accuracy of the test data. ASTM is an organization of concerned consumers, producers, and individuals with common interests who work together to develop standards for industrial products. These tests do not have the force of law and carry no sanctions. They have been established and used to meaningfully describe characteristics of plastics and other materials so the raw material producer, the processor, and the end user will have a common understanding of the material and what it can do.

Included in this section are examples of some of the more commonly referenced tests. The examples are intended to give the reader a brief description of what the test is about, but they are much too general to be used as procedures. The units of measurement for each test are indicated, and key characteristics are listed.

**TABLE 2-26**

Typical Coefficients of Linear Thermal Expansion

<table>
<thead>
<tr>
<th>Material</th>
<th>Typical Coefficient of Thermal Expansion, in./in./°F (cm/cm°C × 10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>56 (100)</td>
</tr>
<tr>
<td>Polyethylene (glass reinforced)</td>
<td>27 (48)</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>28 (50)</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>50 (90)</td>
</tr>
<tr>
<td>Polypropylene (glass reinforced)</td>
<td>22 (40)</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>39 (70)</td>
</tr>
<tr>
<td>Nylon</td>
<td>44 (80)</td>
</tr>
<tr>
<td>Phenolic</td>
<td>38 (68)</td>
</tr>
<tr>
<td>Phenolic (impact modified)</td>
<td>11 (20)</td>
</tr>
<tr>
<td>Polyester (thermoplastic)</td>
<td>36 (65)</td>
</tr>
<tr>
<td>Polyester (thermoset)</td>
<td>31 (55)</td>
</tr>
<tr>
<td>Polyester (glass reinforced)</td>
<td>11 (20)</td>
</tr>
<tr>
<td>Epoxy</td>
<td>28 (50)</td>
</tr>
<tr>
<td>Epoxy (glass reinforced)</td>
<td>11 (20)</td>
</tr>
<tr>
<td>Aluminum</td>
<td>13 (23)</td>
</tr>
<tr>
<td>Steel</td>
<td>6 (11)</td>
</tr>
<tr>
<td>Copper</td>
<td>9.2 (16.6)</td>
</tr>
<tr>
<td>Wood</td>
<td>4 (7.2)</td>
</tr>
<tr>
<td>Glass</td>
<td>4 (7.2)</td>
</tr>
</tbody>
</table>

![Fig. 2-23 Drop weight impact test.](image)
One test may measure a single property or several properties at once. The procedure may be a specific ASTM test such as Izod impact or an informal practical test, as in the case of loaded drums dropped from various heights; however, in every case, the test has been devised to be as accurate as possible. After many years of work by thousands of technical specialists, the tests presently used are generally regarded as suitable. Nevertheless, further improvement is constantly sought. To make tests more accurate, more reproducible, and more meaningful, the plastics industry and interested university and independent groups are continually perfecting tests and developing better ones for the future.

Dart Impact or Falling Dart Test
A dart is dropped on a sample and the energy required to break the sample is calculated. The test results are very dependent on the dart tip radius and diameters of support ring and clamp ring. Various manufacturers use different test fixtures and dart dimensions (see Fig. 2-24).

Units: Foot-pounds (newton-meters) of energy to break (usually F50, where 50% of the samples will break, but sometimes a lower, no-break value for specification purposes).

Test characteristics:
- Can be run at various temperatures.
- Results vary with sheet thickness, but are not exactly proportional.
- Requires a large number of samples (25)—one value is obtained by totaling the break and no-break values.
- Cannot be used for engineering design purposes.
- Very significant in correlation with actual sheet or part impact performance.
- Useful in weathering or paint studies—there is a great difference in surface-up versus surface-down results.
- Useful in detecting degradation of the material.

Izod Impact Test, Method A
This test is done on a Charpy-Izod tester. It measures the impact energy needed to break a notched sample when it is struck with a hammer (see Fig. 2-25).

Units: Foot-pounds of energy per inch of thickness. Hammer speed: 11 ft/s (3 mls).

Test characteristics:
- Can be run on samples of any thickness.
- Results vary with sheet thickness, but are not exactly proportional.
- Requires a large number of samples (25)—one value is obtained by totaling the break and no-break values.
- Cannot be used for engineering design purposes.
- Very significant in correlation with actual sheet or part impact performance.
- Useful in weathering or paint studies—there is a great difference in surface-up versus surface-down results.
- Useful in detecting degradation of the material.

Tensile Properties
Tensile strength, Young’s tensile modulus of elasticity, and elongation are measured by subjecting samples to tension on a universal test machine.

Units: Tensile strength and tensile modulus, psi (pA): elongation, %.

Test characteristics:
- Can be run on samples of any thickness (generally 0.060–0.250 in. [1.5–6.4 mm]) at various temperatures.
- Samples can be injection molded, compression molded, or cut from sheet or parts.
- Modulus is Young’s modulus and can be used in engineering calculations of part stiffness.
- Elongation gives some indication of ductility.
- Strength, elongation, and modulus change if the speed or temperature is changed. The strength and modulus increase at lower temperatures and decrease at higher temperatures.
- Unlike some more traditional materials (steel, aluminum, glass, wood) the modulus and strength of plastic will vary with time under load. Thus, an apparent modulus (which allows for creep), and safety factors for strength must be used in structural design.
- Tensile properties are the most important single indication of strength in a material. The force necessary to pull the specimen apart is determined, along with how much the material stretches before breaking. Tensile properties are depicted in Fig. 2-26.
**Flexural Properties**

Units: Flexural strength and flexural modulus, psi (Pa).

Test characteristics:

- Tests can be run on samples of any thickness (generally 0.060–0.250 in. [1.5–6 mm]) at various temperatures.
- Samples can be injection molded, compression molded, or cut from sheet or parts.
- Dimensions of test fixture can be modified to accommodate very thick or stiff sections.
- Measurements do not give elongation at failure values, but can be used to test to outer fiber elongation.
- Elongation is not uniform—the top is being compressed while the bottom is elongated.
- Strength and modulus vary if the testing speed or temperature is changed.
- Tests of flexural properties measure a specimen’s resistance to bending (flexural strength) and modulus, a design property that can be used to calculate stiffness and determine part (or sheet) thickness required. Figure 2-27 shows an illustration of flexural properties.

**Coefficient of Linear Thermal Expansion**

Tests of linear coefficient of expansion measure the rate at which a sample expands (contracts) with increasing (decreasing) temperature (see Fig. 2-28).

Units: in./in./°F (cm/cm/°C).

Test characteristics:

- This property is often overlooked and is a major factor in the failure of plastics in large structural applications.
- Thermal expansion is very important in design of structural assemblies—it must be considered if dissimilar materials are joined together. Restraint of the plastic will build up high stress at low temperatures.

**Gloss, Gardner Gloss Meter**

A gloss meter measures the portion of light reflected from a surface without scattering.

Reflectance is measured by a Gardner gloss meter at angles of 20°, 60°, and 85° (see Fig. 2-29).

Units: %

Test characteristics:

- The meter can be a portable instrument.
- It is very useful in identifying the gloss of a sheet or part.
- It can identify variations in gloss from place to place on the same part.
- Requires a flat surface measuring 1 × 5 in. (2.54 × 12.7 cm).
- A perfect mirror reflects 100%. Dull surfaces scatter some light and a lower value reaches the detector, which is set for perfect reflection.
- Measurement of reflection at 20° is a severe test and yields lower values. Almost everything is glossy at 80°.
- 60° is the most common measurement angle.

**Density**

**Specific gravity.** Units: Dimensionless (very close to density, which is generally grams per cubic centimeter; water = 1.0).

Units: Bulk density, lb/ft³ (kg/m³)

Specific gravity (ratio of density to that of water), dimensionless. Specific gravity × 0.03615 = lb density per cubic inch (specific gravity × 0.0017 = kilogram density per cubic centimeter).
Measurement of density

ZM weight per unit volume is an important factor in sheet pricing, since material is generally purchased by the pound (kg) and sold by the cubic inch or square foot (cubic centimeter or square meter). It is also important for material purchased in bulk, such as pellets or foam.

Temperature Tests

Heat deflection temperature. This is the temperature at which a center-loaded bar deflects 0.010 in. (0.25 mm) under a stress of 66 or 264 psi (0.46 or 1.8 MPa). The Vicat softening point is the temperature at which a 0.040 in. (1 mm) rod will penetrate into a solid specimen. Figure 2-30 shows how heat deflection temperature and Vicat softening point are measured. These tests give an indication of the temperature levels a material can tolerate without loss of dimensional integrity. However, in actual parts, processing history, particularly orientation effects, has a great influence on dimensional stability. For that reason this test bears very little relation to the temperature a given part can tolerate in use without warping.

Test characteristics:

- Results expressed as unannealed (as molded) or annealed (which increases the heat resistance) ZM for comparisons, this distinction should be carefully noted.
- Vacuum-formed parts under no load may withstand temperatures 20°F (11°C) in excess of the heat deflection tempera-

Hardness Tests

Hardness tests measure the penetration of a ball into a sample; the amount of indentation indicates amount of hardness (see Fig. 2-31). Different scales, ZM Rockwell M and R and Shore D ZM, are used for different hardness ranges (Table 2-27).

The Rockwell hardness scale is used for rigid plastics (those that take permanent set after loading). For Rockwell R, the load is 110 lb (50 kg) with a ½ in. (12.7 mm) ball; for Rockwell M, the load is 120 lb (54 kg) with a ¼ in. (6.4 mm) ball. Scale: 0–125.

Shore D hardness is used for rubbery plastics—those in which the indentation disappears when the load is removed. Scale: 0–100.

Test characteristics:

- Not useful for design purposes. Useful for quality control, since tests require only a small sample of material and in a given polymer can be used to check composition.
- Can be used to give an indication of whether the desired material was used before, if excessive amounts of a different regrind were used, or if material is filled.
- Gives very rough approximation of stiffness.

Flammability

Flammability tests measure the extent to which a material propagates a flame under controlled laboratory conditions. Depending on the type of test, the material is assigned a numerical flame spread rating, a relative rating, or a flame class rating. Numerical flame spread ratings may not reflect the behavior of materials under actual fire conditions.

| Table 2-27 Measurement Scales and Hardness Ranges |
|---------------------------------|---------|---------|---------|
|                                 | Rockwell | Rockwell | Shore   |
|                                 | M       | R       | D       |
| Steel                           | 125     | 125     | 100     |
| SAN                             | 80      | 125     | 100     |
| ABS                             | 0–56    | 89–112  | 70–100  |
| Polypropylene                   | 0       | 50      | 72      |
| High-density polyethylene       | 0       | 40      | 68      |
| Low-density polyethylene        | 0       | 10      | 50      |
SUMMARY OF MATERIAL SELECTION GUIDELINES

The horizontal burn test measures maximum flame speed propagation in inches (millimeters) per minute for a sample 0.20 in. (5 mm) thick or greater with a flame applied rate of 1.5 in. (38 mm)/min. If the sample is less than 0.120 in. (3 mm) thick, the flame application rate will be 3 in. (76 mm)/min.

The tunnel test measures the rate of flame propagation relative to asbestos board (0) and red oak (100). Sample size is 25 in. × 25 ft (64 cm × 7.6 m).

Flame class rating tests burn vertically or horizontally oriented materials to determine which of several flammability classes they belong in. For vertical tests the classes are:

- V-0—average burn less than 5 seconds.
- V-1—average burn less than 25 seconds, no burning drops.
- V-2—less than 25 seconds to burn, with flaming drops.
- V-5—more severe than V-0. A 5 in. (127 mm) flame is applied in five positions with five ignitions. There must be no burn-through and no dripping.

The radiant panel determines a dimensionless flame spread index on a scale where red oak = 100. Sample size is 6 × 18 in. (15 × 46 cm).

SUMMARY OF MATERIAL SELECTION GUIDELINES

Choosing a type of polymer for a certain application is difficult. This is not only because of the large number of polymers available, but also because other types of substances such as metals and ceramics are often considered as well. As a general rule, polymers have the following advantages and disadvantages with respect to other types of materials:

1. Polymers can be rubbery. For an application where a rubbery material is necessary, polymers are essentially the only option.
2. Polymers are resistive to normal atmospheric conditions as well as to very acid or basic environments. This resistivity means that polymers can be used in many environments where metals and ceramics cannot, but this also means polymer waste products degrade slowly or not at all. However, organic solvents will swell or dissolve many polymers.
3. Although polymers may not show visible signs, aging is a problem. Typically, polymers may warp, shrink, creep, or become brittle over a period of years. Many of the additives in polymers reduce problems associated with aging.
4. Most polymers do not have the high-temperature stability of metals or ceramics. The basis of polymers is the carbon-carbon bond which is stable to only about 700˚ F (371˚ C). Most other organic bonds are stable to temperatures far below this value.
5. Polymers are electrical insulators. The thermal conductivity of polymers is also low.
6. The cost of polymers varies widely. Some polymers are extremely inexpensive, and these polymers have replaced more expensive materials in our daily lives. For example, it is easy to recognize where lower-cost polymers have replaced other materials in common kitchenware. Polymers that can replace structural or load-bearing materials generally cost more than the metal counterpart, but the weight of material is usually much lower.

To make an informed choice about a material, the properties that are important for a particular application must be determined. Then, these properties must be translated into material characterization measurements available in product literature. An important resource is the ASTM handbooks. This series of books lists detailed procedures for testing of materials, and usually the properties of materials are reported from tests resulting from them. Further information is found in the Bibliography.
CHAPTER 2

SUMMARY OF MATERIAL SELECTION GUIDELINES

KEY MECHANICAL PROPERTIES

The distinctive mechanical properties of polymers have been the most important reason for the widespread use of these materials in everyday life. Polymers can be both rigid and flexible, and models used to describe mechanical properties contain both types of terms. A general rule of thumb is that polymers over short times or at low temperatures will have properties associated with a glass, while polymers over long times or at high temperatures will have properties associated with viscous liquids. However, polymers also have many properties not normally associated with viscous liquids, such as die swell and second normal stresses. (See Chapter 2 of Dynamics of Polymeric Liquids, listed in the Bibliography, for an excellent description of a number of unique phenomena.) Also, solid polymers can gradually change shape over many years in response to stresses frozen in during the manufacturing process.

There are many measures of mechanical properties, such as tensile strength, impact resistance, tear resistance, and hardness. In polymers, as in most materials, sample failure generally starts around some inhomogeneity within the sample, such as a microscopic crack or a dust particle. To improve the reproducibility of measurements, tests are designed so that the stress is concentrated in one area and sample failure occurs at this point. Therefore, tests should be used only as relative measures and should not be treated as absolute measures of performance. Unfortunately, predictions of mechanical properties for a given shape are not very accurate, which means that usually a prototype part must be built. Scaling up the results of smaller prototypes is also extremely difficult.

Table 2-28 gives typical values for some mechanical properties of different polymers. Unless otherwise indicated, all the values are for unreinforced materials. As is clearly apparent, polymers with a wide variety of mechanical properties can be purchased.

Testing

In tensile tests, a rectangular or dog-bone sample is drawn at a constant rate and the force is measured as a function of distance. Figure 2-32 shows a series of stress-strain curves for different polymers. Experiments where the sample is deformed at a constant rate and the stress is measured are also done in compression and shear geometries.

Impact tests measure the energy required for fracture. Two methods are commonly used in impact tests. In one method, a pendulum swings and strikes the sample and the energy required to fracture the sample is calculated by measuring how far the pendulum travels after hitting the sample (in the Charpy test, the sample is held fixed at both ends, while in the Izod test the sample is held fixed only at one end). In the second method, a weighted object, usually a ball, is dropped from a series of heights until the minimum height is found that causes the sample to break.

Tear strength is measured by introducing a cut into a sample with a razor blade and then measuring the force required to enlarge the crack. Tear strength tests are an extremely important measure for polymers used in the packaging industry. Adhesion tests are similar, except the cut is introduced at the interface between the polymer and the other material.

Hardness tests are similar to compressive tensile stress tests in that both measure the energy required to compress a sample. Generally, however, in hardness tests the force is applied over a very small area of the sample; for example, measuring the deflection of a polymer when a ball is pushed at a constant force into the polymer is a common measure of hardness.

Finally, the resistance of a polymer to a shear force from a small object, that is, a scratch test, is a measure of hardness that is usually termed abrasion resistance testing.

Ductility or Brittleness

Other terminology is often used in reference to the characterization of mechanical properties in polymers. Polymers are ductile if they yield or draw before failure, while polymers are brittle if the material is elastic before failure. This classification is arbitrary since all polymers will undergo a ductile-to-brittle transition if the temperature is low enough or changes rapidly over a short time.

Crazing and Crystallization

Crazing is an important stress-relieving mechanism, especially in polymers blended with small amounts of rubber particles. Crazes are microscopic elliptical voids with the long axis perpendicular to the stress direction. Parallel to the stress direction inside the voids are polymer fibers, typically 50 to 100 nm in diameter, which span the short axis of the ellipse. Another phenomenon important to polymers is the ability of some polymers to crystallize during an applied stress. This stress-induced crystallization is apparent as a steep increase in stress at high (> 50%) strain levels in the tensile curve.

Creep and Warping

Creep and warping are a result of the same underlying phenomenon, but creep refers to shape changes due to an external stress field (that is, gravity), while warping occurs due to an internal stress field that remains after processing. Once again, although polymers have many characteristics associated with solids, they will flow over long enough time scales. Unlike long-term weathering, the long-term creep or warping of a material can be accurately predicted by tests on an accelerated time scale. The basis for these excellent predictions is the WLF equation, which quantitatively relates time and temperature effects to rheological behavior. The interested reader is referred to the book by Ferry (see Bibliography) which contains more information on the WLF equation.

KEY THERMAL PROPERTIES

The upper service temperature of a polymer is determined by the glass or melting transition. The identity of the polymer determines the temperature of these transitions; however, the temperature can be lowered for a particular polymer through the use of plasticizers. Plasticizers and other additives are discussed later in
### SUMMARY OF MATERIAL SELECTION GUIDELINES

#### CHAPTER 2

**TABLE 2-28**

Polymer Mechanical Properties

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Pressure</th>
<th>Tensile Modulus</th>
<th>Stress at Break</th>
<th>Elongation at Break</th>
<th>Notched Izod Impact Strength of Notch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>psi</td>
<td>GPa</td>
<td></td>
<td>%</td>
<td>ft-lb/in</td>
</tr>
<tr>
<td><strong>Thermosets</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrene-butadiene</td>
<td>200,000</td>
<td>1.38</td>
<td>3,800</td>
<td>80</td>
<td>0.4</td>
</tr>
<tr>
<td>Polybutadiene</td>
<td>800</td>
<td>0.0055</td>
<td>750</td>
<td>&gt;1000</td>
<td>flexible</td>
</tr>
<tr>
<td>Polyurethanes</td>
<td>60,000</td>
<td>0.41</td>
<td>13,000</td>
<td>1000</td>
<td>25 to flexible</td>
</tr>
<tr>
<td>Phenols</td>
<td>1,200,000</td>
<td>8.3</td>
<td>7,000</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Urea</td>
<td>1,300,000</td>
<td>9</td>
<td>1,300</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Formaldehydes*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymers</td>
<td>4,700</td>
<td>0.03</td>
<td>9,500</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>Epoxy</td>
<td>350,000</td>
<td>2.41</td>
<td>8,500</td>
<td>5</td>
<td>0.6</td>
</tr>
<tr>
<td><strong>Thermoplastics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDPE</td>
<td>32,500</td>
<td>0.2</td>
<td>2,000</td>
<td>400</td>
<td>flexible</td>
</tr>
<tr>
<td>HDPE</td>
<td>150,000</td>
<td>1</td>
<td>3,500</td>
<td>600</td>
<td>1.7</td>
</tr>
<tr>
<td>PVC (rigid)</td>
<td>450,000</td>
<td>3.1</td>
<td>6,800</td>
<td>60</td>
<td>12</td>
</tr>
<tr>
<td>PVC (flexible)</td>
<td>1,000</td>
<td>0.007</td>
<td>2,500</td>
<td>300</td>
<td>flexible</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>200,000</td>
<td>1.38</td>
<td>5,000</td>
<td>400</td>
<td>0.7</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>460,000</td>
<td>3.17</td>
<td>6,500</td>
<td>3</td>
<td>0.35</td>
</tr>
<tr>
<td>Polystyrene (high impact)</td>
<td>310,000</td>
<td>2.14</td>
<td>4,000</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Polyester</td>
<td>450,000</td>
<td>3.1</td>
<td>8,000</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>ABS</td>
<td>280,000</td>
<td>1.93</td>
<td>5,500</td>
<td>3</td>
<td>8.3</td>
</tr>
<tr>
<td>Nylon (6,6)</td>
<td>490,000</td>
<td>3.4</td>
<td>13,000</td>
<td>20</td>
<td>0.7</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>190,000</td>
<td>1.3</td>
<td>8,000</td>
<td>800</td>
<td>1.7</td>
</tr>
<tr>
<td>Acrylate (PMMA)</td>
<td>400,000</td>
<td>2.8</td>
<td>9,000</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>345,000</td>
<td>2.4</td>
<td>9,000</td>
<td>110</td>
<td>2.3</td>
</tr>
<tr>
<td>Acetal</td>
<td>410,000</td>
<td>2.8</td>
<td>10,000</td>
<td>50</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*Filled with alpha cellulose

(Adapted from Handbook of Plastics Materials and Technology and Modern Plastics Encyclopedia '94. Actual material properties depend greatly on the filler level and the manufacturer and these should serve only as a very broad guideline.)
SUMMARY OF MATERIAL SELECTION GUIDELINES

this chapter. Raising this temperature is extremely difficult and usually necessitates choosing a different polymer altogether. The upper service temperature usually lies 40–50° F (22–28° C) below the actual transition temperature, because polymers will begin to flow or become sticky well below the transition. An extensive list of glass transition temperatures and melting temperatures is found in the Polymer Handbook (see Bibliography). Polymers tend to act more like viscous liquids as the temperature is raised, with a corresponding effect on mechanical properties.

Prolonged exposure to high temperature can lead to oxidative degradation. This will cause the polymer to become increasingly brittle and can cause a color change in the material. These oxidative reactions are especially troublesome in materials that contain a double bond in the main chain, such as isoprene and butadiene. The mechanisms involved are usually complex. Antioxidants are added to nearly all commercial products to help reduce oxidative degradation.

An important safety issue is the behavior of a polymer during a fire. Most polymers will burn because they are primarily carbon and hydrogen, and often additives reduce the flammability. Even without such additives, polymers are not likely to start a fire because they are not very flammable compared to other everyday items. A more critical problem may be that the material may release toxic fumes during a fire.

KEY CHEMICAL PROPERTIES

The resistance of polymers to liquids found normally in nature is very good. The water resistance of most polymers is far superior to that of most other structural materials. Polytetrafluoroethylene (commercially known as Teflon®) is perhaps the most solvent-resistant material known. Many of the condensation polymers are susceptible to hydrolysis; however, generally hydrolysis occurs only when water is present as steam. Strong acids or bases often will not attack polymers. Generally, organic solvents can swell or dissolve polymers.

Permeability is also an extremely important issue, especially in the food packaging industry. A permeable material is one that allows small molecules to pass through quickly (the material’s diffusion constant is high). Small molecules generally pass through voids that exist in amorphous regions. Diffusion through crystalline regions is usually very slow, and does not occur to an appreciable extent. Generally polymers are fairly impermeable to most gases, which allows polymers to be used in applications such as soft drink containers. In a plot of diffusion constant versus molecular size of the diffusing species, generally the transition from a high diffusion constant to a low diffusion constant is abrupt. Solvents generally diffuse much faster than nonsolvents having the same molecular size. Aging of a polymer will decrease its permeability.

Aging and Weathering

Changes in performance for most polymers over a number of years in normal conditions have severely limited the use of polymers in some applications. The seriousness of this problem cannot be overemphasized. Accelerated tests to predict how a polymer will behave over long time scales have met with very limited success. There are a number of changes that are grouped under the term aging, including:

1. Densification.
2. Cross-linking or molecular weight degradation (depends on the polymer).
3. Increase in brittleness.
4. Creep or warping.
5. Loss of additives.

Densification occurs in glassy amorphous polymers, or in the amorphous regions of semicrystalline polymers. As the temperature of an amorphous polymer is lowered, the equilibrium density increases because a single polymer chain with random thermal motions requires less volume at lower temperatures. When a polymer passes through its glass transition, the density is frozen in. As the temperature is reduced further, the equilibrium density of the amorphous polymer is further away from the higher density frozen in at the glass transition. Although the polymer is glassy, it has been shown through very precise measurements that polymers will densify over a period of years. Densification leads to an increase in brittleness of the polymer.

Stability to ultraviolet light from the sun is also very important. Most polymers are not stable over the course of many years while subjected to sunlight, hence UV stabilizers must be added. One can easily fall into a cycle with additives since many antioxidants can also initiate a photochemical reaction. The result of UV absorption—either increased cross-linking or molecular weight degradation—depends on the material. Both of these effects will lead to an increase of brittleness.

Loss of Additives

The loss of additives over a long time is a result of the small but significant vapor pressure of most additives, especially plasticizers. Volatilization of additives can result in an undesirable odor emanating from a polymer. Also, a thin film of plasticizer can build up on a surrounding object; for example, many automobile windows become clouded with plasticizer. Users in the food industry must be sure that a polymer does not contain an additive that could leach into the product and negatively affect its quality or safety. Also, the loss of plasticizer leads to a loss of flexibility.

Environmental Stress

A phenomenon that is extremely important and encompasses some of the more specific factors listed above is termed environmental stress cracking. Simply stated, polymers will crack in some environments and not in others under the same external stress. Typical environments that lead to environmental stress cracking are exposure to organic liquids such as oils or soaps. Typically, biaxial stresses seem to be more likely to cause environmental stress cracking than uniaxial stresses.

FINAL PRODUCT APPEARANCE

Other properties besides the ones discussed here can be important, depending on the application. One that deserves mention is the appearance of the final product. Polymers will generally be translucent, except for crystalline polymers which are allowed to crystallize slowly. Color is also an extremely important attribute. The color of polymer products is totally controlled by additives emanating from a polymer. Also, a thin film of plasticizer can build up on a surrounding object; for example, many automobile windows become clouded with plasticizer. Users in the food industry must be sure that a polymer does not contain an additive that could leach into the product and negatively affect its quality or safety. Also, the loss of plasticizer leads to a loss of flexibility.

SUPPLIERS

This chapter has introduced the different types of polymers available. One crucial piece of information has not been discussed: the places and companies that supply polymers. Laboratory quantities may be available from a chemical supply company. For industrial size quantities, directories are produced annually, and are an
excellent starting point for polymers as well as polymer additives (see Bibliography). Many manufacturers are willing to send small samples (50 lb [23 kg] bags) of material for testing. Toll producers are another option if the particular material cannot be procured commercially.

Material selection decisions will change over time. New additives, reinforcers, or polymer formations can necessitate material substitutions, as can changes in material costs.

References

11. SPI Committee on Resin Statistics.
24. Ibid., p. 3.
26. Ibid., p. 18.
27. Ibid., p. 336.
29. Coloring Plastics, (Cleveland, OH: Ferro Corporation).
### Bibliography


### Blends

- **Characterization of Raw Materials and Final Product**

### Electronic Resources/Databases

- **Computer Aided Material Preselection by Uniform Standards (CAMPUS),** Dow Chemical Company, MEC, 433 Building, Midland, MI 48640. (517) 636-9034, Materials database using ISO standards for uniform test methods and specimens, standard molds, narrow specimen molding conditions specifically defined for each resin family, and uniform test conditions.
- **Engineering and Marketing Databank, Post Office Box H, Yardley, PA 19067, (215) 428-1060.** Plaspec, materials, news, compatibility, shear rate versus viscosity data, supplier directory, and machinery database.
- **International Plastics Selector (IPS),** 15 Inverness Way East, Englewood, CO 80112, (800) 447-4666, Selector II, Property data on CD-ROM. Information for compounding, design, extruding, molding, sales, and purchasing. Plastics /DI/GE/ES/T, mechanical, thermal, and electrical properties of materials. Also lists chemical and environmental resistance and machinability. Adhesives /DI/GE/ES/T, adhesives, sealants, and primers with a description of properties, paired substrates, etc. University of Akron Polymer Information Center, 4040 Embassy Parkway, Akron, OH 44333, (216) 665-5918. Information retrieval services, research assistance, patent searches, and consultant referrals. PolySort, interactive database of companies, products, services, and activities.

### Manufacturing Criteria

**Chemical Marketing Reporter,** Schnell Publishing Corporation.

### Material Safety


### Material Selection Criteria


### Polymer Properties


### Polymerization Chemistry


### Polymers—General

- **Plastics Molders and Manufacturers Group of the Society of Manufacturing Engineers* *Bibliography of Technical Resources on Plastics in the '90s* (Dearborn, MI: Society of Manufacturing Engineers, 1994).
- **Strong, A. Brent,** *Fundamentals of Composites Manufacturing: Materials, Methods, and Applications* (Dearborn, MI: Society of Manufacturing Engineers, 1989).

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### Electronic Resources/Databases

- **Computer Aided Material Preselection by Uniform Standards (CAMPUS),** Dow Chemical Company, MEC, 433 Building, Midland, MI 48640. (517) 636-9034, Materials database using ISO standards for uniform test methods and specimens, standard molds, narrow specimen molding conditions specifically defined for each resin family, and uniform test conditions.
- **Engineering and Marketing Databank, Post Office Box H, Yardley, PA 19067, (215) 428-1060.** Plaspec, materials, news, compatibility, shear rate versus viscosity data, supplier directory, and machinery database.
- **International Plastics Selector (IPS),** 15 Inverness Way East, Englewood, CO 80112, (800) 447-4666, Selector II, Property data on CD-ROM. Information for compounding, design, extruding, molding, sales, and purchasing. Plastics /DI/GE/ES/T, mechanical, thermal, and electrical properties of materials. Also lists chemical and environmental resistance and machinability. Adhesives /DI/GE/ES/T, adhesives, sealants, and primers with a description of properties, paired substrates, etc. University of Akron Polymer Information Center, 4040 Embassy Parkway, Akron, OH 44333, (216) 665-5918. Information retrieval services, research assistance, patent searches, and consultant referrals. PolySort, interactive database of companies, products, services, and activities.

### Manufacturing Criteria

**Chemical Marketing Reporter,** Schnell Publishing Corporation.

### Material Safety


### Material Selection Criteria


### Polymer Properties


### Polymerization Chemistry


### Polymers—General


### Processibility


### Rheology

- **Ferry, J. D.,** *Viscoelastic Properties of Polymers* (New York: John Wiley and Sons, 1980).

### Rubbers

Synthetic Procedures


Thermoplastics


Thermosets

INTRODUCTION

Polymeric materials come in a large variety of forms. They can be solids of different hardness, viscous liquids, or dispersed in water as latex or suspension. Some are converted into products as they are, others are modified, dissolved, blended, or mixed to produce the desired processing and performance characteristics.

POLYMER BEHAVIOR

The behavior of polymers during processing is a critical factor in selecting the appropriate processing method for a given product. One such consideration is the rheological behavior of the polymeric material, that is, its flow behavior as a response to the existing shear rate. This issue is particularly important for melt processing, such as mixing, calendering, compression molding, transfer molding, extrusion, and injection molding. Moreover, there are fundamental differences between rheological behavior of melts, concentrated and dilute solutions of polymers, and water-based polymeric systems.

CHEMICAL REACTIONS

Consider chemical reactions and their rates. In processes such as mixing and shaping, it is not desirable that any reactions occur that affect the flow properties of the material. In particular, cross-linking or polymerization can cause difficulties if the material becomes too viscous for the process, too stiff, or even crumbly. On the other hand, such reactions and their rates are important for the economy of the process. The faster they proceed after the material has attained its desirable shape, the better the overall process economy.

Side reactions may cause problems since they may affect the flow and mechanical properties, dimensions, or appearance of the finished product. Decomposition, another undesirable reaction, can have a profound effect on the flow properties, mechanical properties, and color of the product.

Preventing Reactions

Undesirable chemical reactions during processing can be prevented through the use of inhibitors with or without stabilizers, and reaction components having appropriate reaction rates for given conditions. Of course, proper process parameters (temperature, speed and residence time, and shear rate, when applicable) must also be maintained.

Promoting Reactions

Desirable reactions, such as cross-linking, polymerization, or chain extension, are promoted by catalysts, accelerators, and increased temperature or alternate sources of energy, such as ultraviolet radiation, electron beam, and x-rays. Heat energy can be supplied by electric resistance heating; circulating steam, hot water, or other liquids; circulating hot air; or by dielectric and microwave heating, etc.

The manufacturing process selection for polymers or polymeric compounds depends on a variety of factors, such as:

- Consistency of the material.
- Chemical nature and reactivity of the material.
- Desired shape of the final product.
- Desired dimensions of the final product.
- Number of units of the final product made.
- Cost of the finished product.

A schematic flow-chart illustrating the selection of a polymer and the attendant process technique is shown in Fig. 3-1. Other considerations involved in the process selection, such as relevant processing variables, part geometry, shape, and size, are illustrated in Tables 3-1, 3-2, and 3-3 respectively. In this chapter, we will discuss the selection of the process for a given situation in some detail starting with the material preparation, which is quite often accomplished by blending and/or mixing.

Comparative capital costs and production rates are in Table 3-4. The arbitrary scale used in this table allows a qualitative comparison between the unit capital costs for different processing options. The ranking of major polymer processes according to unit cost is in Table 3-5.
### TABLE 3-1
**Processing Variables for Major Polymer Processes**

<table>
<thead>
<tr>
<th>Process</th>
<th>Viscosity</th>
<th>Thermoset</th>
<th>Thermoplastic</th>
<th>Melt Fracture</th>
<th>Extrudate Swelling</th>
<th>Melt Strength</th>
<th>Rate of Reaction</th>
<th>Rate of Crystallization</th>
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<tr>
<td>Blow Molding</td>
<td>Medium</td>
<td>•</td>
<td></td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Calendering</td>
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<td></td>
<td>•</td>
<td>•</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td>•</td>
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<td></td>
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</tr>
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<td>•</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Extrusion, Film</td>
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</tr>
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<td>•</td>
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</tr>
<tr>
<td>Hand Lay-up or Spray-up</td>
<td>Medium</td>
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<td>•</td>
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<td>•</td>
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<td></td>
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</tr>
<tr>
<td>Injection Molding, Foam</td>
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<td>•</td>
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<td>•</td>
<td>•</td>
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<td>•</td>
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</tr>
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<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

(Courtesy Progelhof and Throne)
### TABLE 3-2
Part Geometry as a Way of Classifying Polymer Processes

<table>
<thead>
<tr>
<th>Linear Forming</th>
<th>Extrusion</th>
<th>Pultrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formation of a Solid Body by Injection into a Cavity</td>
<td>Solid (thermoplastic or thermosetting)</td>
<td>Thermoplastic foam</td>
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<tr>
<td>Reaction injection molding (RIM)</td>
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<td></td>
</tr>
<tr>
<td>Formation of a Hollow Object</td>
<td>Blow molding</td>
<td>Rotational molding</td>
</tr>
<tr>
<td>Filament winding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation of a Solid Object by Prefilling a Cavity</td>
<td>Compression molding (BMC)</td>
<td>Matched die molding (SMC)</td>
</tr>
<tr>
<td>Sheet Forming</td>
<td>Thermoforming</td>
<td>Stretch blow molding</td>
</tr>
</tbody>
</table>

(Courtesy Progelhof and Throne³)

### TABLE 3-3
Shape and Size as Ways of Classifying Polymer Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Shape Limitation</th>
<th>Factor Limiting Maximum Size</th>
<th>Complex Shapes</th>
<th>Controlled Wall Thickness</th>
<th>Open Hollow Shapes</th>
<th>Closed Hollow Shapes</th>
<th>Very Small Items</th>
<th>Plane Area &gt; 10 ft² (0.93 m²)</th>
<th>Inserts</th>
<th>Molded-in Holes</th>
<th>Threads</th>
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<td>Hollow, thin wall</td>
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<td>*</td>
<td></td>
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<td></td>
<td></td>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Extrusion, Film</td>
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<td>Die</td>
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<td></td>
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<td>Linear</td>
<td>Die</td>
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<td>Width of roll</td>
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<td>Surface of revolution</td>
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<td>Mold</td>
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</tr>
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</tr>
<tr>
<td>Injection Molding, Foam</td>
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<td></td>
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</tr>
<tr>
<td>Injection Molding, Reactive</td>
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<td>*</td>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pultrusion</td>
<td>Linear</td>
<td>Die</td>
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<td></td>
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<td></td>
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<tr>
<td>Rotational Molding</td>
<td>Hollow</td>
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</tr>
<tr>
<td>Thermoforming</td>
<td>Thin wall</td>
<td>Platen</td>
<td></td>
<td>*</td>
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<td></td>
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<td></td>
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</table>

(Courtesy Progelhof and Throne⁴)
TABLE 3-4
Comparative Capital Costs and Production Rates for Major Polymer Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Equipment Costs</th>
<th>Tooling Costs</th>
<th>10^3</th>
<th>10^4</th>
<th>10^5</th>
<th>10^6</th>
<th>10^7</th>
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<tr>
<td>Blow Molding</td>
<td>M to H</td>
<td>L to M</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calendering</td>
<td>VL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casting</td>
<td>VL</td>
<td>VL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression Molding</td>
<td>M to H</td>
<td>M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrusion, Film</td>
<td>H to VH</td>
<td>H</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extrusion, Profile</td>
<td>M to H</td>
<td>M</td>
<td></td>
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</tr>
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<td>H</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Hand Lay-up or Spray-up</td>
<td>L</td>
<td>VL to M</td>
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<td>Injection Molding, Compact</td>
<td>M to VH</td>
<td>M to H</td>
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<td>Injection Molding, Foam</td>
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<td>M to H</td>
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<tr>
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<td>L</td>
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<td>L</td>
<td>VL</td>
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<td></td>
</tr>
<tr>
<td>Rotational Molding</td>
<td>M to H</td>
<td>L</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Thermoforming</td>
<td>M to H</td>
<td>L</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Transfer Molding</td>
<td>M to H</td>
<td>M to H</td>
<td></td>
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</tr>
</tbody>
</table>

**Cost Range**

VL (Very Low) <$20,000  L (Low) <$50,000  M (Medium) <$100,000  H (High) <$250,000  VH (Very High) >$250,000

(Courtesy Progelhof and Throne®)

TABLE 3-5
Ranking of Major Polymer Processes According to Unit Cost

| Process                             | Cost
|-------------------------------------|-----|
| Calendering                         | Very low
| Film Extrusion                      |     |
| Solid Injection Molding             |     |
| Wire and Cable Extrusion            |     |
| Blow Molding*                       |     |
| Foam Injection Molding              |     |
| Melt Flow Stamping                  |     |
| Profile Extrusion                   |     |
| Rotational Molding*                 | Low |
| Sheet Extrusion                     |     |
| Thermoforming                       |     |
| Transfer Molding                    |     |
| Reaction Injection Molding          |     |
| Blow Molding*                       |     |
| Compression Molding                 |     |
| Powder Coating                      | Medium|
| Pultrusion                          |     |
| Rotational Molding                  |     |
| Casting                             |     |
| Filament Winding                    |     |
| Hand Lay-up or Spray-up             | High|
| Machining                           |     |

*Varies with part size

(Courtesy Progelhof and Throne®)
BLENDING AND MIXING

The simplest way to blend solids is in a blender incorporating a mechanism such as a paddle, ribbon, screw, or a propeller that will produce a uniform mixture. If all components are solids, the process is called dry blending. If they are all liquids, the blending is done by simple mixing. If both liquid and solid components are in the blend, the choice of the mixing method depends on the component that is largest in volume.

ADDITIVES

In some cases polymeric solids are melted and blended or mixed in the molten stage. Frequently, various additives are included in powders, waxes, resins, pigments, reinforcing agents, liquid or solid plasticizers, colorants or other chemicals. Mixing in the molten stage requires a large input of energy and requires either batch or continuous mixers. The finished mixture is often called a compound or a formula, which may be in the form of pellets, sheets, slabs, or ropes, depending on the next step in the manufacturing process. If a compound is made from a water-based form of the polymer, the additives are either water soluble or in the form of an emulsion (liquid) or a suspension (solid).

When the compounds have been prepared, the selection of the methods to convert them into either a finished or semifinished product is done. (Semi)finished product is used in additional manufacturing steps to make the finished product. Primary processing methods for selected thermoplastics are shown in Table 3-6 and for the selected thermosets in Table 3-7.

<table>
<thead>
<tr>
<th>TABLE 3-6</th>
<th>Primary Processing Methods for Selected Thermoplastics</th>
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<tbody>
<tr>
<td>Process</td>
<td>a</td>
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<td>---</td>
</tr>
<tr>
<td>Blow Molding</td>
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</tr>
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<td>Calendering</td>
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</tr>
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<td>Casting</td>
<td>•</td>
</tr>
<tr>
<td>Compression Molding</td>
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<td>Extrusion, Film</td>
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<td>Extrusion, Fiber</td>
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<td>Extrusion, Profile</td>
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<tr>
<td>Extrusion, Sheet</td>
<td>•</td>
</tr>
<tr>
<td>Extrusion, Wire and Cable</td>
<td>•</td>
</tr>
<tr>
<td>Injection Molding</td>
<td>•</td>
</tr>
<tr>
<td>Rotational Molding</td>
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<tr>
<td>Thermoforming</td>
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<table>
<thead>
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<th>Polymers</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
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<th>l</th>
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<tr>
<td>Polybutylene terephthalate (PBT)</td>
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<tr>
<td>Polypropylene (PP)</td>
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<td>Polycarbonate (PC)</td>
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<tr>
<td>Polystyrene (PS)</td>
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<tr>
<td>Polystyrene (SAN)</td>
<td>•</td>
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<tr>
<td>Polyethylene (PE)</td>
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<tr>
<td>Styrene-acrylonitrile (SAN)</td>
<td>•</td>
<td>•</td>
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</tbody>
</table>

(Adapted from Progelhof and Throne)

<table>
<thead>
<tr>
<th>TABLE 3-7</th>
<th>Primary Processing Methods for Selected Thermosets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>a</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Casting</td>
<td>•</td>
</tr>
<tr>
<td>Compression Molding</td>
<td>•</td>
</tr>
</tbody>
</table>

(continued)
TABLE 3-7
Primary Processing Methods for Selected Thermosets (continued)

<table>
<thead>
<tr>
<th>Process</th>
<th>Polymer (see below)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion, Profile</td>
<td>a b c d e f g h i</td>
</tr>
<tr>
<td>Extrusion, Wire and Cable</td>
<td></td>
</tr>
<tr>
<td>Filament Winding</td>
<td></td>
</tr>
<tr>
<td>Hand Lay-up and Spray-up</td>
<td></td>
</tr>
<tr>
<td>Injection Molding, Reactive (RIM)</td>
<td></td>
</tr>
<tr>
<td>Lamination</td>
<td></td>
</tr>
<tr>
<td>Powder Coating</td>
<td></td>
</tr>
<tr>
<td>Pultrusion</td>
<td></td>
</tr>
<tr>
<td>Rotational Molding</td>
<td></td>
</tr>
<tr>
<td>Transfer Molding</td>
<td></td>
</tr>
</tbody>
</table>

Polymers

a Alkyd  
Diallyl phthalate (DAP)  
Amino melamine

b Urea  
Epoxy  
Phenolic

c Unsaturated polyester  
Polyurethane (PU)  
Silicone

(Adapted from Progelhof and Throne)

SHAPING POLYMERIC MATERIALS

The most common method of giving the desired geometry and dimensions to a polymeric material is to shape it in its softened or molten state. Depending on the complexity of the shape and the desired dimensions (thickness, width, radii), the method of choice will vary: it may be a process producing a simple flat product (film, sheet, slab), one producing a profile (rod, tube or solid profile with a desired cross-section and surface texture), or a process producing a complex or hollow product.

FILMS, SHEETS, AND SLABS

Flat films, sheets, and slabs are the simplest shapes of plastic products. They are classified as films if their gage is 0.010 in. (0.25 mm) or below. Sheets are thicker, with gages greater than 0.010 in. (0.25 mm).4 Very thick sheets, about 0.5 in. (12.7 mm) or thicker, are sometimes referred to as slabs.

The methods to manufacture flat goods from polymeric melts are either calendering or extrusion (if the required product is a long web). Flat goods with limited length (for example, tiles) may be produced by compression molding.

Calendering

The calendering process is a continuous, synchronized method to produce flat products with specified thickness and width by passing them through the nips of a series of cooperating rolls.10 If an embossed sheet is needed, the desired pattern appears on the surface of last rolls. Sometimes a separate embosser is a part of the calender train. The major use of calenders is in the production of rubber goods, not only for making sheets, but also for coating fabrics and combining several components into laminates. In the PVC industry, calenders are used in producing films and sheets from rigid and flexible (plasticized) vinyls. Calendering is also the method of choice for fabric coating and lamination.

Extrusion of Flat Goods

Extrusion is by far the most widely used technology to produce the entire range of flat goods, from films to thick sheets (slabs). Flat extrusion and blown film extrusion are the two most common methods. Typical processing temperature ranges for several extrusion-grade thermoplastics are in Table 3-8.

Blown film extrusion. The typical range of thickness of blown film is 0.0001–0.05 in. (0.0025–1.27 mm) and in some special cases it is possible to produce a sheet up to 0.125 in. (3.18 mm) thick. Special dies allow the production of coextruded blown film consisting of up to five layers. Polymers processed typically by blown film extrusion are polyethylene, polypropylene, EVA, and flexible PVC.12 A typical blown film line is shown in Fig. 3-2.

Extruded films and sheets. This method is useful for the manufacture of thicker films (0.001–0.020 in. [0.0025–0.50 mm]) or sheets up to 0.5 in. (12.7 mm).14 The lower limit for this process is 0.005 in. (0.127 mm)15 although films as thin as 0.002 in. (0.05 mm) are made from some polymers. However, at such a low gage it is difficult to maintain uniform thickness.

Multilayered sheets consisting of up to seven layers are commonly made by extrusion using special dies (see Fig. 3-3).16 Polymers used for sheet extrusion are polyethylene, polypropylene, plasticized PVC, EVA, ABS, polystyrene, polyurethanes, polycarbonate, acrylics, polyamides, and polyesters.
Cast film. The cast film process produces thin films, typically 0.002–0.03 in. (0.05–0.76 mm) thick. Polymers used for this method must have a relatively low melt viscosity at the processing temperature to assure a good flow through the extrusion die. A typical cast film line is depicted by Fig. 3-4.17

Alternately, thin films can be cast from solutions in volatile solvents, dispersions in latent solvents, pastes with plasticizers, or water-based polymeric systems (latexes, dispersions, or suspensions).

Extrusion coating. This process produces a thin coating on paper, foils, fabric, and other substrates. Polymers most widely used in this process are polyethylenes, polypropylenes, polyurethanes, plasticized PVC, EVA, polyamides and ionomers. In the process, a thin film (typically 0.0002–0.015 in. [0.005–0.39 mm]) is extruded through a flat die and combined with the substrate in the first nip of the roll stack.18 Examples of process selection for films and sheeting are in Table 3-9.

MOLDED PARTS

Parts with different shapes and sizes are prepared by shaping a molten or softened polymer by force. There are many methods to select for making molded parts depending on the required shape

---

**TABLE 3-8**

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Processing Temperature Range</th>
<th>(' C)</th>
<th>(' F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>180–240</td>
<td>356–464</td>
<td></td>
</tr>
<tr>
<td>Polyacetal (POM)</td>
<td>185–240</td>
<td>365–437</td>
<td></td>
</tr>
<tr>
<td>Acrylic (PMMA)</td>
<td>180–250</td>
<td>356–482</td>
<td></td>
</tr>
<tr>
<td>Nylon (Polyamide, PA)</td>
<td>260–290</td>
<td>500–554</td>
<td></td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>280–310</td>
<td>536–590</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>160–240</td>
<td>320–464</td>
<td></td>
</tr>
<tr>
<td>Low Density (LDPE)</td>
<td>200–280</td>
<td>392–536</td>
<td></td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>180–260</td>
<td>356–500</td>
<td></td>
</tr>
<tr>
<td>Polyvinyl Chloride, Rigid (RPVC)</td>
<td>160–210</td>
<td>320–410</td>
<td></td>
</tr>
</tbody>
</table>

(Courtesy Progelhof and Throne11)
and dimensions, volume of production, investment cost of the equipment, and the cost of operating the equipment.

**Compression Molding**

Compression molding is the oldest and simplest method of shaping a plastic material by loading it into a heated steel mold and applying pressure. This method is suitable for both thermosets and thermoplastics. The former requires a certain time for the cross-linking reaction to occur. This may take minutes or hours depending on temperature, size of the part, and reactivity of the processed material. Thermoplastics must be cooled down to the point where they are solid and can be removed from the mold without being deformed.
TABLE 3-9 Examples of Process Selection for Films and Sheeting

<table>
<thead>
<tr>
<th>Product</th>
<th>Primary Process(es)</th>
<th>Secondary Process(es)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Tape</td>
<td>Calendering/coating</td>
<td>Slitting</td>
<td>None reinvented</td>
</tr>
<tr>
<td>Flexible PVC Film</td>
<td>Calendering or casting</td>
<td>Slitting</td>
<td>Smooth</td>
</tr>
<tr>
<td></td>
<td>Calendering</td>
<td></td>
<td>Embossed</td>
</tr>
<tr>
<td>Garbage Bag</td>
<td>Blown-film extrusion</td>
<td>Heat sealing</td>
<td></td>
</tr>
<tr>
<td>Grocery Bag</td>
<td>Blown-film extrusion</td>
<td>Heat sealing and printing</td>
<td></td>
</tr>
<tr>
<td>Heat Shrinkable Film</td>
<td>Blown-film extrusion</td>
<td>Stretching (TDO or biaxial) slitting</td>
<td></td>
</tr>
<tr>
<td>Packaging Film</td>
<td>Blown-film extrusion, coextrusion or casting</td>
<td>Biaxial orientation (some films), lamination</td>
<td>Thin films</td>
</tr>
<tr>
<td></td>
<td>Sheet coextrusion</td>
<td>Biaxial orientation (some films), lamination</td>
<td>Thicker films</td>
</tr>
<tr>
<td>PVDF Film</td>
<td>Casting from solvents or latex</td>
<td>Slitting</td>
<td>Very thin films</td>
</tr>
<tr>
<td></td>
<td>Sheet extrusion</td>
<td>Slitting</td>
<td>Thick film</td>
</tr>
<tr>
<td>PVF film</td>
<td>Casting from latent solvent</td>
<td>Slitting</td>
<td></td>
</tr>
<tr>
<td>Rigid PVC Sheet</td>
<td>Sheet extrusion</td>
<td>Trimming</td>
<td></td>
</tr>
</tbody>
</table>

Compared to compression molding, transfer molding has many advantages. The most important one is shorter cycles since fewer and larger preforms are used and heat transfer is improved. Tool costs are lower because of thinner mold sections and the deep loading wells needed in compression molds are not necessary. Mold maintenance cost is less because there is less wear on the mold and much less tendency toward pin breakage. This results in greater accuracy and better molding tolerances. Another advantage is reduced finishing costs because the transfer molded parts have very thin flash or none at all. A detailed comparison of compression and transfer molding is in Table 3-10.

The main limitation of transfer molding is loss of material. The compound left in the pot well and in the sprue and runners is cross-linked and must be discarded. This can represent a high percentage of the weight of molded parts, especially if they are small, though it can be reduced by careful mold design. Also, the flow around inserts and weld lines will often reduce strength of the finished parts.

**Liquid Resin Molding**

Liquid resin molding (LRM) is a combination of liquid resin mixing and dispersing, and transfer molding. Because of low injection pressures (25–50 psi [1.7–3 MPa]) this molding technique is suitable for parts with very fragile inserts. Some formulations used in LRM are processed at temperatures as low as 200 °F (93 °C). Because of this, LRM is a suitable process for encapsulation of heat-sensitive components.

**Resin Transfer Molding**

Resin transfer molding (RTM) is a variation of transfer molding in which matching male and female molds containing precut or preformed fiber reinforcement are clamped together. Liquid resin is pumped under pressure into the mold through injection ports. Resins suitable for this process are vinyl esters, orthophthalic and isophthalic polyesters, and to a limited extent, epoxies, polyurethanes, acrylic/polyester hybrids, and polyamide resins. RTM is an intermediate-volume production process suitable for the production of a variety of parts, some of them relatively large such as truck body components, automobile panels, medical equipment, storage tanks, electrical covers, transportation seating, chemical pumps, and small boats.

**Injection Molding**

Injection molding is a highly versatile and widely used manufacturing method for relatively complex shapes. It has excellent dimensional accuracy. It is well suited for high volume production, with outputs as high as thousands of parts per hour per machine. Gas assisted injection molding is a relatively new method for producing precise hollow molded parts.

With slight process differences, both thermoplastic and thermoset resins can be used in injection molding. The difference is that for thermoplastic materials the injection chamber is heated and the mold is cold. Thermosetting materials the injection chamber is relatively cold and the mold is heated to promote the cross-linking reaction.

Polymeric materials commonly used for injection molding are polyethylene, polypropylene, polyamides, polyvinyl chloride (PVC), acetal, acrylonitrile-butadiene-styrene (ABS), styrene acrylonitrile (SAN), polycarbonate, phenolics, melamine and urea resins, polyurethanes, polystyrene, epoxy resins, polyimides, and elastomeric compounds. Some of these are combined with chopped glass fibers for reinforcement. Typical products made by injection molding are parts for automotive applications (brakes,
transmission components, electrical components), washer pumps, steam irons, and parts for communications and power distribution.

**Reaction Injection Molding**

Reaction injection molding (RIM) is a low-pressure molding process using highly reactive liquid materials. Depending on requirements, the final product is either flexible solids or foams. RIM makes it possible to produce large parts such as automotive bumpers, body panels, appliances, computer housings, etc. It is quite common to produce solid parts weighing up to 200 lb (90 kg). Variations of the RIM process are reinforced reaction injection molding (RRIM), in which reinforcements such as milled fibers or flakes are mixed into the resin before reacting in the mixing head, and structural reaction injection molding (SRIM). In the latter process, chopped fiber preforms or mats are placed into the mold cavity. The resin is then injected, fills the mold, penetrates the reinforcing fibers, and finally cures in place.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Compression</th>
<th>Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading the Mold</td>
<td>1. Powder or preforms.</td>
<td>1. Mold closed at time of loading (assuming top transfer, bottom clamp).</td>
</tr>
<tr>
<td></td>
<td>2. Mold open at time of loading.</td>
<td>2. RF heated preforms placed in transfer pot.</td>
</tr>
<tr>
<td></td>
<td>3. Material positioned for optimum flow.</td>
<td></td>
</tr>
<tr>
<td>Material Temperature Before Molding</td>
<td>1. Cold powder or preforms.</td>
<td>RF heated preforms to 220–280° F (104–138° C).</td>
</tr>
<tr>
<td></td>
<td>2. RF heated preforms to 220–280° F (104–138° C).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Add 700 psi (5 MPa) for each in. of part depth.</td>
<td>2. Clamping ram — minimum tonnage should be 75% of load applied by plunger ram on mold.</td>
</tr>
<tr>
<td>Breathing the Mold</td>
<td>Frequently used to eliminate gas and reduce cure time.</td>
<td>1. Neither practical nor necessary.</td>
</tr>
<tr>
<td></td>
<td>2. Accomplished by proper venting.</td>
<td></td>
</tr>
<tr>
<td>Cure Time (time pressure is being applied on mold)</td>
<td>30–300 sec — will vary with mass of material, thickness of part, and preheating.</td>
<td>45–90 sec — will vary with part geometry.</td>
</tr>
<tr>
<td>Size of Pieces Moldable</td>
<td>Limited only by press capacity.</td>
<td>About 1 lb (0.45kg) maximum.</td>
</tr>
<tr>
<td>Use of Inserts</td>
<td>Limited — inserts apt to be lifted out of position or deformed by closing.</td>
<td>Unlimited — complicated. Inserts readily accommodated.</td>
</tr>
<tr>
<td>Tolerances on Finished Products</td>
<td>1. Fair to good — depends on mold construction and direction of local flow of material during final closing.</td>
<td>Good—close tolerances easier to hold.</td>
</tr>
<tr>
<td></td>
<td>2. Shrinkage across line of flow is less than with line of flow.</td>
<td></td>
</tr>
</tbody>
</table>

*(Courtesy SPI Composites Institute, Plastics Engineering Handbook, 5th Edition)*

3-10
Parts made by RRIM and SRIM are found mainly in the automotive industry (body panels, bumper beams, fascia, floor pans, etc.).

**Blow Molding**

Blow molding produces hollow plastic products without the need to join two or more separately molded parts. The materials most widely used for blow molding are polyethylenes (predominantly high-density), polypropylene, PVC, polyethylene terephthalate (PET), and polystyrene. Engineering thermoplastics such as polycarbonate, polysulfone, amorphous polyamide, and polyphenylene ether blends are increasingly used in blow-molded products for packaging and structural uses. Typical products made by this process are bottles, automotive fuel tanks, bumper fascia, product packages, and containers. Most recent applications are containers with improved barrier properties. In such cases the structural (outside) layer is co-extruded with a barrier layer (ethylene vinyl alcohol, polyvinylidene chloride, or polyamide). Often a special tie layer is needed to assure the adhesion between the two adjacent incompatible layers.

**Thermoforming**

Thermoforming is the process used to form a preheated plastic sheet into a desired shape by mechanical means (tools, plugs, solid molds) or pneumatic means (vacuum or compressed air). When held to the shape of the mold and allowed to cool there, the plastic material retains the shape and detail of the mold. Polymers used for thermoforming are polypropylene, polyethylene, acrylates and methacrylates, PVC, engineering plastics, and fiber-reinforced polymer-based composites and foams. Ranges of thermoforming temperatures for selected thermoplastics are in Table 3-11. Typical applications are solid or foam dinnerware, cups, meat and produce trays, egg cartons, refrigerator liners, computer housings, interior and exterior automotive parts, blisters for packaging (sometimes made of multilayer coextruded sheets), small swimming pools, etc.

**Rotational Molding**

In rotational molding the part is formed from a polymeric melt or powdered thermoplastic resin inside a closed mold or cavity while the mold is rotating biaxially in two planes perpendicular to each other. This process is best suited for large hollow parts requiring stress-free walls, complicated curves, good finish, variety of colors, and uniform wall thickness. With rotational molding it is possible to process multiple colors and different parts simultaneously, to produce multilayer walls, double walls, or to mold in multicolored graphics and inserts. Another advantage of this process is 100% utilization of the material, that is, no scrap is generated. Most thermoplastics can be used in rotational molding with polyethylenes (low-density, linear low density) and medium density, polyvinyl chloride (PVC) (paste or powder) being most popular, but nylon, polycarbonate, polyesters, acrylonitrile-butadiene-styrene (ABS), acetal, acrylucel, cellululfus, polystyrene, epoxies, fluoropolymers, polybutylene, polyurethanes, styrene acrylonitrile (SAN), and silicones can also be used. In addition, heat cross-linkable polyethylene and fiber-reinforced composites or foams can be processed by this method.

### Table 3-11

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Recommended Mold Temperature</th>
<th>Polymer Set Temperature</th>
<th>Lower Forming Temperature</th>
<th>Normal Forming Temperature</th>
<th>Upper Forming Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(° F) (° C)</td>
<td>(° F) (° C)</td>
<td>(° F) (° C)</td>
<td>(° F) (° C)</td>
<td>(° F) (° C)</td>
</tr>
<tr>
<td>ABS</td>
<td>180 81</td>
<td>185 85</td>
<td>260 127</td>
<td>295 146</td>
<td>360 182</td>
</tr>
<tr>
<td>Acrylonitrile</td>
<td>- -</td>
<td>185 85</td>
<td>260 127</td>
<td>300 149</td>
<td>360 182</td>
</tr>
<tr>
<td>Acetate (CA)</td>
<td>- -</td>
<td>160 71</td>
<td>260 127</td>
<td>310 154</td>
<td>360 182</td>
</tr>
<tr>
<td>Acrylic (PMMA)</td>
<td>190 88</td>
<td>185 85</td>
<td>300 149</td>
<td>350 177</td>
<td>380 193</td>
</tr>
<tr>
<td>Acrylic/PVC</td>
<td>- -</td>
<td>175 79</td>
<td>325 163</td>
<td>370 188</td>
<td>400 204</td>
</tr>
<tr>
<td>Butyrate (CAB)</td>
<td>- -</td>
<td>175 79</td>
<td>260 127</td>
<td>295 146</td>
<td>360 182</td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>260 127</td>
<td>280 138</td>
<td>335 168</td>
<td>375 191</td>
<td>400 204</td>
</tr>
<tr>
<td>Polytetraphthalate (PET)</td>
<td>- -</td>
<td>170 77</td>
<td>260 121</td>
<td>300 149</td>
<td>330 166</td>
</tr>
<tr>
<td>Polyether Sulfone (PES)</td>
<td>- -</td>
<td>400 204</td>
<td>525 274</td>
<td>600 316</td>
<td>700 371</td>
</tr>
<tr>
<td>20% Glass-Reinforced Polyether Sulfone</td>
<td>- -</td>
<td>410 210</td>
<td>535 279</td>
<td>650 343</td>
<td>720 382</td>
</tr>
<tr>
<td>High Density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene (HDPE)</td>
<td>160 71</td>
<td>180 82</td>
<td>260 127</td>
<td>295 146</td>
<td>360 182</td>
</tr>
<tr>
<td>Propionate (CAP)</td>
<td>- -</td>
<td>190 88</td>
<td>260 127</td>
<td>295 146</td>
<td>360 182</td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>- -</td>
<td>190 88</td>
<td>290 143</td>
<td>310-325 154-163</td>
<td>330 166</td>
</tr>
<tr>
<td>40% Glass-Reinforced Polypropylene</td>
<td>- -</td>
<td>195 91</td>
<td>270 132</td>
<td>400 204</td>
<td>450 232</td>
</tr>
<tr>
<td>Polysulfone (PSO)</td>
<td>325 163</td>
<td>325 163</td>
<td>375 191</td>
<td>475 246</td>
<td>575 302</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>180 82</td>
<td>185 85</td>
<td>260 127</td>
<td>300 149</td>
<td>360 182</td>
</tr>
<tr>
<td>PTFE/FEP</td>
<td>- -</td>
<td>300 149</td>
<td>450 232</td>
<td>550 288</td>
<td>620 327</td>
</tr>
<tr>
<td>Rigid PVC</td>
<td>140 60</td>
<td>150 66</td>
<td>220 104</td>
<td>280 138</td>
<td>210 154</td>
</tr>
<tr>
<td>Modified Polyphenylene Oxide (mPPO)</td>
<td>- -</td>
<td>210 99</td>
<td>325 163</td>
<td>375 188</td>
<td>400 204</td>
</tr>
</tbody>
</table>

(Courtesy Progelhof and Throne)
The physical properties of products made by rotational molding are usually very different from those produced by injection molding or blow molding because of the long thermal cycles in the former. Because of the versatility and simplicity of this process, parts can vary from a golf ball to a 22.5 gal (85.5 L) agricultural tank. Typical products are fuel tanks, furniture, tilt trucks, industrial containers, modular bathrooms, telephone booths, boat hulls, garbage cans, portable outhouses, light globes, ice buckets, and toys. Examples of process selection for the production of molded parts are in Table 3-12.

EXTRUSION OF PIPE, TUBING, AND PROFILES
In the extrusion of tubes and profiles, the extrusion die is designed to produce an extrudate with the required shape and dimensions. The melt flows through the die and then is cooled to solidify. Pipe and tubing with thick walls is usually cooled through simple open water troughs. If a hollow extrudate has thin walls or if it requires high dimensional accuracy, it is pulled through a calibrator (sizing sleeve) that cools its surface rapidly, thus assuring the required outside diameter. Solid extruded profiles are usually cooled by forced air, water spray, or in water troughs.

Wires and cables are coated continuously by dies that direct the flow of the melt perpendicular to the direction of the axis of the extruder screw’s axis. Cooling of extrusion coated wires and cables is accomplished in a simple water trough.

Extruded products of this type are either wound up onto reels or cut in line to a desired length. Examples of material and process selection for extruded pipe, tubing, profile, and wire products are in Table 3-13.

FOAM PROCESSING
The majority of plastic products are made so that they are essentially homogeneous; any porosity represents a defect. However, sometimes porosity is required. Expanded or foamed materials (polymeric foams) have a significant reduction in density, an increase in heat and sound insulation, softness, and flotation, in addition to a reduction of material consumption.

There are many processing techniques to produce foams, including:

- Production of continuous slab stock by pouring using multi-component foam machines employing impingement mixing.

---

**TABLE 3-12**
Examples of Process Selection for the Production of Molded Parts

<table>
<thead>
<tr>
<th>Product</th>
<th>Primary Process</th>
<th>Secondary Process(es)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive Bumper</td>
<td>Blow molding</td>
<td>Painting</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>RIM</td>
<td>Painting</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>RRIM</td>
<td>Painting</td>
<td>With fiber reinforcement</td>
</tr>
<tr>
<td>Automotive Fuel Tank</td>
<td>Rotational molding</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Beverage Bottle</td>
<td>Blow molding</td>
<td>—</td>
<td>Coextruded parison</td>
</tr>
<tr>
<td>Blister Packaging</td>
<td>Thermoforming</td>
<td>Deflashing</td>
<td>—</td>
</tr>
<tr>
<td>Chair</td>
<td>Compression molding</td>
<td>Deflashing</td>
<td>—</td>
</tr>
<tr>
<td>O-ring (large)</td>
<td>Compression molding</td>
<td>Deflashing</td>
<td>—</td>
</tr>
<tr>
<td>O-ring (small)</td>
<td>Compression molding</td>
<td>Deflashing</td>
<td>Small production volume</td>
</tr>
<tr>
<td></td>
<td>Transfer molding</td>
<td>Deflashing (minor)</td>
<td>Medium production volume</td>
</tr>
<tr>
<td></td>
<td>Injection molding</td>
<td>—</td>
<td>Large production volume</td>
</tr>
<tr>
<td>Serving Tray</td>
<td>Thermoforming</td>
<td>Trimming</td>
<td>—</td>
</tr>
<tr>
<td>Sewer Manifold</td>
<td>Rotational molding</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Toy Ball</td>
<td>Rotational molding</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

**TABLE 3-13**
Examples of Material and Process Selection for Extruded Pipe, Tubing, Profiles, and Wire Products

<table>
<thead>
<tr>
<th>Product</th>
<th>Base Polymer</th>
<th>Secondary Process(es)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible Tubing</td>
<td>PE, PP, PU, PVC</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Insulated Wire</td>
<td>PE, PP, PVC, PU</td>
<td>—</td>
<td>Cross-head extrusion, radiation cross-linking in some cases</td>
</tr>
<tr>
<td>Multilayer Pipe or Tubing</td>
<td>Thermoplastics (many)</td>
<td>Cutting (pipe)</td>
<td>Coextrusion</td>
</tr>
<tr>
<td>Thin-walled Tubing</td>
<td>PE, PP, PVC, PU, TPE, cross-linkable elastomers</td>
<td>Calibration (sizing), cross-linking (if applicable)</td>
<td>Cross-linking mainly by heat</td>
</tr>
<tr>
<td>Weather Stripping</td>
<td>PVC, TPE, cross-linkable elastomers</td>
<td>Calibration, cross-linking (if applicable)</td>
<td>Cross-linking mainly by heat</td>
</tr>
</tbody>
</table>
• Compression molding.
• Reaction injection molding, usually by impingement mixing.
• Foaming in place, by pouring from a dual or multicomponent head.
• Spraying of foamed materials.
• Extrusion of foams using expandable beads or pellets.
• Injection molding of expandable beads or pellets.
• Rotational molding of foams.
• Frothing of foams by introducing either air or a low-boiling volatile solvent.
• Lamination of foams.
• Precipitation foam process, in which a polymer phase is formed by polymerization or precipitation from a liquid that is later allowed to escape.

From the view of mechanical properties, there are essentially two types of foams: flexible and rigid. However, their physical and chemical properties are so varied that discussing them is beyond the scope of this book.

The major industries using flexible foams are:
• Furniture.
• Transportation.
• Bedding.
• Packaging.
• Textile.
• Toys and novelties.

Rigid foams are used in the following industries:
• Building and construction.
• Appliances.
• Tanks/pipes.
• Packaging.
• Furniture.
• Flotation devices.
• Moldings (decorative).
• Business machine housings.
• Food and drink containers.

Polymeric foams are produced in a variety of densities ranging from 0.1 lb/ft^3 (1.6 kg/m^3) to over 60 lb/ft^3 (961 kg/m^3). The choice of polymer for the manufacture of foams depends on the type of foam produced and the process required. The largest volume by far is represented by polystyrene, polyurethanes, and elastomers, although other materials such as PVC, polyolefins (polyethylene and polypropylene), cross-linked polyolefins, ethylene-vinyl acetate, silicones, phenolics, urea-formaldehyde resins, epoxy resins, and fluoropolymers are often used in relatively large volumes for specialized applications. Examples of process selection for a variety of foamed products are in Table 3-14.

<table>
<thead>
<tr>
<th>Product</th>
<th>Base Polymer</th>
<th>Primary Process(es)</th>
<th>Secondary Process(es)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automotive Fascia</td>
<td>PU</td>
<td>RIM</td>
<td>Painting</td>
<td>—</td>
</tr>
<tr>
<td>Automotive Seating</td>
<td>PU</td>
<td>Molding</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Cellular Pipe</td>
<td>PVC, PE, PP</td>
<td>Foam extrusion</td>
<td>Cutting to length</td>
<td>—</td>
</tr>
<tr>
<td>Closed Cell Elastomeric Foam</td>
<td>Polychloroprene (CR)</td>
<td>Two step expansion in mold</td>
<td>Slitting</td>
<td>Cross-linking by Heat</td>
</tr>
<tr>
<td>Commercial Roofing Insulation</td>
<td>PU</td>
<td>Liquid foaming</td>
<td>Slitting</td>
<td>—</td>
</tr>
<tr>
<td>Egg Carton</td>
<td>PS</td>
<td>Sheet extrusion and thermoforming</td>
<td>Trimming</td>
<td>—</td>
</tr>
<tr>
<td>Flexible Packaging</td>
<td>PU</td>
<td>Liquid foaming</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Foam Cups</td>
<td>PS</td>
<td>Bead expansion and molding</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Foamed Slab Stock</td>
<td>PU</td>
<td>Liquid foaming</td>
<td>Slitting</td>
<td>Several processes</td>
</tr>
<tr>
<td>Furniture (for example, chairs)</td>
<td>PU</td>
<td>Molding</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Heat Resistant Gasket</td>
<td>Silicone elastomer</td>
<td>Liquid foaming</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Latex Foam (sheets)</td>
<td>Natural and synthetic latex</td>
<td>Frothing and casting</td>
<td>Slitting</td>
<td>—</td>
</tr>
<tr>
<td>Latex Foam (shaped)</td>
<td>Natural and synthetic latex</td>
<td>Frothing and molding</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Loose Fill Protective Packaging</td>
<td>PS</td>
<td>Bead expansion</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Refrigerator Insulation</td>
<td>PU</td>
<td>Liquid foaming and pouring</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Wall and Roof Insulation Slabs</td>
<td>PS</td>
<td>Foam extrusion</td>
<td>Slitting</td>
<td>—</td>
</tr>
<tr>
<td>Wire Insulation, Cellular</td>
<td>PE</td>
<td>Foam extrusion</td>
<td>Electron beam cross-linking (some)</td>
<td>—</td>
</tr>
</tbody>
</table>
Fiber-reinforced composites is another group of polymer-based materials that differs in several ways from common plastics. The matrix and fiber reinforcement form a composite system with properties not attainable by the individual components acting alone. The fiber reinforcement produces a significant increase in stiffness and strength. The matrix functions as a binder for the fibers, serves as a medium for the transfer of stresses, and provides protection against abrasion and environmental effects.

Fiber-reinforced polymer-based composites are produced by a variety of manufacturing methods. Some of them are identical to those used for nonreinforced plastics (compression, transfer and injection molding, extrusion, calendering, rotational molding, thermoforming), some are standard methods with some modifications (reinforced reaction injection molding [RRIM], structured reaction injection molding [SRIM], resin transfer molding [RTM]), and some are specific to composite manufacturing. These are: hand lay-up, spray-up, vacuum pressure bag and autoclave molding, filament winding, pultrusion, and centrifugal casting. A comparison of common composite process considerations is in Table 3-15.41

HAND LAY-UP
Hand lay-up is a proven, widely used method for the manufacturing of extremely large components. It is highly labor intensive and not suitable for large volume production. Typical products made by hand lay-up are boat hulls, auto and truck body parts, swimming pools, tanks, corrosion resistant equipment, electrical equipment, furniture, ducts, and air handling equipment. Resins used in hand lay-up are liquid general purpose polyesters, vinyl esters and epoxy resins, and glass fibers. Mats and woven fabrics are used as reinforcement.42

SPRAY-UP
Spray-up resembles the hand lay-up in many fundamental aspects but the main difference is the catalyzed resin sprayed onto the mold by a specialized spray-up gun. This gun simultaneously chops continuous reinforcement into suitable lengths and sprays it along with the resin. General purpose polyesters are most commonly used for spray-up. Fiber reinforcement is mainly chopped glass added to the resin, however, sometimes additional reinforcement such as woven roving or woven fabrics are applied.

The products made by spray-up are similar to those made by hand lay-up. The spray-up guns can be used in automated systems and, consequently, allow higher productivity than hand lay-up.

VACUUM BAG MOLDING
In vacuum bag molding a flexible bag is placed over the reinforcement and resin. Vacuum is used to expel the air remaining between the bag and mold surface.

PRESSURE BAG MOLDING
This is a variation on vacuum bag molding where higher than atmospheric pressure is required. A flexible bag is placed over the reinforcement and resin and pressure (up to 50 psi [3 MPa]) is applied to the bag until cure is achieved. The resins used in both vacuum bag and pressure bag molding can cure either at ambient or slightly elevated temperatures.

AUTOCLAVE MOLDING
In autoclave molding, the vacuum and pressure bag molding processes are essentially combined. The mold and composite part, with vacuum applied, is moved into an autoclave for curing. Both heat and external pressure are applied by means of high pressure steam. In three processes, either wet resin systems or pre-pregs (preimpregnated fabrics or fibers) are used. The preparation and lay-up can be done by the combination of both.

Vacuum bag, pressure bag and autoclave molding are used predominantly in producing high-performance aircraft parts and parts for aerospace vehicles.

FILAMENT WINDING
In a filament winding process, a band of continuous resin-impregnated rovings or monofilaments is wrapped around a rotating mandrel and cured to produce an asymmetric hollow part. Resins used in filament winding are mainly thermosets (polyesters, epoxy resins). Recent developments include the use of thermoplastics, which require a major process modification.

Typical products made by filament winding are pressure vessels, oxygen tanks, pipelines, drive shafts, helicopter blades, conical rocket motor cases, and large underground gasoline storage tanks.43

PULTRUSION
Pultrusion is a continuous molding process for producing long, straight structural members of constant cross-sectional area. The reinforcing continuous fibers (rovings) are impregnated by liquid resin in a bath and then pulled through a long preheated die used for both shaping and curing the product.44

Resins used in pultrusion are polyesters, vinyl esters, and epoxies. Recent developments include the use of thermoplastics (for example, polyetheretherketone [PEEK] and polysulfone). The products made by pultrusion are typically solid rods, hollow tubes, flat sheets, and various types of beams.

CENTRIFUGAL CASTING
In centrifugal casting, reinforcements and resin are deposited against the inside surface of a rotating mold. Centrifugal force holds the materials in place until the resin is cured. This method is used for manufacturing large diameter pipes and tanks.45 Examples of process selection for the production of fiber reinforced composites are in Table 3-16.
### Table 3-15: Comparison of Common Composite Process Considerations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Size Limitations</td>
<td>Mold size</td>
<td>Press rating and size</td>
<td>Press rating and size</td>
<td>Press rating and size</td>
<td>Metering equipment</td>
<td>Machine size</td>
<td>Materials/equipment</td>
<td>Equipment</td>
<td>Machine size</td>
</tr>
<tr>
<td>Shape Limitations</td>
<td>Mold</td>
<td>Mold</td>
<td>Mold</td>
<td>Mold</td>
<td>Mold</td>
<td>Lineal</td>
<td>Surface of revolution</td>
<td>Mold</td>
<td></td>
</tr>
<tr>
<td>Production Volume</td>
<td>Low-medium</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Medium-high</td>
<td>Medium</td>
<td>Medium</td>
<td>Low-medium</td>
<td>High</td>
</tr>
<tr>
<td>Cycle Time</td>
<td>30 min–24 h</td>
<td>20 sec–5 min</td>
<td>30 sec–5 min</td>
<td>1½–5 min</td>
<td>30 sec–5 min</td>
<td>10–20 min</td>
<td>n/a</td>
<td>5 min–5 h</td>
<td>3 sec–15 min</td>
</tr>
<tr>
<td>Strength Orientation</td>
<td>Random (usually)</td>
<td>Random to oriented</td>
<td>Random to oriented</td>
<td>Random</td>
<td>With flow</td>
<td>Random to oriented</td>
<td>Highly oriented</td>
<td>Highly oriented</td>
<td>Random</td>
</tr>
<tr>
<td>Strength Category</td>
<td>Medium to high</td>
<td>Low to high</td>
<td>Low to medium</td>
<td>Medium to high</td>
<td>Low to medium</td>
<td>Medium to high</td>
<td>High</td>
<td>Very high</td>
<td>Low to medium</td>
</tr>
<tr>
<td>Typical Draft Angle</td>
<td>2º</td>
<td>1–3º</td>
<td>1–3º</td>
<td>3º</td>
<td>1º</td>
<td>n/a</td>
<td>0–3º</td>
<td>1º</td>
<td></td>
</tr>
<tr>
<td>Minimum Inside Radius (in.)</td>
<td>0.25</td>
<td>0.06</td>
<td>0.06</td>
<td>0.125</td>
<td>0.125</td>
<td>0.25</td>
<td>0.060</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Ribs</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (flow direction)</td>
<td>Secondary operation</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Bosses</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Undercuts</td>
<td>Yes</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Lineal</td>
<td>No</td>
<td>Possible</td>
</tr>
<tr>
<td>Molded Holes</td>
<td>Possible</td>
<td>Yes</td>
<td>Yes</td>
<td>Possible</td>
<td>Yes</td>
<td>Yes</td>
<td>Lineal (hollow)</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Built-in Cores</td>
<td>Yes</td>
<td>Possible</td>
<td>Possible</td>
<td>Possible</td>
<td>Yes</td>
<td>Yes</td>
<td>Lineal</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Metal Inserts</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Lineal</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Finished Surfaces</td>
<td>One</td>
<td>Both</td>
<td>Both</td>
<td>Both</td>
<td>Both</td>
<td>Both</td>
<td>All</td>
<td>One</td>
<td>Both</td>
</tr>
<tr>
<td>Surface Appearance</td>
<td>Fair to good</td>
<td>Good to excellent</td>
<td>Good to excellent</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Fair to good</td>
<td>Poor to good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Gel-coat Surface</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Surfacing Mat</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Combination with Thermoplastic Liner</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Translucency</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Tool Cost</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low to medium</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Capital Equipment Cost</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low to medium</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

(Courtesy SPI Composites Institute, Introduction to Composites Reference Handbook)
## PROCESSING LIQUID POLYMERIC SYSTEMS

The vast majority of plastic products is produced by shaping a polymeric melt with relatively high forces at relatively high temperatures. However, there are manufacturing methods based on liquid raw materials. Some of them are very thin, with viscosities similar to that of water, others are syrupy in consistency or thick enough to require heat for processing. There are even some products that are solids at ambient temperatures and require melting prior to use. There are essentially three groups of polymeric materials processed as liquids: solutions in volatile solvents, water-based systems and liquid polymers, prepolymers, and reactants. This division is rather crude, because there are systems that do not fit these categories (for example PVC pastes, water based systems with co-solvents, polymers processed with latent solvents or water based prepolymer, or reactants).

### PROCESSING OF POLYMER SOLUTIONS

A great number of polymers can be dissolved in volatile solvents to form solutions of varied viscosities. Such solutions are utilized to impregnate fabric, form thin films by casting on carriers, or to produce dipped products. A significant amount of polymers in the form of solutions is used for paints, sealants, coatings, and adhesives.

A special case in this category is systems consisting of solid polymers such as polyvinyl fluoride and latent solvents (for example, propylene carbonate) with low volatility. Such mixtures form thick pastes used mainly for film casting or paste extrusion.

Another group of polymer and liquid nonvolatile plasticizers is plastisols consisting of PVC and varied amounts of plasticizers. These represent a large segment of the flexible PVC technology. The products made from plastisols are films, sheets, extruded goods, wire and cable, molded parts, rotationally molded goods, dipped products, coated fabrics, flooring, and foams.

The current trend is to replace systems based on volatile organic compounds (VOCs) by water-based systems, which are much more friendly to the environment.
PROCESSING OF POLYMERIC LATEXES AND SUSPENSIONS

Polymers produced by emulsion or suspension polymerization can be maintained as water-based latex dispersions or suspensions. That is, in the same state as the polymerization process. Sometimes special stabilizing additives are used. Such water-based systems are gaining in importance over the past decade mainly because of their positive environmental impact. Another advantage is that the molecular weight of the polymer has a negligible effect on the viscosity of the latex or dispersion. This is often important in the production of films, for example, where high molecular weight is desirable to assure adequate physical properties of the final product.

Water-based systems often require compounding, such as addition of stabilizers, surfactants, defoamers, cross-linking agents, pigments and colorants, flame retardants, plasticizers, co-solvents, viscosifiers, tackifiers, etc.

In such cases, solid additives, insoluble in water, are frequently added predispersed and water insoluble liquid additives are added as emulsions.

Products made from such systems include impregnated and coated fabrics, cast films, fibers, foams, adhesives and sealants. A significant volume of water-based polymeric systems are used in many paints and coatings such as: polyvinyl chloride (PVC), polyvinylidene chloride (PVDC), acrylics, elastomers (natural, styrene butadiene rubber [SBR], nitrile rubber [NBR], polychloroprene, and fluoroelastomers), polyurethanes, epoxies, and fluoropolymers (polytetrafluoroethylenes [PTFE], polyvinylidene fluoride [PVDF] and polychlorotrifluoroethylene [PCTFE]).

PROCESSING OF LIQUID POLYMERS AND PREPOLYMERS

Some polymeric materials are available in liquid form. These may be monomers, oligomers, prepolymer or two or more liquid components that may react into a rigid or rubbery product with considerably higher molecular weight.

The chemical reactions involved in processing of such liquids can be:

- Polymerization.
- Polycondensation.
- Cross-linking.
- Chain extension (sometimes combined with cross-linking).

Processing methods used for such liquid materials are:

- Reaction injection molding (RIM).
- Reinforced reaction injection molding (RRIM) and structural reaction injection molding (SRIM).
- Resin transfer molding (RTM).
- Filament winding.
- Pultrusion.
- Coating, often combined with ultraviolet (UV) or electron beam (EB) cure (cross-linking).
- Casting (batch or continuous).
- Rotational molding.
- Hand lay-up, spray-up, bag molding, autoclave molding.

This list is not complete since the field is constantly growing. A large proportion of liquid polymers, monomers, oligomers, and prepolymer is used in two-component packages. Such systems may be used for processing by some of the methods mentioned (coating, casting, RIM), or may be distributed as coatings, sealants, adhesives, encapsulating compounds, or repair materials.

Examples of polymers processed by the listed methods are polyesters, vinyl esters, epoxies, methyl methacrylate, mixtures of polyethers, polyesters or hydroxylated butadienes with isocyanates, polyurethane prepolymers, and systems based on polysulfides. Examples of process selection for processing liquid polymeric systems are in Table 3-17.

<table>
<thead>
<tr>
<th>Product</th>
<th>Base Polymer</th>
<th>Primary Process</th>
<th>Secondary Process(es)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coated Fabrics</td>
<td>PVC plastisol</td>
<td>Coating</td>
<td>Lamination and/or slitting</td>
<td>Some are cross-linked, mainly by heat</td>
</tr>
<tr>
<td></td>
<td>PVC latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CR latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NBR latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acrylic latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EVA latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VA latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyurethane (solutions or latex)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluoropolymer dispersions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silicone elastomers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Encapsulating Compounds</td>
<td>Silicone elastomers</td>
<td>Compounding</td>
<td>Packaging</td>
<td>One or two part systems</td>
</tr>
<tr>
<td></td>
<td>Epoxy resins</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyurethane prepolymers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gaskets</td>
<td>Silicone elastomers</td>
<td>Casting</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Protective Gloves</td>
<td>PVC plastisol</td>
<td>Dipping and cross-linking</td>
<td>—</td>
<td>Cross-linking by heat (NR, CR, NBR only)</td>
</tr>
<tr>
<td></td>
<td>PVC latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NR latex</td>
<td></td>
<td></td>
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<td>CR latex</td>
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<td></td>
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<tr>
<td></td>
<td>NBR latex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toys</td>
<td>PVC plastisol NR latex</td>
<td>Casting or rotational molding</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>
THE VINYL DIP MOLDING PROCESS

Vinyl dip molding is a manufacturing process that involves heating a pre-shaped metal form and submerging it into a liquid PVC compound (plastisol). The metal form is then removed from the tank of plastisol and put into an oven to cure the material that has adhered to the form. After curing, it is cooled and removed from the form as a finished product.

Dip molding of plastics entails only modest tooling and set-up costs, yet the process often competes with high-production methods requiring costly dies and elaborate machinery. In addition, today’s sophisticated dip molding equipment has removed the need for much of the manual skill formerly required to make parts. Dip molding fills an important niche in the spectrum of plastic molding processes. It overlaps somewhat with injection molding for large production requirements (as do many processes, for that matter), but it also can produce a dozen or a thousand parts economically. Some shapes not producible by other processes can be molded readily by dipping. In addition, the quality of dipped parts has improved considerably with the development of formulations that combine quick pickup and rapid runoff characteristics.

Parts made by dip molding can be of any size, limited only by the size of available equipment. However, the dimensions of most production parts seldom exceed 18 in. (46 cm). Mold costs are very low compared with those of other plastic molding processes. Lead time is as short as a week or two, and the process produces glossy, stress-free parts with no parting line.

Dip molding also has limitations, of course. Parts must be flexible and hollow and must consist of a continuous surface having at least one open end. Wall thickness must be essentially uniform, and that thickness cannot be controlled to the extent that it can in a matched-metal die.

Material selection for dip-molded parts is limited to the vinyl plastisols—liquid compounds of polyvinyl chloride (PVC) resin dispersed in plasticizers and usually including stabilizers, fillers, pigments, and other additives. However, because formulation of the plastisols can be widely varied, this single material family can provide a broad range of properties.

THE PROCESS

The dip molding process is one of the simplest methods for making plastic parts. A metal mold shaped to the internal dimensions of the part is heated and immersed in plastisol, which gels and adheres to the mold surface. After a brief dwell, the mold and the deposited PVC are withdrawn from the liquid and heated to cure the compound into a solid state. The molding, which has a natural high-gloss finish, is cooled in a water bath and, while still warm, is stripped from the mold, which is immediately reheated and sent through the cycle again.

While the process is simple and implemented easily with low-cost capital equipment, today’s production dip molding shop features highly automated systems. For example, equipment now in use provides quick-change means for both molds and plastisol materials, and cycle time has been reduced to the range of four to five minutes for most parts. Some new machines have the versatility to produce more than 40 different parts from any of six different plastisol formulations during the same production run. Tooling for dip molding consists of a male mold only. The number of molds made for a given part depends on how many parts are required in a given amount of time. Most molds are fabricated in aluminum and are usually cast from a wooden pattern. Prototype parts can be made in short order—sometimes requiring only a week—and production runs of only 40 to 50 parts are usually economically practical. Another advantage of the simple one-piece tooling is that design changes are readily implemented by modification of the easy-to-machine aluminum molds.

Typical secondary operations on dip-molded parts include varnish application as well as printing procedures. The parts are readily punched or trimmed to suit design requirements, usually by automated equipment.

Parts that require decoration, identification, or instructions are printed by various methods. Flat parts are usually printed by silkscreen or hot foil techniques; contoured moldings are often processed by pad transfer printing, a relatively new method that uses a soft silicone pad. Any of these printing methods can be used along with an embossing operation, which is done with a heated, patterned branding plate.

Grips and sleeves are among the most typical applications for the dip molding process. However, the process can also be used to manufacture bellows and boots, protective seals and covers, intricately-designed ducts, as well as medical, furniture, and automotive components.

Advantages and Limitations

Dip molding has the advantages of low tooling costs, short lead times on tooling, the ability to vary surface texture of parts without using different tooling, and the ability to mold complex hollow shapes. Because PVC materials are often used, parts are weather resistant, have good dielectric properties, and can be made in many colors. PVC may not withstand high temperature, however. Parts larger than 19 in. (48 cm) in diameter or 22 in. (56 cm) long are difficult to dip mold. Dimensional control of the outer surface of the dip molded part is not easily maintained.

SELECTION CRITERIA/ALTERNATE PROCESSES

From a costing perspective, dip molding fills an important niche among the other molding processes. Dip molding is most competitive with injection molding, but occasionally one can choose blow molding or extrusion versus dip molding.

Compared to the other molding processes, one of the distinct advantages of dip molding is low-cost tooling. This is because the atmospheric pressure process allows less expensive tooling; high-pressure molding equipment is not required. In most applications, dip mold tooling consists of machined aluminum mandrels that are made for a fraction of the cost of complicated injection molds. Depending on part configuration, sometimes castings are used instead of machined forms. Prototypes are produced for virtually no cost, and the ability to make modifications makes this the perfect process when design concepts are not finalized.

From a piece price perspective, dip molding is comparable with injection molding or more expensive, depending on the particular part configuration and the need for secondary operations. Generally, the smaller the part, the more competitive the dip molding process. If secondary operations, such as punching or trimming are involved, dip molding becomes more expensive because these require separate operations. With injection molding they can be molded into the part.

Another factor that can make dip molding more expensive is the fact that vinyl dispersion resins used in dip molding are more expensive than the injection molding grades of vinyl. This cost differential tends to be relatively minor, however, because of the light part weight in most dip molded applications.

There are numerous benefits of the simple yet versatile dip molding process. Many parts that are now injection molded can be dip molded at a considerable savings in time and money. Table 3-18 illustrates the advantages of dip versus injection molding.
SECONDARY MANUFACTURING PROCESSES

Most plastic products do not require additional processing since they are produced in the required shape, with required dimensions and mechanical properties. However, certain products need additional processing, such as deflashing, machining and drilling, cutting, calibration, slitting, stretching, painting, surface treatments, metallization, and printing.

DEFLASHING
Required when the molded part has flash, that is, excess material from the mold. There are many methods, like cutting, grinding, rolling in drums (sometimes at cryogenic temperatures).

MACHINING
An operation necessary when a very close dimensional tolerance is specified, which is not achieved by simple molding or extrusion. Sometimes the primary operation does not permit undercuts, grooves, or special shapes, and machining is the only way to accomplish that. Drilling is done when it is not possible to make holes during the primary manufacturing process.

CUTTING
An operation done in line with the primary operation such as extrusion, pultrusion, and calendering, or off line. Its purpose is to obtain a product with a specified length.

CALIBRATION (OR SIZING)
Frequently a downstream operation in an extrusion line for plastic pipe, tubes and profiles. Its purpose is to solidify the extrudate, control its dimensions and make it strong enough to resist the take-off forces.

SLITTING
An operation used mainly for coated fabrics, films, and sheets where a certain width is required. Examples are films, reinforced tapes, and sheets. Slitting widths range from fractions of an inch up to several feet.

STRETCHING
Used either to produce a thinner film or sheet or to introduce orientation or crystallinity within the sheet or film. The stretching is done in the longitudinal (machine) direction, transverse (cross-machine) direction, or both directions (biaxial orientation). The longitudinal orientation is done mainly by means of a set of rollers with increasing surface speeds. The transverse orientation is performed by clips moving on chains in a tenter frame having a continuously adjustable width. A tenter frame has several heated zones with independently adjustable temperatures. Biaxial orientation can be done either in two steps with longitudinal orientation first followed by transverse orientation, for example, or simultaneously on special equipment. A simplified diagram of an orientation line is in Fig. 3-5.

SURFACE FINISHES
Other specialized surface treatments of plastics are:
- Corona discharge, plasma treatment, chemical etching.
- Electroplating, sputtering.

![Fig. 3-5 A simplified diagram of an orientation line. (Courtesy Marshall and Williams Co.)](image-url)
• Vacuum metallization
• Printing
• Laser marking
• Painting. Usually required only if the product material is not the desired color. Sometimes painting can offer protection against UV radiation or a corrosive environment.

ASSEMBLY
In some cases, the final product is assembled from several components. There are many methods to do that but the most frequently used are: heat sealing, ultrasonic welding, impulse and radio frequency (RF) sealing,54,55 the use of adhesives and solvents, and finally, mechanical methods (screws, rivets, pins).

PROCESSES FOR ALTERING MATERIAL PROPERTIES
Occasionally special heat treatment of semifinished or finished products is necessary to alter their mechanical properties or appearance. Such procedures are annealing and quenching, mainly used for amorphous or semicrystalline thermoplastics.

Annealing is done by heating the material at a specific temperature for a definite period of time and then cooling it slowly to room temperature. This process is used to control the degree of crystallinity and/or orientation of the material or to remove internal stresses in the product introduced by the primary processing. The result of annealing is an improved impact resistance and reduced tendency to crazing and cracking in service.56

Quenching is a sudden cooling of a material following melting or heating to a specific temperature after the primary process (extrusion, molding). The main purpose of this operation is to control crystallinity.

Depending on conditions and the nature of the polymer, quenching either can prevent crystallization, which reduces stiffness of the material, or produce a large number of fine crystals, which often improves the product's clarity.57 Quenching is most effective for thin products (films and fibers). In thick parts it affects mainly the outer skin of the product.

References
5. Progelhof and Throne, p. 400.
17. Progelhof and Throne, p. 410.
27. Berins, p. 244.
29. Introduction to Composites, pp. 40-41.
34. Progelhof and Throne, p. 429.
35. Introduction to Composites, p. 51.
37. Berins, p. 429.
38. Modern Plastics Encyclopedia, p. 244.
41. Introduction to Composites, p. 59.
42. Introduction to Composites, p. 28.
43. Introduction to Composites, p. 53.
44. Introduction to Composites, p. 53.
47. Introduction to Composites, p. 508.

Encyclopedias and Handbooks

Technology Monographs
Kopsch, H., Kalandertechnik (Munich: Hanser, 1978) in German.


 **Dictionaries (English)**


 **Dictionaries (Other Languages)**


 **Periodicals**

 Advanced Composites (Eugene, OR: Advanstar Communications).


 Kunststoffe/plast europe, (Munich: Carl Hanser Verlag, bilingual edition, German/English).


 Paper, Film and Foil Converter (Chicago, IL: Maclean Hunter Publishing Co.).

 Plastics Compounding (Eugene, OR: Advanstar Communications).

 Plastics Design Forum (Eugene, OR: Advanstar Communications).

 Plastics Engineering (Brookfield, CT: Society of Plastics Engineers).

 Plastics Machinery and Equipment (Eugene, OR: Advanstar Communications).

 Plastics News (Detroit, MI: Crain Communications).

 Plastics Technology (New York: Bill Communications).

 Plastics World (Melville, NY: PTN Publishing Co.).
Designing molds is an iterative process. Initial decisions include gate location, parting line, mold layout, and insert location and sizes. Moving through the problem-solving stage, the designer often encounters issues that inevitably change some of the initial decisions. The sequential design steps must then be retracted. Successful designs require input from the plastic-part end user, the molder, and the moldmaker. Molded material properties and project cost limitations also govern tool design.

This chapter is a general guide for designing molds. Although the discussion is biased toward plastic injection molds, there are principles that apply to other processes as well. Although each design demands a slightly different approach, the following items are required in every case:

- A well designed plastic part.
- A properly designed mold built with quality workmanship.
- A knowledgeable molder.

PLASTIC PART DESIGN BASICS

Material

The molding material influences many design decisions. Most materials used in injection molding require the use of a cooled mold. However, some plastics, such as polyetherimide or polyphenylene sulfide, may require a heated mold. Even though running a colder mold may improve cycle time on certain plastics, the part from a colder mold generally has a higher level of residual stresses. While this is acceptable for some parts, it may cause part failure in demanding applications. It is more important to use a large volume of coolant, flowing through properly placed lines, to remove heat from the molded material.

Molds for polyvinyl chloride (PVC) parts demand special consideration. The extremely corrosive nature of PVC requires mold materials that resist attack from this and similar plastics. Appropriate mold materials include stainless steel, beryllium copper, and plated steels.

Flexible-material parts featuring threads or undercuts are often molded and demolded without unscrewing mechanisms or side actions. Some of these flexible materials include the polyolefins, such as polypropylene and polyethylene, flexible PVC, liquid silicone, and members of the thermoplastic elastomer family. For this reason, the designer should refer to the material specification sheets to determine the molded material properties.

Walls

A uniform wall thickness in the main body of a part provides the best performance, minimizing problems of nonuniform shrinkage, sink marks, voids, and residual stresses. In cases where wall thickness changes are necessary, gradual changes minimize large temperature changes during plastic solidification. Thick part sections are cored out, as shown in Fig. 4-1.

A wall draft angle of 1–3° facilitates ejection. However, depending on the molded material, much lower angles (as low as 0.125°) may suffice. A draft of 1–1.5° per 0.001 in. (0.025 mm) of texture depth is used on textured surfaces.

Radii

Sharp corners on the part should be minimized. If radii are not specified on a product drawing, the moldmaker will leave sharp corners in the mold. Internal part radii (external mold radii) often create more work for the mold builder and may not be added unless specified. Internal part radii of 0–0.005 in. (0–0.13 mm) can drastically reduce Izod impact strength. A 0.020 in. (0.51 mm) internal part radius can increase the Izod impact strength of a nylon specimen by a factor of three.

An internal radius of approximately 50% of the wall thickness is best, when conditions permit. Values above 60% provide a minimal improvement. An external radius equal to 150% of the wall thickness ensures an even wall thickness. At the intersection of a wall and a rib, a radius that is 25% of the wall thickness is recommended (see Fig. 4-2).

Ribs

Ribbing is used as a substitute for thick walls when strength calculations require walls thicker than recommended. As previously mentioned, a radius at the rib-wall intersection improves part performance. Furthermore, a rib thickness that does not exceed two-thirds of the wall thickness minimizes sink marks (surface depressions) and other stresses.

With most materials, however, some amount of sink is unavoidable. Texturing the wall outside the rib intersection is one method of masking sink marks. Molding a decorative rib or other protrusion, such as engraving, on the outside wall where the sink is exposed serves the same purpose.

The Contributors of this chapter are: Drew Fleming, Director, The Society of the Plastics Industry, Inc. (SPI), Moldmakers Division; Tom Harcourt, President, Harcourt & Associates, Inc.; Rocky Huber, CMfgT, Mold Engineer, Ivanhoe Tool & Die Co., Inc.; Dennis Ferguson, Ph.D., Molding Research Engineer, 3M Company; Peter Rancourt, Account Manager, Nutmeg Chrome Corporation; Peter Rigby, GE Superabrasives–France; William Tobin, President, WJT Associates; Brett Young, GE Superabrasives–USA.

The Reviewers of this chapter are: Gerald Hobson, Hobson Brothers; Fred Steil, Mechanical Engineering Manager, D-M-E Company.
**Bosses**

A boss height that is at least 2.5 times the boss inside diameter is recommended. The outside diameter is generally twice that of the inside diameter, and the inside diameter is equal to the pitch diameter of the self-tapping screw used with it. Separate the boss from the wall to maintain wall uniformity. However, if the boss is connected by a rib, the previous product design guidelines apply.

**Tolerances**

Part tolerances affect many mold design aspects. The designer must evaluate the tolerance with respect to part geometry, molded material, and action of the tool. The choice of plastic again significantly affects the design approach. Material such as polycarbonate has uniform and predictable shrinkages of approximately 0.6%. Other materials, such as the olefinic thermoplastic elastomers, have widely varying shrinkages that depend on part thickness, orientation to flow direction, and mold temperature.

In cases that require close tolerances, steel-safe the mold dimensions (that is, mold cores [male components] are oversized and cavities [female components] are undersized). Once the mold is completed and run for sampling and the plastic parts are inspected, mold components are then machined according to measured results. On close-tolerance pieces, the additional machining cost is minimal compared to the potential costs of reducing cavity sizes, increasing core sizes, or changing mold component locations.

When shrinkage and other performance factors are unknown, a prototype tool is often built first. This permits determining these unknowns for a fraction of the cost of a production tool. A prototype tool also allows the manufacturer to market test its product and supply that product until production tooling is completed.

Wall thickness tolerance is commonly misunderstood. This parameter is often specified as a nominal dimension with a plus/minus tolerance. While the part may be functional within these ranges, cores that are off center with respect to the cavity cause additional problems.

If the mold for this part yields a wall thickness variation caused by off-center cores, several things occur: The plastic flows through the gate (the orifice at the end of the runner that leads the plastic directly into the cavity) and fills the cavity through the path of least resistance. This causes the material to flow primarily down the side with the greater wall thickness, further causing pressure to build on the opposite side of the core. The core is further pushed toward the side with the thinner wall.

The thicker-wall side of the part shrinks more than the thinner side. This condition is characterized by the banana-shaped distortion that results from the uneven shrinkage. Continued bending and stressing of the core in this manner can cause the steel to crystallize and eventually fail.

A total variation due to eccentricity of no more than 5% of the specified wall thickness is preferred. For a nominal wall thickness of 0.060 in. (1.52 mm), this would allow a tolerance of ±0.0015 in. (±0.038 mm). This also tightens the tolerance on thin-walled parts, where a uniform wall is of the utmost importance. A thin walled part of 0.020 in. (0.51 mm) thickness requires an accuracy of ±0.0005 in. (±0.013 mm) for successful molding.

In addition to wall thickness, the concentricity of the bores for cavities, and cores with themselves and the gate is extremely critical when top-center gating long, slender, unsupported cores. Industry standards for tolerance are specified in Standards & Practices of Plastics Molders. A sample sheet for polystyrene is shown in Fig. 4-3. These data sheets, along with other pertinent information, are available from material suppliers.

**Other Features**

When a part has a hole through it, there is a flow line, or weld line, on one side of the part where the material flowing around the core comes together. This condition exists even if the core protrudes only two-thirds of the way through the wall, for example.

In filled materials, strength calculations are computed at the weld line on base material properties; little filler crosses the weld line boundary. Weld lines in load-bearing areas should be avoided. Unfilled materials are also weaker at the weld line because the plastic is colder when it comes together and it may pick up moisture or other contaminants as it surrounds the upstanding coring. A 15% strength reduction allowance is generally adequate.

**MOLD DESIGN BASICS**

**Parting Line**

Determining the parting line (P.L.) location is one of the first mold design decisions. This is the location on the part and in the mold where the two halves of the mold separate. On a side-action tool, there may be other lines of separation where components come together, but the level at which the sides of the tool split is generally accepted as the parting line location. This surface may be flat or irregular, as shown in Fig. 4-4.

There are many factors that influence parting line location and shape. A flat or regular parting line, usually the least expensive, is most common. Placing the parting line in a location where the halves form the same outside surface of a molded part is more difficult for the mold builder and consequently more expensive (see Fig. 4-5).

The parting line location usually permits demolding the product using no side actions or secondary operations. For this reason, tapers molded on the part often control the parting line location so that no undercuts are ejected. The parting line location also facilitates molding radii and/or sharp corners in the part. Ease of mold machining is another important consideration when choosing an appropriate parting line.
### Standards & Practices of Plastics Molders

<table>
<thead>
<tr>
<th>Drawing Code</th>
<th>Dimensions (Inches)</th>
<th>Plus or Minus in Thousands of an Inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>A = Diameter</td>
<td>0.000</td>
<td>Comm. ±</td>
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<tr>
<td></td>
<td>0.500</td>
<td>Fine ±</td>
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<tr>
<td></td>
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</tr>
<tr>
<td>B = Depth</td>
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<td></td>
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<td>C = Height</td>
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<td>D = Bottom Wall</td>
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<td></td>
<td>0.126 to 0.250</td>
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<td></td>
<td>0.251 to 0.500</td>
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<td></td>
<td>0.501 &amp; over</td>
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<td>E = Side Wall</td>
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<td>0.251 to 0.500</td>
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</tr>
<tr>
<td></td>
<td>0.501 to 1.000</td>
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<td>F = Hole Size Diameter</td>
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<td>0.251 to 0.500</td>
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<td>G = Hole Size Depth</td>
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<td>3.001 to 6.000</td>
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<td>H = Corners, Ribs, Fillets</td>
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<td>Surface finish</td>
<td>(See note #7)</td>
<td></td>
</tr>
<tr>
<td>Color Stability</td>
<td>(See note #7)</td>
<td></td>
</tr>
</tbody>
</table>

**Reference notes**

1. These tolerances do not include allowance for aging characteristics of material.
2. Tolerances are based on 0.125 in. (3.18 mm) wall section.
3. Parting line must be taken into consideration.
4. Part design should maintain a wall thickness as nearly constant as possible. Complete uniformity in this dimension is sometimes impossible to achieve. Walls of nonuniform thickness should be gradually blended from thick to thin.
5. Care must be taken that the ratio of the depth of a cored hole to its diameter does not reach a point that will result in excessive pin damage.
6. These values should be increased whenever compatible with desired design and good molding techniques.
7. Customer–molder understanding is necessary prior to tooling.

*Fig. 4-3 Production tolerances for polystyrene parts. (Courtesy The Society of the Plastics Industry, Inc.)*
A witness line, or flash line, is invariably present on the molded part at the parting line regardless of how accurately the mold halves are aligned. For this reason, parting lines are not located on diameters or surfaces where close tolerances are required or where the witness line would be aesthetically displeasing. A simple parting line is best because it is easier to machine and repair than an irregular design. In summary, the parting line shape and location are determined by part geometry, gate and ejection type and location, tolerances required, machining method, venting system, mold type, and cost.

Inserts

Inserts are used in mold design and construction for several reasons, including cost, ease of manufacture, repairability of the mold, necessity, and ease of molding. Machining a hole and installing a standard, off-the-shelf core pin is generally less expensive than machining a core from the existing stock standing in the cavities. With an inserted design, if the core pin breaks during molding, the mold is easier to repair. Other times there is no feasible way to manufacture the mold without using inserts. Changes in the availability and reliability of electrical discharge machining (EDM) over the last 25–30 years have reduced the reliance on inserts to produce complex shapes. Wire EDM machines can produce complex male and female pieces that fit together accurately, and this equipment should be used when appropriate.

Insert use is limited only by the product design and the ingenuity of the mold designer and moldmaker.

Side Actions

Side-action molds are common in the injection molding industry; side actions release the undercuts on the outside of molded parts. Male threads on plastic parts are most often produced by this method.

Side actions are activated by one or more of the following methods: cam pins, cylinders, pulling devices, or springs. Side-action molds are more expensive to build and require more maintenance than conventional tooling.

Spring-activated side actions are generally undesirable, because control of their movement is limited. These devices can be used to remove small core pins, but the mold must be kept clean to assure their reliable operation. The springs are designed to feature an internal pin. This contains the coils and prevents subsequent damage when the spring inevitably breaks from fatigue.

Figure 4-6 shows a basic cam slide–cam pin arrangement. The cam pin is fixed to a plate that moves relative to the cam slide. This relative motion causes the cam to slide along the length of the cam pin, creating the desired motion.

A hydraulic cylinder connected to the cam slide and mounted to the outside of the mold is often used to activate the side action. Pneumatic cylinders may be used, but they generally produce less force and their movements are more difficult to control compared to their hydraulic counterparts. Regardless of whether a cam pin or cylinder is used, the cam slide is backed up by a cam lock to resist the forces caused by the injection pressure.

Provisions that keep the slide from moving while disengaged from the cam pin include springs, spring-loaded devices, and off-the-shelf clamps.

Material Path

The molten plastic material first enters the mold at the sprue. A sprue is the main feed channel connecting the machine nozzle with the runners. The minimum required opening in the sprue bushing, often referred to as the O dimension, is specified in the material data sheets. Once the material enters the sprue, it is deliv-
ered to the cavities in one or more of the following ways: through a runner passage in a conventional two-plate mold (Fig. 4-7), via a runner passage and sprue drops in a three-plate mold (Fig. 4-8), through a heated sprue bushing to a runner system, through a heated sprue directly into the cavity, through an insulated runner to the cavities through an internally heated manifold and probes, through an external heated manifold to the runner, or through heated nozzles directly to the cavities.

Two-plate Mold

The two-plate mold, shown in Fig. 4-7, is the most common and generally least expensive mold type. Plastic enters the sprue bushing, passes through the runner system to the gate, and finally fills the cavity. The material enters the cavity, adhering to the cavity and core walls while flowing within itself. Those surfaces in contact with the steel solidify first, and as the material shrinks toward its outer skin, more material passes through the gate into the cavity to fill the void in the center of the part until the gate freezes off. The frozen gate holds the cavity pressure until the plastic is solidified.

The mold then opens, and the molding machine activates its knockout mechanism, causing the ejector system to demold the parts. The empty mold is closed and begins another cycle.

A heated sprue bushing is often used in a two-plate mold, particularly in cases where the cavity plate is very thick. The heated sprue bushing allows several advantages:

- A portion of the plastic in the sprue remains molten within the bushing, requiring less regrinding.
- Preheated molten material is available for the next shot of parts.
- Because the sprue bushing’s opening is tapered larger toward the parting line of the mold, a conventional sprue bushing causes the plastic cross-section at the sprue mouth to become so large that it can control the cycle of the mold.

Three-plate Mold

The three-plate mold is shown in the closed and open positions (see Figs. 4-8 and 4-9). This construction is primarily used for parts that are top-center gated.

In this design, plastic enters the sprue bushing as before, travels through a trapezoidal runner cut in the runner plate, and passes through the sprue drop to reach the gate. Two extra plates are usually required for this construction. The first parting line is between the pin plate and the runner plate. The sucker pin pulls the sprue drop out, which causes the gate to break or separate. Once the travel for stripper bolt a is met, the next parting line is between the A and B halves of the mold. This separation can be caused by shoulder bolts or, when the opening is too large or there is insufficient room for shoulder bolts, by straps, chains, or other external mechanisms.

The cavity plate pulls the pin plate forward; this strips the sprue drops from the sucker pins. When removing runners with a picker or robot, the runner system should remain in the mold. This is achieved by machining a small counterbore in two of the top sucker pin bushings. The counterbore must not be so deep that it prevents the sucker pins from extracting the sprue drops.

Once the plastic has entered the cavity, the runner is stripped, and the mold is fully open, the tool performs in the same manner as a two-plate mold. The movement of the runner and pin plates can similarly be mechanized by using hydraulic or pneumatic cylinders mounted internally or externally.

Hot Sprue Bushings

There are several types of heated sprue bushings available in a variety of sizes. They are generally used in one of two ways. In molds with an exceptionally thick A half, a heated sprue bushing may be used to bring the plastic to the parting line runner. This also reduces the amount of material that is reground. In the second application, used in single-cavity tools, the sprue acts as the gate, requiring a secondary operation to remove the sprue from the part. On smaller parts, a heated sprue bushing is used to gate directly into the part; this is known as runnerless molding.

When using heated sprue bushings, the contact areas between the bushing and the mold and components should be minimized. This prevents the mold from acting like a heat sink, which can tax the bushing’s ability to generate adequate heat and melt the plastic. The bushing is ground short enough so that, even after thermal expansion, a washer approximately 0.020 in. (0.51 mm) thick can
be molded on its top surface. This reduces heat transfer and guarantees that the bushing is not crushed from contact with the B side of the tool.

Number of Cavities

The number of mold cavities is determined by the company or person who is buying the parts or by the molder. It is a compromise between tooling and manufacturing costs and part cost. A mold with a larger number of cavities can usually produce parts at a lower piece cost when a large quantity of the item is required. From the molder’s point of view, the number of suggested cavities is based on an empirical rule that the yearly activity of parts is divided into an ordering frequency of about every 50 days; this 50-day requirement should be produced in 200 hours of three-shift operation.\(^4\) For example, if the yearly activity is 100,000 pieces, the 50-day requirement (based on a 250-day year) is 20,000. For an estimated cycle of 60 shots/h (60 pieces/cavity/h), the number of cavities required is as follows:

\[
20,000 \text{ pieces} \div 200 \text{ h} = 100 \text{ pieces/h required}
\]

\[
100 \text{ pieces/h} \div 60 \text{ pieces/cavity/h} = 1.67 \text{ or 2 cavities.}
\]

Several considerations are necessary when selecting the number of cavities. When a low volume of molded parts is required, a single-cavity tool often suffices. These tools are often built with prototype-quality materials to reduce costs. When a group of similar parts is run, as with a right- and left-hand assembly, a family tool is...
built. This type of tool has more than one cavity and makes more than one type of part at a time.

In these cases, one or more cavities of each part are contained in the same mold frame. These cavities may be run together, or the mold may feature runner shutoffs that allow molding parts individually.

**Shrinkage**

The molten plastic is forced into the mold cavity, where it is held until it solidifies. As the cooling takes place, both inside and outside of the mold, the cooled material becomes smaller than the core and cavity that formed it. This shrinkage is volumetric, since the specific volume of a substance decreases with temperature. The mold design must incorporate a shrinkage factor that is based on the molded material.

For materials with relatively stable and predictable shrinkages (0.8–1.0%), cured sizes are accurately predicted in the literature. Plastics with shrinkage rates of 1.0–1.5% behave predictably when the parts are top-center gated. However, with higher-shrinkage materials, the shrinkage is best determined by previous experience, interpolating material manufacturers’ charts, or building a prototype tool.

Higher-shrinkage materials have a different shrinkage factor in the flow direction compared to that perpendicular to the flow in the cavity. This becomes the principal difficulty in predicting

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Fig. 4-9 Three-plate mold runner passage (opened).
shrinkage in edge-or subgated cavities. Crystalline materials continue shrinking for days (and up to a year) after molding. Although 95% of the shrinkage occurs in the first 24 hours after molding, many quality control departments require monitoring shrinkage for up to 72 hours.

Shrinkage of filled materials often varies widely within a cavity due to fiber orientation. Other materials, such as glass-filled polycarbonate, have very small, predictable shrinkages.

According to material manufacturers, the shrinkage of a given plastic is a function of mould temperature, melt temperature, wall thickness, injection pressure, cycle time, part geometry, gate location and size, and the condition of the molding machine. Variables that can cause additional shrinkage include higher mold and melt temperatures, thicker walls, lower injection pressures, shorter cycles, gating into a thin section of the part, and insufficient gate size.

As molten material enters the cavity, it cools and solidifies upon contact with the cooler mold surface. The flow of plastic is annular (circular) and as the material cools on its outer and inner surface and shrinks away from its center, the molding machine cannot accommodate the pressure increase. If the cavity pressure builds, the surface skin of the runner solidifies, and the vent does not flash.

According to material manufacturers, the shrinkage of a given plastic is a function of mold temperature, melt temperature, wall thickness, injection pressure, cycle time, part geometry, gate location and size, and the condition of the molding machine. Variables that can cause additional shrinkage include higher mold and melt temperatures, thicker walls, lower injection pressures, shorter cycles, gating into a thin section of the part, and insufficient gate size.

As molten material enters the cavity, it cools and solidifies upon contact with the cooler mold surface. The flow of plastic is annular (circular) and as the material cools on its outer and inner surface and shrinks away from its center, the molding machine forces more material through the gate, filling the void created by shrinkage with new material. “If it were possible to have high enough heat transfer rates through the plastic so that the part would solidify to room temperature throughout at the same time as the gate froze, there would be no shrinkage at all.”

“Product shrinkage and cycle time are a direct result of the operating of the mold. They are controlled by the mold’s presses and ancillary equipment and the technique of the personnel. Since the moldmaker has no control over these factors, shrinkage and cycle time are the responsibility of the molders.”

**Vents**

As the molten plastic passes through the passages machined in the mold, the air filling those passages is displaced. Unless the designer makes provision for the compressing gas to escape, it can ignite and leave the familiar burn mark on the molded part. Other problems caused by insufficient venting include short shots (an inability to fill the mold), poor weld lines, splay (characterized by a streaky surface appearance on the part), and increased internal part stresses. Inadequate venting is one of the ten most common molding mistakes.

The depth and location of the vent depend on the material and geometry of the plastic part as well as the gating and geometry of the mold design. Unfortunately, decisions regarding vent placement are often left to the moldmaker. The designer must consider venting an integral part of the mold design process.

Large, flat parts are vented on the parting line approximately every inch around the periphery of the cavity, as shown in Fig. 4-10. Vents are generally 0.25 in. (6.4 mm) wide with depths varying from 0.0003–0.004 in. (0.008–0.10 mm), depending on the molded material, the mold temperature, the injection pressure, and the location of the vent area in relation to the gate.

The vent depth is constant for a given land length, which is generally 0.06 in. (1.6 mm). After the land, the vent depth is increased to 0.005–0.020 in. (0.13–0.51 mm). The land must lead outside the mold to avoid compression of the gases, which would void the effect of the vent. Material processing sheets available from plastics suppliers contain suggested vent depths.

The runners are vented at two to four times the depth of the cavity vents because when material initially passes through the runner, very little pressure builds up. The plastic material flows by adhering to the passage outer surface and then flows within itself in annular rings. By the time the cavity pressure builds, the surface skin of the runner solidifies, and the vent does not flash.

The portion of the cavity that fills last requires a vent. In the case of the sleeve that is molded from a subgate at the parting line, the gases are trapped at the far end of the cavity. By designating a hole in the cavity, a vent on the end of the core, and a passage to the atmosphere in the mold frame, a defect-free part is molded.

Gating and venting for molding a cap are shown in Fig. 4-11. If a subgate is used to fill the part from the parting line, the cap would either not fill or the part would suffer from burn marks and/or poor weld lines. In this case, a three-plate mold (or a manifold with a top-center gate), vented at the parting line, is preferred. Cap-shaped parts can be made in subgated molds, but these tools usually have grooves cut in the core or feature an increasing wall thickness toward the top of the part. This allows the material to flow over the top of the core and down toward the parting line and the vents.

When filling the protrusions on the part shown in Fig. 4-12, ejector pins are often placed at the protrusions because they act as vents. Flats ground on the pins aid removal of the trapped gases. In determining the depth of a vent where mating parts are joined, the fit to which the mating pieces are ground is important. While a 0.001 in. (0.025 mm) deep vent may be appropriate at the parting line, a shallower vent is sufficient if other clearance is present at the mating surfaces.

Vents tend to fill with a residue and become clogged. They must be periodically cleaned or, preferably, located on moving parts so they are self-cleaning. This type of vent is known as a working vent. Because of the clogging effect from the material gases, porous vent pins are usually unsuccessful. On molds that are particularly difficult to fill, the gases are evacuated by connecting a vacuum reservoir to the vent passages.

When designing the venting system, the surface area of the cavity and the mold material’s ability to withstand the clamping tonnage must be considered. Materials with a tensile strength of 180 ksi (1240 MN/m²) can safely withstand 5 tons/in² (69 MN/m²) of compression loading. When designing with other materials, this 18:1 loading ratio provides a reasonable guideline.

Minimal venting is normally machined in a new mold. Production evaluations, including short shots (that determine which portion of the cavity fills last), then provide guidelines for the final vent configuration.

**Slides**

Design slides so that they move on wear plates. For example, hardened steel slides perform best when they move against bronze gibbs. Grease fittings are installed near the slides where possible to prolong tool life.

**Water Lines**

Mold water lines provide the best service when designed to accept quick-disconnect fittings. The water line holes are countersunk into the mold so the fittings are protected from damage during mold handling. A large counterebore diameter facilitates attaching the quick-disconnect fittings.

Water lines are designed for top or side entry into the mold. Top-mounted lines require drains cut into the top of the mold. This permits small leaks to run off the mold in a given direction without fouling the cavity. Side-entry water lines may require attaching 30–90° connectors to avoid hose kinks.

**Sprue Bushing**

The mold sprue bushing accepts the press nozzle when plastic is injected into the mold. The sprue bushing radius is designed to match the nozzle radius. If a mold is run in several presses, each press must feature an identical nozzle radius.
In addition to radius considerations, the sprue bushing is designed to accept the proper type of nozzle. Antidrool nozzles are often used to improve productivity and reduce scrap. However, because of their restrictive design, these nozzles can burn low-melt-index materials due to shear heating.

Runners and Gates

Runner system. In conventional two- and three-plate molds, the runner system is the passage that brings the plastic from the sprue bushing to the cavity gate. Properly designed runner systems are large enough to bring material to the cavity without excessive pressure drop. Thick cross-section runners should be avoided, because they can control the length of the molding cycle. If a mold has an oversize runner, a cooled runner plate or a cooling circuit immediately below the runner can compensate for this condition. Similarly, a cooled sprue improves cycle times of molds with large sprues.

Two runner cross-section designs are used: the full-round and the trapezoidal shapes. The most efficient shape is the full-round runner, where a semicircular shape is cut into both mold halves. This is also the more expensive design, since the runner must be cut twice and with reasonable accuracy so that the two halves match. A full-round runner is designed with a diameter of 1.5–2.0 times the part wall thickness. A trapezoid-shaped runner, which is cut into only one plate, is slightly less efficient but less costly (see Fig. 4-13). Semicircular and rectangular runners are not recommended; they are inefficient because of their high surface area-to-volume ratio. The larger surface area causes excessive plastic cooling.

In multicavity molds, the runner system is designed for identical flow length to each cavity. Although this theoretically supplies a balanced injection pressure to each cavity, the gates of the outer cavities are usually opened following the initial mold shots so that these cavities fill completely. With this in mind, a ladder-type runner system can minimize the material in the runner. The system is then balanced by decreasing the runner size near the sprue. After evaluating short shots, gate sizes are adjusted until each cavity fills at the same rate.

The material that first enters the mold is cooled by contact with the mold. Cold slugs placed at the sprue opening and at each runner junction trap the cooled material before it reaches the cavity. The well at the sprue opening usually contains an undercut to pull the sprue drop from the bushing. When a long sprue bushing is used and the opening becomes large, a tree-shaped sprue puller...
pin is used to core out the sprue opening and pull out the sprue drop. See Figure 4-14 for good and poor runner designs.

All runner intersections should have radii at the corners, no undercuts on the sidewalls, and should be polished. The largest cross-section of the intersection of the sprue and runner should be 2.5–3.0 times the part wall thickness. Although off-the-shelf sprue bushings may save cost, they often violate this guideline. Some molding materials, such as polyphenylene sulfide, respond poorly to sharp corners and transitions in plastic flow. S-shaped runners for these materials are preferred over L- or T-shaped designs.

Insulated runner molds. While insulated runner molds are still in use, few new ones are built. The advancement of other runnerless molding technologies has produced superior-performance designs. Insulated runner molds are constructed with large runners between plates that are fixed during molding. The plastic on the outer surface solidifies, and the material flows through the center of the passage. These molds function well when molding polypropylene, polyethylene, and styrene, provided that the cycles are fast and continuous. Unless new material is passed through the system regularly, the core of the passage freezes off (plastic solidifies in passage). All cavities must start to fill within a few cycles of one another. Molds of more than 32 cavities are generally not recommended.

When the passage freezes off, or if color changes are necessary, the bolts that hold the runner plates are removed. Straps or clamps allow opening the molding machine to strip the runner from the plates.

Runnerless molding system. Runnerless molding systems are attractive when a large runner must be reground from a conventional mold design. Lower melt temperatures are used with runnerless systems compared to conventional hot-runner systems, because the excess heat that is normally added to overcome the temperature losses in a conventional system is not required. Cycle times are often reduced, because the plastic solidification occurs only in the cavity. The thickest plastic cross-section is the last to cure; this area is often the runner, especially in molds with many cavities. In high-volume molding situations, a manifold and controller eliminate the need for a granulator and robot or picker for the runner. Injection
pressures are lower in runnerless molding systems, be-cause the material remains fluid until it reaches the gate. This eliminates compensating for pressure losses in the runner system.

Although cost is one disadvantage of the hot-runner system, start-ups of these systems are also longer. The manifold block must reach operating temperature. Color changes in the molded material often take longer, and gate vestiges, particularly in polypropylene and the elastomeric materials, are difficult to control.

Establishing the correct gate size in runnerless molding systems is particularly critical. A large gate does not freeze off properly, drooling plastic into the cavity when the mold is open. This condition also leaves a large gate vestige. Gate sizes are initially small, because a gate is easily machined deeper or larger. Gates must be accurately duplicated in all cavities, and minimal land lengths perform best.

Hot runner systems are also contaminated by foreign material introduced to the system. Contaminated systems often require substantial clean-out time.

Electric heater cartridges keep the plastic material molten within a manifold or distributor block; the block’s temperature is maintained by a controller. Thermocouples mounted on the block signal the controller to activate the heaters as required.

There are many hot runner systems available. The molder normally chooses the type and brand based on experience. Most molders prefer to minimize the types of systems within their plant for
two reasons. First, if a system works well and the vendor's technical support is acceptable, a molder retains this brand. Second, certain manifolds are not compatible with some controllers. Minimizing these variations streamlines a molder's operation.

Combination hot/cold-runner system. Another variation of a manifold distribution system of plastic is the hot runner feeding short cold or conventional runners. This design minimizes the amount of runner used when a part cannot be probed directly. In this method, the manifold brings the molten plastic to the center of a cluster of cavities. Two or more cavities are then fed by a short conventional runner that is gated by the system's heated drop. This method is effective in large molds that would normally require a long runner passage to balance the feed to each cavity.

The main disadvantage of this runner type occurs when the molded part and the runner section have similar lengths. In the absence of this condition, a series of conveyer belts is typically set up. A space that is wide enough for the smaller components to fall through is provided between the belts, allowing separation of the parts from the runner. When the runner size is similar to the part size, this type of separation becomes difficult and unreliable. Connecting the short runner sections with a thin cross-section channel can improve demolding. While this section does not deliver melt to the cavities, it facilitates separating the product from the material that is reground.

A variety of tips are used to feed the molten plastic from the manifold to the cavity. These include the standard point-gate style tip, the multiple-gate tip, the edge gate-style drop, and the valve gate-style drop.

The valve gate operates hydraulically or pneumatically to open and close the gate tip. This type is initially the most expensive and incurs high maintenance costs. The valve gate is used when gate vestige is extremely critical, because it leaves the least-noticeable witness mark in the gate area. After many cycles, the valve gate's moving parts begin to wear. Without proper maintenance, this can cause leakage and/or flash, and stringing at the gate.

Gates. The gate is the orifice at the end of the runner that leads the plastic directly into the cavity. Gate location is usually decided by the mold designer and/or moldmaker, but some knowledge of gating is necessary for proper design. The gate area is highly stressed, particularly when molding with small gate diameters, and therefore the gate should not be located in load-bearing areas. Gates are best located at the thickest section of the part, and away from areas that require subsequent finishing.

Small gates are one of the ten most common mistakes that molders must deal with. Moldmakers start with small-diameter gates and open them after mold sampling, a steel-safe condition.

The product designer must note on the part drawing a preferred gate location, areas where gates are not permissible, or that gate location must be approved by product engineering before tooling is built.

Gates should be placed where trimming is easiest; this is especially important on edge-gated and direct sprue-gated parts. Properly placed gates also force trapped gases toward the parting line or other working vents. Gates should direct the melt stream toward a cavity wall or core pin to break up the flow pattern; this provides a better surface appearance. Finally, gating the center of round parts improves part concentricity.

Restricted gates, generally less than 0.060 in. (1.52 mm) deep, are approximately 60% of the average wall thickness and depend on the molded material. The restricted gate freezes off once the material stops flowing. This frozen gate keeps the cavity pressure from pushing material back into the runner. Since the gate freezes off so quickly, all the cavities must fill at the same time. Otherwise, some cavities contain short shots while others show parting line flash or other signs of overpacking.

Gates in multicavity molds are often final-sized in the press. This is done by making short shots and adjusting the gate sizes until all cavities fill at the same rate.

When experiencing insufficient filling, sink marks, or bubbles, sufficient runner size must be verified before increasing the gate size. If there is little change in the molded part after a substantial change in injection pressure, an undersized runner may be the cause.

Sharp corners are not permissible on the edges of gates for transparent or optical parts. A minimum 0.005 in. (0.127 mm) radius is stoned on the gate edges to permit smooth polymer flow.

Several gate types are shown in Fig. 4-15. Edge gates and subgates are the most common types in conventional two-plate molds. With the edge gate, the part remains attached to the runner system when demolded. This is an advantage when molding small pieces, because it ensures that each piece is demolded in each shot. The pieces are then degated in a secondary operation.

When molding parts made from acrylic or other brittle materials, edge-gated parts are automatically degated by incorporating a staggered ejection system in the mold. Movement of the runner ejection pins is delayed slightly compared to that of the cavity ejection mechanism. This causes the brittle material to fracture at the gate, and the molded parts are separated from the runner.

The most common request, however, is for an automatic running tool. The subgate provides this capability for most materials, since the sharp edge at the top of the gate separates the part from the runner upon ejection. The locations of the subgate and gate sucker or ejector are critical.

On rigid materials, the angle of inclination to the centerline of the gate is at least 45°. The gate ejector should be close to the gate.

On flexible materials, the angle of inclination can approach zero as long as the gate is ejected by a sucker pin that is relatively far from the gate. This arrangement causes the gate to flex as it is being withdrawn. A small radius (0.005–0.015 in. [0.127–0.38 mm]) is stoned on the top edge of the gate to prevent shaving material from the gate as it flexes. The fine shavings, if left on the mold face, would damage the parting line when the mold is closed. This is especially critical when molding materials such as ABS or polycarbonate, because they have high compressive strengths.

Another application of the subgate is called the trick gate. In cases where a gate vestige is not acceptable on the outside of a part, the gate is fed into an ejector pin hole. A portion of the ejector pin is ground away, reduced toward the molded part. The remaining post is then readily broken off by the molding machine operator.

The three-plate mold is most often injected through a pinpoint gate. These gates, usually less than 0.100 in. (2.54 mm) in diameter, work well with a wide variety of materials.

When a round part has a runner around its outside or inside and the runner is connected to the part by a thin continuous ring, this design is called a disc, diaphragm, or ring fan gate. This type of gate allows an even filling of the round cavity without weld lines and with excellent concentricity. The gate is removed in a secondary operation after molding.

Round parts with a through hole may be multiple-gated from within by edge or subgates. This arrangement is called a spoke gate, a spider gate, or a wagon-wheel gate. This type of gate, which feeds the part better than a single gate but less evenly than a disc or diaphragm gate, shows weld lines. However, it uses less material than the disc or diaphragm gate, fills better than a single gate, and does not require a subsequent machining operation.
Single-cavity molds for large parts are often injected through a direct sprue gate, which must be removed after molding.

Flash gates and fan gates are used, particularly on large thin parts, when part warpage is a concern. A thin gate (0.010–0.025 in. [0.25–0.64 mm] deep), approximately one-fourth of the cavity width, and a minimal land length are used.

Flat, thin parts are also injected through a tab gate. The gate enters at a tab, which may be left as an integral part of the molded piece. If it is not left on the part, the tab is removed by shearing, clipping, or sawing. The tab contains the residual stresses always found at the gate and fully plasticizes the material before it enters the cavity, providing better flow characteristics.

Subgates and edge gates are often used in multiples to improve cavity filling, to minimize part warpage and distortion, and to minimize or eliminate core deflection. On molds for round parts with long cores that are supported on both ends, two opposing gates minimize core deflection in the center of the part.

Design for Manufacturability

The designer must consider mold manufacturability from the first design stage, that is, when the product drawing is reviewed. At this stage, the designer can propose part configuration changes that reduce mold complexity and cost. As previously mentioned, molds generally require drafts for part ejection. If a product design demands zero draft, moving mold components permit removal of the molded part. Straight walls and undercuts in the molded part are specified only where necessary.
MOLD QUALIFICATION

There are three types of mold qualifications: functional, dimensional, and statistical. As the name implies, functional qualifications determine if the part functions as intended. If parts submitted for functional qualification have critical uncentered dimensions but pass functional tests, print changes are requested to center these values.

In dimensional qualifications, the molder and the customer check several molded parts for all print dimensions. If out-of-tolerance dimensions are found, mold changes are not recommended until functional qualifications are complete.

Statistical qualifications, performed only after completing the functional and dimensional tests, are the most expensive and difficult evaluations. Statistical qualifications are performed by measuring critical dimensions for a statistically significant part run (a 30-piece sample is common). Sample runs also include parts made from different plastics. The print and/or mold is again fine-tuned following the statistical-sample results.

MOLD OPERATION AND OPTIMIZATION

A coolant flow check is performed before injecting a mold. Pressure drops and flow rates are determined by attaching meters to the coolant lines.

Turbulent flow is ideal for heat exchange because laminar flow can insulate the water lines from efficient heat transfer. A 1.5 gal/min (5.7-L/min) flow rate through a 0.4 in. (11.1 mm)-diameter line, for example, indicates turbulent flow. Insufficient flow rates require increased coolant pressure or shorter lines and a 10–20-psi (69–138-kPa) drop between the inlet and outlet indicates a restricted water line. Once the proper coolant flow is achieved, the complete set-up is documented for future runs.

Initial material and mold temperatures are set to those recommended by the material manufacturer. The mold should be opened and closed several times, checking for alignment and mechanism operation. The safety mechanism ensures that the press does not close on a part, damaging the mold.

Mold optimization provides a benchmark for future trials and production runs. Short shots are made first, and the feed is gradually increased until a filled part is achieved. This provides the initial shot size.

If the vents are inoperative, the clamp pressure is probably excessive. The feed rate is decreased until a short shot results; it is then increased while lowering the fill pressure until there is no further drop in pressure. The fill timer is then set to halt material flow before the mold is filled. Clamp pressure is decreased until slight parting line flash appears. Finally, clamp pressure is increased until the parting line flash is gone.

Disregarding any part sinks, several parts are weighed. The fill time is decreased until a weight loss occurs. Weight loss signifies that the gate is no longer solid enough to hold the cavity pressure. Fill time is then slightly increased to ensure that the gate freezes off. The fill pressure is slightly increased to eliminate any sink marks. If this procedure does not eliminate the sink marks, the gate is enlarged to allow adequate packing before it freezes off.

The mold should be opened only far enough to eject the part; ejection should start before the mold is fully open. Multiple ejection cycles are unacceptable. Increased cavity draft angles or accelerated ejectors are required if the parts do not eject on the first cycle.

Once any ejection problems are solved, the mold is cycled for about 20 minutes. When the tool runs with no further adjustments, all mold and press settings are recorded in the mold guide, and parts are submitted for inspection.

MOLD QUALIFICATION

A mold is qualified by running several cycles, determining the press parameters, and evaluating the molded parts. Part dimensions are categorized as tooling construction dimensions, critical dimensions, and inspection dimensions.

Tooling construction dimensions are only critical for constructing the mold. If the molded part reveals out-of-tolerance values for these dimensions and if the dimensions do not affect part functionality, a (blue)print change is requested from the customer so the print matches the part. Critical dimensions impact part functionality, and the mold is usually revised if these dimensions are out of tolerance. Inspectable dimensions, which may also be critical dimensions, are checked throughout production runs to assure process stability. Inspection dimensions are often checked by gages. Certified gages and properly trained inspectors are essential.

There are three types of mold qualifications: functional, dimensional, and statistical. As the name implies, functional qualifications determine if the part functions as intended. If parts submitted for functional qualification have critical uncentered dimensions but pass functional tests, print changes are requested to center these values.

In dimensional qualifications, the molder and the customer check several molded parts for all print dimensions. If out-of-tolerance dimensions are found, mold changes are not recommended until functional qualifications are complete.

Statistical qualifications, performed only after completing the functional and dimensional tests, are the most expensive and difficult evaluations. Statistical qualifications are performed by measuring critical dimensions for a statistically significant part run (a 30-piece sample is common). Sample runs also include parts made from different plastics. The print and/or mold is again fine-tuned following the statistical-sample results.

MOLD OPERATION AND OPTIMIZATION

A coolant flow check is performed before injecting a mold. Pressure drops and flow rates are determined by attaching meters to the coolant lines.

Turbulent flow is ideal for heat exchange because laminar flow can insulate the water lines from efficient heat transfer. A 1.5 gal/min (5.7-L/min) flow rate through a 0.4 in. (11.1 mm)-diameter line, for example, indicates turbulent flow. Insufficient flow rates require increased coolant pressure or shorter lines and a 10–20-psi (69–138-kPa) drop between the inlet and outlet indicates a restricted water line. Once the proper coolant flow is achieved, the complete set-up is documented for future runs.

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Once any ejection problems are solved, the mold is cycled for about 20 minutes. When the tool runs with no further adjustments, all mold and press settings are recorded in the mold guide, and parts are submitted for inspection.
The mold guide is helpful in the following areas:

- Evaluation of clamp pressures, fill speeds, and shot size determines whether the mold can run in a smaller press with a lower operating cost.
- Accuracy in determining the cycle time, required number of operators, packaging, and secondary operations is enhanced.
- Material consumption is clearly determined.

All future production runs and mold trials are begun at these optimized conditions.

PREVENTIVE MAINTENANCE

Optimum mold performance relies on good preventive maintenance. Maintenance can be enhanced by early design considerations and by using appropriate, high-quality replacement parts.

Routine maintenance includes cleaning the vents, assuring that the mold face is clean, and checking all mechanisms and slides for free movement. A brief check of each mold before and after every production run assures trouble-free operation.

Low-volume molds made of soft steel degrade at the parting line due to clamping pressure. Periodic refurbishment, including descaling water lines, polishing cavities, reworking vents, and realigning worn mechanisms, is required.

High-volume or statistically qualified molds require extensive and well documented maintenance procedures. This includes stress relieving the parting lines and replacing worn cavities and other mold components. Mold recertification is required after any major rework.

MOLDING PRESS INFORMATION

Molding machine issues significantly impact mold design decisions. Press-related items include shot size, clamping force, tie-bar spacing, platen size and clamping hole pattern, knockout bar spacing, and minimum and maximum mold thicknesses.

Shot Size

The shot size, or shot volume, of a press is the amount of plasticized material injected into a mold in one cure cycle. The shot size in most U.S. machines is measured in ounces and is based on the specific gravity of styrene. Shot volume is first determined by calculating the volume of the part or parts being designed, and that of the runner system. This figure is then altered in two ways. First, press capacity is reduced when running material other than styrene. The new capacity is 65–90% of the original value, depending on how fast a cubic inch of material can be brought to melt temperature in comparison with styrene. Material suppliers can provide this and other plastic properties. These material data sheets and design guides are valuable information for the mold designer, moldmaker, molder, and product designer.

Second, press capacity must be adjusted for the specific gravity of the molded material. The specific gravity of styrene (1.05) is divided by that of the molded material. Again, this reflects the industry standard for machine specifications based on styrene properties. If, for example, a molder is running a grade of acetal with a specific gravity of 1.41, the adjusted press capacity is 1.05/1.41 = 0.745 or 74.5%.

Shot size calculations for heat-sensitive materials are critical, because the shot size required to fill the mold should be at least 20% of the machine’s shot capacity. This prevents the material from degrading due to excessive exposure to heat in the injection barrel. The molding machine must also have sufficient capacity to fill all cavities and the runner system.

A general reference is that the average volume of material shot into the runner and cavities should not exceed 50% of the press capacity. The range is 20–80% depending on the type of material used.

Clamping Force

Press clamp tonnage governs which press runs a given mold. The clamping force required to hold a mold closed is a function of the cavities and runner system’s projected area, the molded material, and the length of flow versus wall thickness of the molded part. Other variables that affect the clamping pressure (but are not factored into these calculations) are gate and runner sizes, mold and material temperatures, mold venting, and the condition and capabilities of the press.

Design guides and data sheets are used to determine the pressures involved for various materials. For most plastics, 2 tons/in.² (28 MN/m²) is an adequate clamping force. The following suggestions for molding polypropylene are found in the literature. For wall thicknesses greater than 0.060 in. (1.52 mm), the required clamp force is 2–3 tons/in.² (28–41 MN/m²). For wall thicknesses of 0.030–0.060 in. (0.76–1.52 mm), use 3–4 tons/in.² (41–55 MN/m²). For wall thicknesses less than 0.030 in. (0.76 mm), use 4–5 tons/in.² (55–69 MN/m²).

For polycarbonate resin, 3–5 tons/in.² (41–69 MN/m²) are sufficient. However, for filled resins, 4–6 tons/in.² (55–83 MN/m²) are required. Poly carbonate parts are molded with as little as 1.5 tons/in.² (21 MN/m²). Nylon, due to its fluidity, requires as much as 7 tons/in.² (97 MN/m²) of clamping force during injection.

Clamping force calculations rely on an accurate projected area determination. Projected area is not the surface area of the molded part but rather the area of the molding surface that is parallel to the parting line. For example, the projected area of a cylinder that is 2 in. (51 mm) in diameter by 4 in. (102 mm) long, when molded lying parallel to the parting line, has the same projected area as a flat plate that is 2 in. (51 mm) wide by 4 in. (102 mm) long. Any openings in the part reduce its projected area.

Tie-bar Spacing

After a press is selected, it governs the overall size of a new mold. The tie-bar spacing determines the width of the mold. Some shops run rectangular molds horizontally, while others run them vertically. Knowing this preference allows the designer to fit the mold within the tie bars. Any external mold mechanisms are designed and installed so that they may be removed from the mold. In addition to facilitating mold installation and removal, this feature prevents the external items from controlling the size of the mold between the tie bars.

An alternative design, used only with permission of the molder, is to cut the corners off of the mold or to scallop the mold frame sides to permit tie bar clearance. This is usually a last resort, since one or more tie bars must be removed and installed each time the mold is placed in the press. On molds with corners removed, the mold’s diagonal dimension is calculated to determine if it can be placed sideways between the tie rods before it is rotated to the molding position.

Platen Size and Clamping Hole Pattern

Platen size is an important design consideration. A platen is either of the sturdy mounting plates of a press, usually a pair, to which the entire mold assembly is bolted. The mold must not extend beyond the platen, leaving the mold plates unsupported. Adequate mold clamping fixtures are also mandatory. When cooling connections, pull straps, and other external mechanisms interfere with the preferred clamp placement, extra clamp slots are cut into the end of the mold.
CHAPTER 4

MOLD DESIGN CONSIDERATIONS

Knockout-bar Spacing

Openings are provided in the ejector housing to allow the molding machine knockout rods to enter the mold; these rods subsequently push the ejector or stripper plate forward. Industry standards define knockout-bar spacing, and the molding press data sheet should be consulted early in the design stage.

Effective ejector plate designs allow the press knockout rods to evenly activate the plate without bending the plate or the rods. Plates can be bent when a single center knockout is used to activate a long plate. The designer must consider the location and possible interference of the knockout holes, support pillars, ejector pins, and water lines.

The stroke length of the knockout mechanism is another important design consideration. The press must have sufficient stroke length to eject the part from the B or moving side of the tool. Several approaches are used to overcome an insufficient stroke length. The ejector plates can be pulled forward by straps or chains attached to the stationary half of the tool. A second option is to add external hydraulic or pneumatic cylinders to activate the ejector.

Minimum and Maximum Mold Thickness

All molding machines have a “minimum press daylight” dimension, which represents the thinnest mold that can run in the press. When an existing mold is too thin to run in a desired press, plates or steel bars called parallels are attached to the mold. Parallels are only used if calculations determine that they provide sufficient support under the projected clamping force. Some presses are also equipped with clamping unit spacers, which allow a wider range of mold thicknesses.

Maximum press daylight opening is an equally important consideration. Sufficient maximum opening ensures that the press can perform the intended opening, stripping, and knockout functions. Molds with moving plates, such as three-plate stripper-plate molds, are especially critical. Stripper plates must have sufficient travel to eject parts from the cores and to allow the parts to fall between the plates. Three-plate molds must open wide enough for the runner to fall between the plates or to have a picker or robot reach between the plates to remove the runner and/or parts.

OTHER CONSIDERATIONS

Complex molds require a sequence of actions from the molding machine. These actions include multistaged openings, core pulls at specific mold opening points, and ejection before the mold is fully open. The designer and molder must determine if a press has the necessary sequences or if a substitute sequence is acceptable.

Safety switches are added to molds with special features such as unscrewing and hydraulic or pneumatic core pulls. This feature ensures that the machine does not open or close at a point in the sequence that would damage mold plates, side actions, ejectors, or other mechanisms. Safety switches are also added when ejector pins are located below side-action components. This ensures that the press does not engage the knockouts unless the side actions are fully retracted.

Molders have other preferences that merit discussion. When the operator faces the mold, the stationary half is typically on the right, and the movable plate is on the operator’s left. As a result, water lines are usually connected to both halves of the mold on the side opposite the operator. Many molders prefer to keep water connections away from the mold top and away from the operator side, although this may be unavoidable.

Electrical wires from a heated sprue bushing or a manifold are brought through channels to the outside of the mold. Wiring is often run through the top of the mold, that is, the end that is in the up position when the tool is run. Water lines should be placed away from electrical connections.

Ejection System

Once the cavity is filled with molten material and the material solidifies, the press opens. If the mold was designed and run properly, the solidified parts are retained on the side of the tool that contains the ejection mechanism. The parts are then removed from the mold.

Tapers on the core facilitate part ejection. Although the taper angle depends on the molded material and the core surface finish, most molds perform well with a 1° core taper. Cores without tapers operate best if they are draw stoned, with the stone lines parallel to the ejection line.

There are several methods of ejecting parts. Off-the-shelf ejector pins are available from a variety of manufacturers. These pins are usually made from a hot-worked die steel with a 40 Rockwell C (Rc) core hardness; the outside is nitrided to achieve a surface hardness of R$_e$ 65–74. This high external hardness gives the pins excellent galling resistance, and the R$_e$ 40 core hardness provides toughness to withstand demolding loads. Because this high external hardness can cause edge chipping, a commercially available through-hardened pin may be used. These pins, made from high-speed steel, are hardened throughout to R$_e$ 60–65. Through-hardened pins resist chipping and galling.

Another product that is readily available but more costly is the ejector blade. This device is used in areas that are too narrow for a properly sized ejector pin, such as narrow walls and ribs. Ejector blades are essentially rectangular-shaped ejector pins.

When a boss is molded around a core pin, an ejector sleeve is used to demold the part. Since the core pin is mounted below the ejector assembly, the cost for sleeve ejection is higher than that for pin ejection. Additionally, if there is coolant in a core surrounded by an ejection sleeve, the designer adds a plate to the standard mold frame.

A stripper plate provides another common ejection method. Although this device is generally used in place of an ejector housing, the two may be used simultaneously. The stripper plate contains stripper rings, used extensively for ejecting round parts, or stripper bars.

A less popular ejection method is the air blast. In this design, air poppets or valves are used to break the vacuum or provide ejection assistance on large, deep parts. Air-activated devices also provide even internal pressure that prevents flexible parts from inverting when stripping undercuts. Air poppets work most dependably if air line lubrication is provided. A minimum of oil is used to avoid contaminating the molded parts.

A variation of the ejector pin is the valve ejector pin. This device provides a larger ejection surface area in sites where flexible parts have minimal clearance for ejector pins.

Two-stage or staggered ejection is achieved several ways. Off-the-shelf items can be used. Hydraulic or pneumatic cylinders and extra plates with delay space are also used to achieve staggered ejection.

Another ejection method, classified as a side action, is known as a Z-pin, walk-out pin, or lifter. This item moves to the side as it moves forward, allowing it to release undercuts and act as an ejector.

In all ejection methods, the cross-sectional area of the pin, sleeve, blade, or other device must be large enough to demold the part without penetrating it.

The ejection mechanism is generally on the B-side of the mold, as this is the location of the press ejection unit. However, ejection may be from the stationary A-side of the tool for the following reasons:

4-16
• Pieces with critical aesthetic requirements may require that all gate vestiges and ejector pin marks be on one side of the molded part.

• Parts cured in very thick cavity plates and parts that demand a conventional runner that cannot be fed with a heated sprue bushing may be more economically produced with a shorter sprue.

Provision for activation is required for A-side part ejection. This activation can be accomplished with pull straps, chains, shoulder bolts, or hydraulic or pneumatic cylinders.

**Hand-loaded Inserts**

Hand-loaded mold inserts provide an economical way to mold internal threads or similar configurations in prototype or low-volume parts. The operator places the inserts directly into the mold or onto a removable block that is loaded into the mold. Plastic is injected into the mold, and the cured part and insert are removed when the press opens. The insert is then unscrewed from the part and returned to the mold for the next cycle. This approach is less expensive than using an unscrewing mold.

**Unscrewing Molds**

Automatic unscrewing molds are effective and economical in producing parts with small- to medium-sized internal threads. The appropriate threads, compensated for shrinkage, are cut into the cores. When the mold opens, a double-acting hydraulic cylinder rotates the cores (featuring gear teeth) via one or more racks fastened to a yoke. As the racks move past the cores, the rack’s teeth mesh with those of the core, and the relative motion provides the necessary number of unscrewing revolutions.

Cam bars are also attached to the yoke. These bars feature angles that separate the stripper plate, by means of a cam follower, at a rate that allows the plate to move forward with the molded parts. The stripper rings generally feature teeth around the mouth of the tapered shut off, and within the molding area, to keep the parts from spinning as the cores unscrew. When the racks and cam bars have moved the distance necessary to demold the parts, the parts fall off of the stripper plate.

The unscrewing mold is a precision piece of machinery. The bearing diameters require close tolerances to properly maintain alignment of the cores, cavities, and stripper rings. Moving pieces must be made from the proper materials, be heat treated to an appropriate hardness, and be lubricated.

Unscrewing actions can be accomplished by other mechanisms including electric motors and proprietary methods. Collapsible cores are also used to mold full or interrupted threads.

**HEAT TRANSFER**

Heat transfer is an important mold feature. In addition to providing adequate heating or cooling, properly placed coolant lines and heaters provide uniform heat transfer. Drilled holes must be placed a safe distance from the molding surface to prevent plate cracking caused by mold cycling. Poor part knit lines and cold spots can also result from improperly drilled holes.

Most molds require cooling to remove the heat contained in the plastic material. Although cooling is usually accomplished with water, air can be used (but only as a last resort). Air cooling is used in components that are too small for liquid coolant lines (for example, pins less than 0.12 in. [3.18 mm] in diameter).

Water lines and channels are placed directly in the cavity and cores whenever possible, since a reduction in heat transfer occurs across any boundary. Cooling lines can also be placed in the support plates if additional heat removal is necessary. Excessive looping of water lines causes higher inlet/outlet coolant temperature differentials. This design also removes heat nonuniformly from the cavities.

Water line fittings, such as quick disconnects, are designed with an inside diameter that is similar to that of the coolant line drilled in the mold to avoid pressure drops and air pockets in the water line. Similarly, when sizing bubbler water lines, the cross-sectional area between the bubbler and water hole should be equal to that area inside the bubbler. The area above a bubbler or baffle is also equal to the area on either side of the bubbler or baffle to avoid an air pocket or pressure drop at the drill point of the water hole.

The following formula permits calculating the quantity of heat removed from the mold:

\[ Q = W(S[T_1 - T_2] + L) \]

where:

\[ \begin{align*}
Q &= \text{heat removed, Btu/h (kJ/h)} \\
W &= \text{weight of the plastic material processed, lb/h (kg/h)} \\
S &= 3600 \times \text{weight of parts and runner = cycle time} \\
T_1 &= \text{melt temperature, } ^\circ\text{F (} ^\circ\text{C)} \\
T_2 &= \text{product temperature when ejected, } ^\circ\text{F (} ^\circ\text{C)} \\
L &= \text{the latent heat of fusion for the material, Btu/lb (kJ/kg)}
\end{align*} \]

The specific heat of the substance, S, is found in the material processing sheets.

The latent heat of fusion is the amount of heat required to bring a substance through a phase change. The latent heat of fusion required to transform ice at 32°F (0°C) into water at the same temperature is 144 Btu/lb (335 kJ/kg). An identical value is required to change water to steam. For amorphous materials, L = 0. If the heat content of the material is known, then Q = Wα, where α represents the heat content of the material.

The mass or weight of water that must pass through the mold to remove heat is determined through the following relationship:

\[ H = Km(T_3 - T_4) \]

where:

\[ \begin{align*}
H &= \text{heat removed in material, Btu/h (kJ/h)} \\
K &= \text{heat transfer efficiency constant, Btu/lb}^\circ\text{F (kJ/kg} ^\circ\text{C)} \\
m &= \text{mass (weight) of water required to remove heat, lb/h (kg/h)} \\
T_1 &= \text{temperature of the water exiting the mold, } ^\circ\text{F (} ^\circ\text{C)} \\
T_4 &= \text{temperature of the water entering the mold, } ^\circ\text{F (} ^\circ\text{C)}
\end{align*} \]

For critical applications, a 5°F (3°C) temperature differential is preferred. In general, a 10°F (6°C) gradient is acceptable. Typical K values are shown in Table 4.1.

By setting H (quantity of heat contained in the plasticized material) equal to Q (amount of heat removed by the water), the amount of water required is calculated as follows:

\[ m = \frac{W(S[T_1 - T_2] + L)}{K(T_3 - T_4)} \]

As previously mentioned, turbulent coolant flow is required for maximum heat exchange; turbulent flow removes about twice the amount of heat as laminar flow. A flow parameter known as the Reynolds number is calculated to determine whether flow is laminar or turbulent. In a circular passage, a Reynolds number less than 2000 indicates laminar flow. Between Ne 2000 and 4000, the flow may be laminar or turbulent. Flow characterized by Reynolds numbers greater than 4000 is turbulent. To ensure maximum cooling efficiency, mold coolant flows greater than Ne 4000 are required.2
In fluid mechanics, the Reynolds number \( (N_R) \) is a ratio:

\[
N_R = \frac{\rho v d}{\mu} \tag{4}
\]

where:
- \( \rho \) = fluid density
- \( v \) = fluid velocity
- \( d \) = pipe inside diameter
- \( \mu \) = fluid viscosity

The Reynolds number is significant when the effect of viscosity is important in controlling the velocities or the flow pattern. It is a dimensionless parameter and can be determined by the following:

\[
\rho = \frac{\text{slug/ft}^3}{(1 \text{ kg/m}^3)}
\]

\[
v = \frac{\text{ft/sec}}{(m/sec)}
\]

\[
d = \text{ft} (m)
\]

\[
\mu = \frac{\text{lb-sec/ft}^2}{(g-sec/m^2)}
\]

The kinematic viscosity of water varies with temperature. The viscosity changes at a faster rate at lower temperatures than it does at higher temperatures (see Table 4-2).

Using an average viscosity of 0.0020 in.\(^2\)/sec (1.3 centistokes), which corresponds to a temperature slightly less than 50° F (10° C), accepted flow rates for the most common water line sizes are shown in Table 4-3.

Extensive calculations are available to determine the required amount of mold steel surrounding coolant lines. However, a conservative rule is to place the center of a water line at least two times its diameter from the mold surface. A pitch spacing of three to five diameters provides reasonably uniform cavity temperatures. When strength calculations and space permit, plenty of coolant lines are placed in a mold. Water temperature and flow rate then determine appropriate molding temperatures.

### Cooling Methods

Mold cooling is accomplished in several ways. Water lines can be drilled in the core, cavity, and mold frame. The water enters the mold components directly through pipes threaded into the component blocks, or is transferred from the mold frame through water lines with O-rings preventing leakage.

Water is often channeled around round cavities, both on the outside and around the base. Cores have internal cooling holes, and water is directed by baffles or bubblers. Figure 4-16 shows a water connection arrangement for bubblers. Baffles are used if a
Heating Methods

Electric cartridge heaters are used to warm some molds. Oil is used in drilled coolant lines in conjunction with water heating units for temperatures that approach the boiling point of water. Heating cartridges can be located in drilled and reamed holes with minimal clearance for the cartridge; these holes must have a good surface finish. This clearance/finish combination ensures maximum heat transfer. Cartridges are coated with an antiseize compound for easy removal.

Two basic calculations are used to determine the proper number of heating elements. The first determines the wattage required to warm the steel to operating temperature in the required time. The second is used to calculate the wattage required to maintain the necessary molding temperature.

When heating elements are used, the amount of heat that is lost from the mold must be minimized. Insulator pads, fastened to the outside of the mold, minimize heat loss from the mold to the platen.

The energy required to heat a mold to operating temperature in a given time is calculated as follows:

\[ E = \frac{(WST)}{t} \]

where:

- \( E \) = energy required, Btu/h (kJ/h)
- \( W \) = weight of steel, lb (kg)
- \( S \) = specific heat of steel
  - \( 0.12 \) Btu/lb\(^°\) F (0.502 kJ/kg\(^°\) C)
- \( T \) = temperature change, °F (°C)
- \( t \) = time to reach temperature \( T \) in hours (h)

The energy required is converted from Btu per hour to kilowatts by dividing Btu per hour by 3412.

The following formula permits calculating the heat losses due to convection and radiation:

\[ Q = qA \]

where:

- \( Q \) = total heat loss, kW·g (kJ)
- \( q \) = specific heat loss, kW·g/ft\(^2\) (kJ/m\(^2\))
- \( A \) = exposed surface area of the mold, ft\(^2\) (m\(^2\))

Typical heat loss values for steel are shown in Table 4-4.

These are maximum heat loss values for vertically mounted members. Horizontally mounted plates and piping yield lower heat losses.

The last calculation determines the heat loss due to conduction through the insulator pad, which is mounted on the outside of a mold that requires heater cartridges.

\[ Q = \frac{cA(T_1 - T_2)}{t} \]

where:

- \( Q \) = heat loss, Btu/h (kJ/h)
- \( c \) = thermal conductivity of the insulator, Btu/h/ft/°F (kJ/h/m/°C)
- \( A \) = conduction area, ft\(^2\) (m\(^2\))
- \( T_1 \) = press platen temperature, °F (°C)
- \( T_2 \) = mold temperature, °F (°C)
- \( t \) = thickness of the insulator pad, ft (m)

The heat loss in Btu/h is divided by 3412 to determine the value in kilowatts.

The total energy required to support molding is obtained by summing the values in equations 5-7 and adding a 20% safety margin. Additional heat transfer calculations are found in the literature.13

METALLURGICAL ASPECTS

Virtually all moldmaking materials are alloys. An alloy is a material exhibiting metallic properties that is composed of at least two chemical elements, at least one of which is a metal. A brief description of common alloying elements and their effects on steel properties is as follows:

Carbon
Carbon has the greatest effect on the hardness, depth of hardening, and strength of steel. Higher carbon contents increase these features while decreasing ductility and toughness. Carbon also combines with other carbide-forming elements, such as iron, chromium, molybdenum, vanadium, and tungsten, to form hard carbide particles. These carbides increase the wear properties of steel. Steel with a carbon content of 0.20% or less is classified as low-carbon steel; its hardness does not increase significantly when heated and quenched. Steel with 0.20–0.60% carbon is medium-carbon steel, while high-carbon steel contains 0.70–1.30% carbon.

Sulfur
Although sulfur is present in most commercial steels in levels below 0.05%, this element is increased to 0.08–0.35% in free-machining steels.

Manganese
Manganese is also found in most mold steels. It acts as a deoxidizer and combines with sulfur to form manganese sulfide, which improves hot workability. Hardenability is also increased at minimal cost by adding this element.

Silicon
This element primarily acts as a deoxidant. Silicon also increases the hardenability of steels carrying nongraphitizing elements.

Nickel
Nickel strengthens unquenched or annealed steels, increases the hardenability of low-alloy steels, and lowers the critical temperatures.

### Table 4-4

<table>
<thead>
<tr>
<th>Temperature, °F (°C)</th>
<th>Heat Loss, W·s² (J/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 (93)</td>
<td>80 (7.4)</td>
</tr>
<tr>
<td>300 (149)</td>
<td>200 (18.5)</td>
</tr>
<tr>
<td>400 (204)</td>
<td>335 (31)</td>
</tr>
<tr>
<td>500 (260)</td>
<td>500 (46)</td>
</tr>
<tr>
<td>600 (316)</td>
<td>730 (68)</td>
</tr>
</tbody>
</table>
temperature for heat treating, which allows less distortion. Nickel is the primary element in the maraging class of steels. Its presence, in combination with aluminum and titanium, causes the intermetallic compound, on aging, to increase in hardness and strength.

**Chromium**

Chromium best improves hardenability when included in high-carbon steel. When chromium is present at levels exceeding 11%, these steels become corrosion-resistant stainless steels. Chromium also increases abrasion resistance.

**Molybdenum**

This element increases hardenability and is therefore often used in plastic-mold steels. Molybdenum also counteracts temper brittleness, increases creep strength and red hardness, and enhances the corrosion resistance of stainless steel.

**Vanadium**

Vanadium is added to control grain size and increase wear resistance. This element combines with carbon to form vanadium carbide, which is harder than the aluminum oxide used in grinding wheels.

**Cobalt**

This element contributes to red hardness. It is used in maraging steels where it imparts strength without depressing the temperature that signifies martensite formation.

**Aluminum**

Aluminum combines with nickel or titanium to form an intermetallic compound that precipitates with age to provide hardness and strength. It is also used as an alloying element in nitriding steels.

**Titanium**

This element, found in the maraging steels, combines with nickel and/or iron to form an intermetallic compound that precipitates with age and contributes to strength.

### MOLD MATERIAL

Molds must be designed and built to withstand wear, stresses caused by clamping and molding pressures, and thermal stresses. Metals, primarily steels, are the most common moldmaking materials due to their high compressive strengths. Because moldmaking is labor intensive, the material cost is a small portion of the overall mold cost. The incorrect choice of materials can lead to damage and operating problems.

To prevent corrosion, electroless nickel-plated steel is specified for the plates containing water lines. When selecting these and other mold materials, the thermal conductivities of the various materials must be considered. Selected conductivities are presented in Table 4-5.

#### Tool Materials and Applications

**Type H-13.** Type H-13 is a common plastic injection mold material. This is a hot-worked die steel that shows little change in properties for temperatures up to 900°F (482°C). This steel is often hardened to R$_c$ 52–54, but it is tougher at R$_c$ 48. If higher hardness is needed for wear properties, Type H-13 can be nitried as long as the components have sufficient thickness for strength.

When cavity or core surfaces are finished prior to heat treatment, the heat treatment process is specified as vacuum hardened and nitrogen tempered. This process prevents scale from forming during heat treating.

Type H-13 is a tough tool steel that is not prone to cracking, has good polishability characteristics, and is relatively stable in heat treatment. This steel is commonly used for cores, cavities, and other mold components.

### TABLE 4-5

<table>
<thead>
<tr>
<th>Thermal Conductivities of Metals</th>
<th>Btu/h·ft·°F</th>
<th>kJ/h·m·°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 stainless steel</td>
<td>13</td>
<td>25.0</td>
</tr>
<tr>
<td>H-13 steel</td>
<td>15</td>
<td>28.8</td>
</tr>
<tr>
<td>P-20 steel</td>
<td>17</td>
<td>32.7</td>
</tr>
<tr>
<td>A-10 steel</td>
<td>18</td>
<td>34.6</td>
</tr>
<tr>
<td>S-7 steel</td>
<td>21</td>
<td>40.4</td>
</tr>
<tr>
<td>Beryllium copper (BeCu)</td>
<td>62</td>
<td>119</td>
</tr>
<tr>
<td>Aluminum</td>
<td>80–130</td>
<td>154–250</td>
</tr>
<tr>
<td>Bronze alloy*</td>
<td>120</td>
<td>231</td>
</tr>
<tr>
<td>Bronze alloy*</td>
<td>190</td>
<td>365</td>
</tr>
<tr>
<td>QC-7 aluminum</td>
<td>91</td>
<td>175</td>
</tr>
</tbody>
</table>

* Depending on alloy composition

Type 420. Type 420 stainless steel is a common air-hardening tool steel for cavities and cores. It is used in molds where corrosion is a concern, such as when molding polyvinyl chloride (PVC) or acetal. Type 420 steel can be highly polished with care, because it is only hardened to R$_c$ 50–52. This material is available as a mold-quality tool steel produced by the electroslag remelt (ESR) method.

Because of Type 420’s lower hardness, its compressive strength is lower than that of other mold steels. Although this factor does not cause molding problems, Type 420 is prone to compressive damage called hobbing if the mold is closed on a part or runner. However, a modified version of Type 420 that can be heat treated to R$_c$ 56 is now available.

Type 420’s lower thermal conductivity is an advantage when making molds for thin-walled parts. Steels that retard heat removal from the plastic allow the cavity to fill before the plastic solidifies.

Type P-20. Type P-20 is a prehardened steel that is used in molds for large plastic parts. Type P-20 is used to make large mold components that may distort or crack if heat treated. The steel can be carburized if a higher hardness is needed for improved wear. As with any surface treatment, carburizing does not substantially increase the steel’s compressive strength.

Type S-7. Type S-7 is a shock-resisting tool steel that has a good combination of toughness and stability. Although its dimensions increase slightly during heat treatment, growth is less than 0.1%. Type S-7 can be air hardened if its cross-sectional thickness is less than 2 in. (50.8 mm), but oil hardening is required for larger thicknesses. This steel, usually heat treated to R$_c$ 56–58, is frequently used for stripper rings. Type S-7 is not readily available as a mold-quality tool steel but is usually free of inclusions.

Type M-2. Type M-2 high-speed steel is used to produce small core pins. This material, usually hardened to R$_c$ 62–64, is also ideal for high heat applications up to 1150°F (621°C).

Other steels. Types A-10 and O-6 are both graphite-containing tool steels used in injection molds. Type A-10 is an air-hardening steel, and Type O-6 is an oil-hardening graphitic steel. Both are used in applications where the lubricating qualities of graphite impregnation are desired. Ordinarily hardened to R$_c$ 58–60, they are used to make gibbs, wear pads, cam locks, and slides. Because the graphite particles may migrate into the molding material, these steels are not acceptable for cavities and cores used to mold medical products.

Standard metallurgical guidelines are applied when choosing steels for wear situations. Even though graphitic steels may be used on slides and gibbs, they are not acceptable for surfaces on which these components move. Dissimilar metals that differ by at
least six Rockwell hardness points must be used when designing sliding or moving components.

Types A-2 and D-2 steels are used for small- to medium-sized parts where higher hardness improves wear properties. Because these steels are heat treated to R, 58–62, toughness is poorer when compared to other steels. Type A-2 and D-2 steels are not appropriate for high-bending or -torsional applications. Type D-2, used in punch and die work, has a low machinability rating.

Maraging steels in 250, 300, and 350 grades are used in plastic injection molds. These steels are age hardened at 900°F (482°C) for three hours. Grade 350 is harder than 250, but 250 exhibits higher toughness. Grade 350 has a low machinability rating. These steels may be heat treated to R, 46–58, depending on the grade.

Type O-1 is a high-carbon, oil-hardening tool steel used for mold components such as back-up plates, slides, gibs, wear pads, cam locks, and stops. However, oil-hardening steels distort more than their air-hardening counterparts in heat treatment. Type O-1 displays a black scale following heat treating that makes it unsuitable for prefinished cavities and cores.

Beryllium copper. Beryllium copper (BeCu) and its alloys are used in areas that require high thermal conductivity but can withstand lower hardness. BeCu is used for small-diameter core pins and other areas in which water cooling is difficult. If higher hardness is needed, the alloy is chromium plated.

Beryllium copper cavities are also made in a high-pressure casting process. While these castings may achieve a R, 40–48 hardness, they are susceptible to surface peening.

**Steels for Mold Frames**

Mold bases are made from one of five steels: Type 1, 2, 3, or 5 or stainless steel. Type 1, a medium-carbon steel, is used on prototype and low-production-volume molds. Although this steel is less expensive and softer than other grades, it is highly machinable.

Type 2 mold steel is the most common. The American Iron and Steel Institute (AISI) Type 4130 steel is supplied at a Brinell hardness of 280–320. This steel is considered the industry standard for mold frames with hardened, inserted cavities and cores.

For superior molds requiring longer life or in molds where the cavity is cut directly into the mold frame, Type 3 steel is used. This is an AISI-modified Type 4130 (P-20) steel. This material, made with the electroslag remelt process, is an inclusion-free mold-quality grade. Its machinability index is lower than Type 2, but it is readily machinable.

Type 5 steel is an AISI-Society of Automotive Engineers (SAE) H-13-grade mold base steel. This material is specified for the most demanding applications or for molds with cavities cut directly into the mold plates.

Stainless steel mold frames, typically Type 420 or a free-machining version called Type 420F, are used when corrosion is a problem. The advent of the Type 420F (420 that is sulfurized to improve machinability) has made stainless steel frames more popular in recent years. Even though other steels initially have a higher thermal conductivity, stainless steels remove heat better over time, because the conductivity-reducing residue that builds up on basic steels is not a factor.

Material cost for Type 420F stainless steel can be twice that of Type 2 material. However, because the stainless steel machines readily and presents a better surface finish, stainless steel mold frames are often machined in less time on computer numerical control (CNC) equipment. As a result, the additional cost for Type 420 frames is limited to that of the raw material.

**Production Mold Materials**

When designing a mold, the choice of material and its heat treatment are essential. The mold material cost, the nature and shape of the molded part, the production environment, and the molded material properties guide the initial design phases. The machining process and its effect on the material and its geometry are also considered. Because production molds can cost from a few thousand dollars to over $500,000, the initial design parameters must be correct.

Steel is the most common injection mold material due to its high tensile and compressive strengths. The most common steel types are prehardened, carburizing, oil-hardening, air-hardening, stainless, and maraging. The experienced designer, as well as the journeyman and apprentice, can gain valuable design insights by discussing mold applications with a metallurgist at a heat treater or steel supplier.

When designing highly polished mold components, mold-quality tool steels are used. These steels, often formulated by the electroslag remelt process, are pure and free from inclusions.

Steel hardness is an important factor when specifying materials for polished components. Higher-hardness steels are polished and maintain their polish better than softer steels. A minimum of R, 50 assures good polishability. Steels softer than R, 30 are difficult to polish and maintain.

A common misconception about hardness is its relationship to bending. At stresses less than the yield point, soft and hard steels bend equally for a given load. Bending is influenced by the material's modulus of elasticity, which is unaffected by heat treating. A steel's compressive strength, however, increases dramatically with heat treating.

**Prototype Mold Materials**

Prototype molds are built to determine a product's marketability, to prove a part's functionality, or to evaluate shrinkage, warpage, and other molding aspects. Valuable lessons can be learned before committing funds to a production tool. Marketing information that helps determine the required number of mold cavities is also gathered from prototype parts.

Type P-20 steel is popular for prototype tools because of its machinability, polishability, and prehardened condition. Aluminum is also used to build prototype molds. Newer grades of aluminum are highly machinable and have yield strengths that are 75% of P-20, a hardness of R, 16, and thermal conductivities of 91 Btu/h/ft/°F.

Certain aluminums can be polished to an SPI-SPE No. 2 finish. The higher thermal conductivity of aluminum allows these molds to run as much as 25% faster than similar steel tools. The primary disadvantages of aluminum are its gummyness when machining and its inability to resist surface hobbing. Aluminum surface hardness is increased by anodizing or nickel plating. Polytetrafluoroethylene (PTFE) can be added to either surface treatment to add lubricity.

AISI 4140 steel is frequently used for prototypes and limited-run production tooling. This is a chromium-molybdenum steel used in applications similar to those requiring Type P-20 steel.
MOLD PLATING

Mold bases and components are plated and surface treated to resist wear, reduce friction, resist corrosion, add lubrication, impart surface protection, and alter cavity dimensions.

Hard chrome plating, in which chrome is applied electrolytically, is common in the moldmaking industry. Long slender chrome plated cores are susceptible to hydrogen embrittlement and should be baked at 350°F (177°C) for two hours. Chrome plating, due to its high hardness, provides an excellent wear surface but is brittle and prone to chipping. For that reason, chrome is not applied in areas that are subjected to shock or impact.

Titanium nitride (TiN) provides a high-surface hardness and improves mold release properties. TiN is applied by physical vapor deposition (PVD) and chemical vapor deposition (CVD) processes. The low-temperature PVD method is suitable for tool steels. This process is performed at temperatures lower than 500°F (260°C). It is used to coat BeCu cores as well as tool steel, greatly increasing a core’s release characteristics.

Electroless nickel is primarily applied to mold frames, although it is also used on cavities and cores. Providing corrosion resistance and higher surface hardness, electroless nickel is applied in thicknesses of 0.0001–0.002 in. (0.0025–0.05 mm).

Other surface treatments include variations of chrome and nickel combined with other substances such as PTFE, carbide, and phosphorus. Surface impregnation treatments also feature agents such as molybdenum disulfide, which acts as a lubricant. These treatments are migratory and must be reapplied periodically.

In general, plating extends the life of molds and is used for wear and part release, as well as corrosion and erosion protection. Coatings are used extensively in the moldmaking industry and are applied to all types of molding processes such as injection, compression, rotary, etc. These coatings are needed because they increase cycle time, lower core friction, and sometimes may reduce or eliminate the need for mold release compounds. Determining the features and benefits of any plating application is very important. Good research on plating will result in a better coating application.

CHROMIUM

Chromium plating is the oldest coating on the market. All other electrolytic applied coatings are compared with it as a benchmark. It offers some uncommon features and can be polished to an A1 finish (see Table 4-6). It has excellent wear properties with corrosion resistance, and has a coefficient of friction of 0.15. The corrosion resistance of hard chromium is affected significantly by the condition of the base metal. Reduce imperfections to obtain the best possible corrosion resistance. A properly ground or polished tool plated with hard chromium has a smooth homogeneous surface and is free of defects. It will pass a 72-hour standard salt spray test with ease. Polishing after plating will lower the coefficient of friction and increase the corrosion protection.

Understanding the plating process and electrode/anode design is critical when plating chromium. When plating critical sharp edges or shut-off areas, it is common to use a thief to draw plate material away from those areas. There are two types of anodes: tank and conforming anodes. Tank anodes are used for plating large flat plates. Conforming anodes are used on a bar or fixtures and are designed around the shape of the tool. They are used in most plastic injection molds where tolerance control is important. The racking fixtures are designed so that changing loads is easy if many parts are plated. To accomplish this, elevate the piece or plated part with a small block of steel. By removing the block, the mold can be lowered without disturbing the set-up. The coating can be chemically stripped and replated many times. Excessive edge buildup is always a concern.

Summary

This coating is highly effective for excellent wear and release capabilities, as well as maintaining high finishes. It is also a great choice for fire retardant and glass-filled materials. Table 4-7 compares the various characteristics of all the plating types described in this section.

ENGINEERING NICKEL

Engineering nickel is electrolytically applied and is designed for tool repair or dimensional change. It is made up of a fine grain of pure nickel. Because there is a high demand for production, keeping the tools in use is a major concern. Often, there is not much time to rebuild a new tool. There are several alternatives for repair: welding, chrome plating, or engineering nickel. Welding will always be a strong option in tool repair. However, when the high temperatures of the welding process are undesirable or where

<table>
<thead>
<tr>
<th>Type of Finish</th>
<th>Current SPI Finish Numbers</th>
<th>Description</th>
<th>Previous Finish Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Polish</td>
<td>A1</td>
<td>Comparable to</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>Slightly finer than</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>More imperfections than</td>
<td>2</td>
</tr>
<tr>
<td>Paper</td>
<td>B1</td>
<td>Finer than</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td>Slightly finer than</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>Comparable to</td>
<td>3</td>
</tr>
<tr>
<td>Stone</td>
<td>C1</td>
<td>Finer than</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>Slightly finer than</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>Comparable to</td>
<td>4</td>
</tr>
<tr>
<td>Dry Blasted</td>
<td>D1</td>
<td>Finer than</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>D2</td>
<td>Comparable to</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>D3</td>
<td>A little more coarse than</td>
<td>5</td>
</tr>
</tbody>
</table>

(Courtesy The Society of the Plastics Industry, Inc., Moldmakers Division)
TUNGSTEN NICKEL

Summary

this coating shows no signs of breakdown. Applied to most areas. After 70 hours of ASTM salt spray testing, plating requirements will be met. This coating can be selectively applied to most areas when repairing a stripper ring, a bead is welded on the shut-off edge. Then engineering nickel is applied on the remaining portion to create a dimensionally correct mold after machining. This will be machined in one process and produces a very hard edge due to the welding. Engineering nickel, sometimes called sulfamate nickel, can be easily stripped. However, this is a slow process. It is recommended that if large amounts of plating must be removed, it should be machined off. Like chromium, this is an electrolytically applied process using special fixtures or anodes to control the plating process. It is extremely difficult to control an edge buildup. Special thieves are designed to help reduce an edge buildup. The uniformity of this coating is easier to control on outside diameter (OD) surfaces. In all applications, it is more desirable to plate over the edges of the plated material (substrate). The most difficult part of the plating process is getting adequate plate in a low-density area or the corner. By plating onto the adjacent wall, it is more likely that the plating process is getting adequate plate in a low-density area or the corner. By plating onto the adjacent wall, it is more likely that the plating process is getting adequate plate in a low-density area or the corner. By plating onto the adjacent wall, it is more likely that the plating process is getting adequate plate in a low-density area or the corner. The uniformal tool. Tungsten nickel is unique in many ways. Unlike chromium, which is crystalline in structure, tungsten nickel is an amorphous coating that offers protection against corrosion and chemical attack. Tungsten nickel is considered a suitable replacement for chromium plating because it is more environmentally friendly. In some areas, it offers benefits that exceed chromium plating. Because chromium is crystalline in structure, gases can permeate the coating and attack the base metal. Polishing the chromium after plating greatly reduces this possibility. With the amorphous-like structure of tungsten nickel, this concern is virtually eliminated. The coatings can be polished to an A1 finish and the coefficient of friction is equal to chrome plating with approximately the same hardness.

If part of the tool is plated for repair, chrome can be applied over the entire molding area to camouflage the repair work. Sometimes, when repairing a stripper ring, a bead is welded on the shut-off edge. Then engineering nickel is applied on the remaining portion to create a dimensionally correct mold after machining. This will be machined in one process and produces a very hard edge due to the welding. Engineering nickel, sometimes called sulfamate nickel, can be easily stripped. However, this is a slow process. It is recommended that if large amounts of plating must be removed, it should be machined off. Like chromium, this is an electrolytically applied process using special fixtures or anodes to control the plating process. It is extremely difficult to control an edge buildup. Special thieves are designed to help reduce an edge buildup. The uniformity of this coating is easier to control on outside diameter (OD) surfaces. In all applications, it is more desirable to plate over the edges of the plated material (substrate). The most difficult part of the plating process is getting adequate plate in a low-density area or the corner. By plating onto the adjacent wall, it is more likely that plating requirements will be met. This coating can be selectively applied to most areas. After 70 hours of ASTM salt spray testing, this coating shows no signs of breakdown.

Summary

Engineering or sulfamate nickel can be considered for tool repair and dimensional change. It can often extend the life of a tool.

TUNGSTEN NICKEL

Chromium, engineering nickel and tungsten nickel are all electrolytically applied. This means conforming anodes or electrodes are used in the plating process to dissipate the plating over a particular tool. Tungsten nickel is unique in many ways. Unlike chromium, which is crystalline in structure, tungsten nickel is an amorphous coating that offers protection against corrosion and chemical attack. Tungsten nickel is considered a suitable replacement for chromium plating because it is more environmentally friendly. In some areas, it offers benefits that exceed chromium plating. Because chromium is crystalline in structure, gases can permeate the coating and attack the base metal. Polishing the chromium after plating greatly reduces this possibility. With the amorphous-like structure of tungsten nickel, this concern is virtually eliminated. The coatings can be polished to an A1 finish and the coefficient of friction is equal to chrome plating with approximately the same hardness.

This coating is extremely durable and can be chemically stripped. Tabor wear testing showed that tungsten nickel outlasted chrome and electroless nickel. The coating is very ductile and the corrosion resistance surpasses most other applications. This coating survived seven days immersed in 5% sodium chloride acidified with acetic acid to a pH of two and saturated with hydrogen sulfide (NACE test). There were no signs of corrosion.

A tungsten nickel polytetrafluoroethylene (PTFE) coating has PTFE evenly dispersed throughout the plating. This lowers the coefficient of friction and adds a new dimension to the tungsten nickel.

Summary

Tungsten nickel has potential for use as a substitute for chromium plating.

ELECTROLESS NICKEL

Unlike electrolytically applied coatings, electroless nickel (EN) is applied without current. There are no conforming electrodes or anodes needed for the plating process to take place. The base metal is stimulated before the plating by going through a series of pretreatment tanks. One of the best features of this coating is that it plates uniformly. There are no buildups on the edges as in electrolytically applied plating processes. The ability of this coating to flow into deep slots and pockets uniformly is a great advantage over electrolytically applied coatings where plating buildup is a problem and invites the opportunity for chipping and peeling.
With this coating, a very tight uniform plating range is maintained. Electroless nickel has slightly lower adhesion capabilities than electrolytically applied coatings. Electroless nickel can exhibit embrittlement problems on very sharp edges. Tank cleanliness and chemical maintenance are mandatory to ensure the success of this coating. The hardness range is controlled by the additives in the plating bath and baking after plating.

The plater has the option of choosing many different types of electroless nickel formulas or baths. This choice controls several properties such as the hardness, corrosion capabilities, plating rates per hour, and the general quality of the nickel itself. Electroless nickel offers great corrosion protection when gases from PVC or environmental corrosion are a factor. A high-phosphorus electroless nickel (10-12%) offers the best corrosion protection and durability.

A 0.001 in. (0.025 mm) thick deposit will withstand 1,000 hours of salt spray and can pass a 180° bend test without separating from the underlying base metal.

The inherent lubricity and low-friction properties of EN result in smoother release of most molded products. This coating can be polished up to an A1 finish. The coating offers a wide window of application and has been used on firearms, molds, machinery, medical tools, mold base plates, etc. Electroless nickel can be chemically removed without harming the base metal. This process usually takes from one to three days, depending on the plating thickness. Plating the entire tool is most desirable and cost-effective. However, to plate the mold selectively, a process called masking is used. This is done with three coats of a special paint and cured after each coat. Plugs and stoppers can also be used for masking.

Summary

This is a coating that can be uniformly applied and offers great corrosion protection and wear capabilities.

CHROME POLYTETRAFLUOROETHYLENE

This finish offers many of the same features and benefits as chromium plating, that is, low coefficient of friction and excellent wear capabilities. This coating was developed through extensive knowledge of chrome and nickel polytetrafluoroethylene (PTFE) coatings. It offers excellent release and is often used where most other coatings fail in this area. The application of the product is very unusual because PTFE particles are dispersed in the chromium deposit. Polytetrafluoroethylene is composed of small particles measuring 0.00025 in. (0.00635 mm). The results from the Tabor abrasion test show that chrome PTFE had 24% less weight loss than equivalent amounts of chromium. The test conditions were 10,000 cycles with less than a 2 lb (0.9 kg) load using CS-17 wheel on test coupons, each bearing 0.0004 in. (0.01 mm) of plating.

A standard plating procedure is used to apply this coating and it can be easily chemically removed. Masking, if needed, can be easily achieved by the same masking procedure used in chrome plating, that is, paint, lead foil, lead tape, nonconductive tape, etc. Choose this coating instead of chromium when looking for extra wear or release. The increased lubricities are especially well suited for molding applications using plastic, epoxy, silicone and rubber, fire retardant, and glass filled materials. PTFE particles also increase the corrosion protection of this coating and the coefficient of friction is lower than chrome (approximately 0.10). When exposed to salt spray testing, this coating exceeded 500 hours without showing any signs of deterioration.

Summary

This coating is a choice where extra release and wear are needed. This application has performed in areas where all others have failed.

NICKEL PTFE

Nickel PTFE coatings are not new to the industry. There are several different approaches to applying nickel PTFE. The usual procedure is to plate the molding tool with electroless nickel, then spray it with PTFE particles. The final stage is baking the part at a high temperature, 700 or 800˚ F (371 or 427˚ C), to dissolve the PTFE particles into the electroless nickel coating. This application works well; however, because PTFE particles are not completely impregnated in the electroless nickel coating, a premature loss of PTFE particles occurs before the coating is totally worn off the tool and the effect of the PTFE coating is lost.

Nickel PTFE now uses a totally different plating process. PTFE is composed of small particles measuring 0.00025 in. (0.00635 mm). The PTFE particles are dispersed throughout the electroless nickel coating. This is not a multiple step operation, nor is there any high heat used. The PTFE particles suspended throughout the electroless nickel coating is a great advantage. (Full release benefits of the PTFE particles are maintained throughout the thickness of the coating with no premature loss of release.) The electroless nickel bath contains 80% high phosphorus (10-12%) electroless nickel and 20% PTFE particles. This coating is electroless in application and no special electrodes or conforming anodes are needed. It can flow uniformly in most slots and pockets of the molding tool. There are several different types of electroless nickel solutions. Each bath offers different surface properties and a bath for hardness, plating rates, color, brightness, corrosion resistance, etc., can be selected. A high phosphorus (10-12%) electroless nickel used in plating applications over 0.001 in. (0.0254 mm) thick will withstand approximately 1000 hours of salt spray testing. The ability to plate uniformly on complex surfaces is a major benefit when compared to electrolytic coatings. If this application is applied correctly, it can pass a 180° bend test without peeling from the underlying base metal.

The hardness of this coating varies from 48–65 R, (Rockwell Hardness Scale). Hardness is controlled by the electroless nickel formula used and baking after plating. There is a special paint used for selective masking of this coating. However, plugs and stoppers can also prevent the plating from going into holes. This coating can be chemically stripped in 1–3 days. PTFE particles lower the coefficient of friction better than conventional plating baths. However, in some applications, the PTFE particles increase wear or life of the coating when used with abrasive materials such as glass filler or fire retardants. This is probably due to the low coefficient of friction. The molding material has less of an opportunity to come in direct contact with the coating. PTFE particles increase corrosion resistance from chemical attack.

Summary

This coating has a wide application window that offers great wear and release capabilities. Cost is relatively inexpensive when compared with other coatings. The matrix of this coating makes it stand alone against other polytetrafluoroethylene (PTFE) nickel coatings. In addition, this finish will help lower or eliminate the use of mold release and can be polished to an A2 finish.

ELECTROLESS NICKEL CHROMIUM

This coating consists of two plating applications—high phosphorus (10–12%) electroless nickel, and hard chromium plating. Its main function is to change the size of the tool dimensionally; for ex-
ample, to coat a tool with electroless nickel to bring it back into tolerance. This electroless application will flow into cracks and crevices uniformly with no edge buildup. The electroless nickel offers extremely high corrosion protection against gasing. Hard chromium adds excellent release and wear capabilities to this coating. The coating can be applied in most molding applications. It is a good choice when small uniform dimensional change is needed and the hardness of chrome is required. This finish can be polished to an A1 finish and has surpassed 144 hours of salt spray testing. Selective masking can be achieved, if desirable, and the coating is easily chemically removed.

**Summary**

This coating offers uniform dimensional change and superior corrosion protection, and provides increased life to complex tools and assemblies. It offers excellent mold wear and release. For information on other tool surface enhancements and coatings, see Table 18-5 in Chapter 18 of this handbook.

**RECORDKEEPING**

The process of designing, quoting, purchasing, debugging, operating, and maintaining molds demands good recordkeeping. Because many steps are involved for each mold and dozens of molds are on hand, the mold manager benefits by forecasting delivery dates and startup schedules, and by tracking repairs and other modifications. Figures 4-17, 4-18, and 4-19 provide examples of recordkeeping forms. Formal, involved records may not be required; simple, one-page records often suffice.

**FLOW ANALYSIS**

As the injection molding industry gains confidence in molding analyses, these tools become faster and less costly. Two-dimensional (2D) flow analysis is faster and less expensive than its three-dimensional (3D) counterpart. However, 2D analysis is somewhat limited in predicting certain complex plastic flow patterns.

While 2D and 3D analyses are used to evaluate flow in the hot manifold, sprues, runners, gates, and cavities, 3D analysis is primarily used for cavity filling.

**THREE-DIMENSIONAL ANALYSIS**

In 3D analysis, a geometric mesh is generated, and a finite element analysis is conducted. The cavity configuration is constructed with lines and points called nodes using a preprocessor; a postprocessor analyzes the data and creates colorful representations of the part. The representations show the flow, temperature, stress, and pressure profiles in the part. The primary benefit of this approach—if an accurate model is built—is that potential problem areas in complex flows are exposed.

**TWO-DIMENSIONAL ANALYSIS**

Two-dimensional analysis is accomplished by laying out the entire plastic shot, dividing it into flows and sections. The runner, gate, and cavity dimensions are entered into a mold file, and material rheology data, molding parameters, and the mold file are then entered into the 2D program. Pressures, filling times, stresses, and end-of-fill temperatures are generated by the software for each section of the mold file in sequence. The output information is then analyzed, and inputs are adjusted and rerun until a balance is obtained.

The analysis results are used to improve injection molding performance and address the following issues:

- Part filling.
- Weld line location.
- Cavity-filling uniformity.
- Optimum wall thickness.
- Best gate locations.
- Optimum runner sizes.
- Proper melt temperature.
- Expected cooling time.
- Effect of a hot runner on cavity filling.

**Advantages**

Two-dimensional flow analysis is less costly than its 3D counterpart. The 2D software itself is less expensive, and the time-consuming creation of a 3D geometric mesh is eliminated. Two-dimensional analysis is also better suited to successive iterations of data, for example, wall thickness, melt or mold temperature, fill time, and runner or gate size. A 2D analysis may also be used to troubleshoot molds before making modifications to the tool. Finally, less computer time is required to run a 2D analysis.

**Analysis Steps**

Eight steps are used to complete a 2D analysis.

1. Rheology data are gathered for the molded material resin. These data consist of eight identifying numbers, which are stored in the program’s library and reused as needed. The numbers represent thermal conductivity, specific heat, and density at melt temperature; freeze temperature; no-flow temperature; a viscosity factor; a shear factor; and a temperature factor.
2. Gate location(s) are determined. An intuitive choice is made first, and the program is run. The results are then analyzed, and modifications are made until a balance or otherwise favorable results are obtained.
3. The shot is divided into flows and sections. A flow is a flow path of the melt through the sprue, runner, gate, and cavity. When the flow path divides, another flow path is created. Each flow is divided into sections as the geometry of the flow changes. The output of the program is pressure, fill time, stress, end-of-fill temperature, and cooling time for each section in every flow.
4. Flow distance is measured manually for each section of each flow in the flow path of the cavity. Other sections (sprue, run-
### Mold Progress Report

<table>
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<tr>
<th>Design</th>
<th>Date</th>
<th>Mold Base</th>
<th>Date</th>
<th>Cavities/Cores</th>
<th>Date</th>
<th>Comments</th>
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<td>Polish/Texture</td>
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**Weeks:** 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35

**Fig. 4-17** Mold progress report. (Courtesy SPI Moldmakers Division)
<table>
<thead>
<tr>
<th>Customer Name</th>
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<tbody>
<tr>
<td>RFQ #</td>
<td>Quote #</td>
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<tr>
<td>of</td>
<td>Total No. of Cavities</td>
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</table>

### Type of Mold

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<tr>
<td>Compression</td>
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<tr>
<td>Transfer</td>
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<tr>
<td>Other</td>
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### Design by

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<th>Notes</th>
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<tr>
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<td>Customer</td>
<td>Layout Only</td>
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### Mold Construction

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<tr>
<td>Mold Base Steel</td>
<td>#1, #2, #3</td>
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<tr>
<td>3 Plane</td>
<td>S.S.</td>
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<tr>
<td>Stripper</td>
<td></td>
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<tr>
<td>Insulated Runner</td>
<td>Inserted</td>
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<tr>
<td>Reverse Ejection</td>
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<td>Primary Cavity</td>
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### Type of Gate

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<tr>
<td>Center Space</td>
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<tr>
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<td>E.J. Blade</td>
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<tr>
<td>Pin Point</td>
<td>Sleeve</td>
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<td>Hot Bushing</td>
<td>Stripper</td>
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<td>Post Gate</td>
<td>Air</td>
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<td>Other</td>
<td>E.J. Bar</td>
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<td>Easing</td>
<td>Unseating (Auto)</td>
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<td>Special Features</td>
<td>Guide Ejectors</td>
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<td>Cavities</td>
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<td>Cavities</td>
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### Cooling / Heating

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<td>Cavities</td>
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<tr>
<td>Cores</td>
<td>Boxes</td>
</tr>
<tr>
<td>Cores</td>
<td>Mold Base</td>
</tr>
<tr>
<td>Cores</td>
<td>Other (Specify)</td>
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<tr>
<td>Micro Switches</td>
<td>Engravings</td>
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<tr>
<td>Moldmaker</td>
<td>Molder</td>
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<tr>
<td>Supplied by</td>
<td>Mounted by</td>
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### Material

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<tr>
<td>Cores</td>
<td>Tool Steel</td>
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<tr>
<td>Cores</td>
<td>Ben. Copper</td>
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<tr>
<td>Cores</td>
<td>Pre-Hard</td>
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### Hardness

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### Moldmaker

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<td>Mold Flow Analysis By</td>
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<td>Controller Supplied By</td>
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<td>Molder</td>
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### Molder

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Fig. 4-18 Mold data sheet: example 1. (Courtesy SPI Moldmakers Division)
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<tr>
<td>Account Manager __________________________</td>
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<tr>
<td>Date of Request _________________________</td>
</tr>
<tr>
<td>Quote Due ______________________________</td>
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<tr>
<td>Job Number Assigned _____________________</td>
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<table>
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<tr>
<td>Customer _________________________________</td>
</tr>
<tr>
<td>Attention ________________________________</td>
</tr>
<tr>
<td>Phone ________________________________</td>
</tr>
<tr>
<td>Inquiry No. ______________________________</td>
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<table>
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<th><strong>PRODUCT INFORMATION</strong></th>
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<tr>
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<td>Revised ____________________</td>
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<tr>
<td>Part Name ________________________________</td>
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<tr>
<td>Plastic Material __________________________</td>
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<td>Supplier ________________________________</td>
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<table>
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<tr>
<td>Molding Machine ______________________________________________________________________</td>
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<td>Clamp _____________________ tons U.S.</td>
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<tr>
<td>Locking Ring ______________ in. Diameter</td>
</tr>
<tr>
<td>Machine Knock Out Spacing __________ in.</td>
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<tr>
<td>Clamp Stroke ______________ in.</td>
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<tr>
<td>Minimum Mold Height __________ in.</td>
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<tr>
<td>Maximum Mold Height __________ in.</td>
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</tr>
<tr>
<td>Customer ______________________________</td>
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</tr>
<tr>
<td>Design Type __________________________</td>
</tr>
<tr>
<td>No. 1 __________________________________</td>
</tr>
<tr>
<td>No. 2 __________________________________</td>
</tr>
<tr>
<td>No. 3 __________________________________</td>
</tr>
<tr>
<td>Other, Specify ______________________</td>
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<tr>
<td>Title Blocks __________________________</td>
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<td>Vendor ________________________________</td>
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<td>Product CAD/CAM Data Base Furnished by Customer? ______________________</td>
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<td>Format IGES __________________________</td>
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<tr>
<td>No. of Molds ____________________</td>
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<tr>
<td>No. of Cavities ____________________</td>
</tr>
<tr>
<td>Cavity Per Block ____________________</td>
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<tr>
<td>Spares with Mold ______________________________________________________________________</td>
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<tr>
<td>Type of Mold __________________________</td>
</tr>
<tr>
<td>Two-plate __________________________</td>
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<td>Three-plate __________________________</td>
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<td>Hot Tip ______________</td>
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<tr>
<td>Pins ________________</td>
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<tr>
<td>Sleeves ______________</td>
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<td>Return Pins ______________</td>
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<td>Hydraulic Cylinder __________</td>
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Fig. 4-19 Mold data sheet: example 2. (Courtesy Caco-Pacific Corporation)
### ALIGNMENT
- Tapered Round
- Tapered Between Individual Cavity/Core
- Vertical Straight
- Leader Pins

### ELECTRICAL
- Power Connector Type
- Thermocouple Connector Type
- Transducer Type
- Other, Specify
- Terminal Box Built By
- Electrical Controller Built By

### AIR REQUIRED
- Cavity
- Core
- Mold Base
- Other
- Inlet Location

### COOLING/TEMPERATURE CONTROL
- Cavity
- Core
- Plates
- Connectors
- Flush
- External “In” Location
- “Out” Location
- Brand of Connectors

### MOLD BASE DATA
- Purchase Built By
- Vendor Custom Base

### MOLD BASE MATERIAL
- 4130 Prehard
- 420-SS Prehard
- Nickel Plate
- Water Plates Only
- Other
- All Plates
- Insulation Plates

### MOLDING COMPONENTS
- Material
- Hardness
- Surface Finish
- Cavity ID Sequence
- Engraving
- Other
- Texture
- Surface Treatment

#### Main Cavity
- Material
- Hardness
- Surface Finish
- Cavity ID Sequence
- Location of Cavity Identification
- Manufacturing Method

#### Main Core
- Material
- Hardness
- Surface Finish
- Cavity ID Sequence

### MOLDING COMPONENTS MOLD BASE MOUNTING METHOD
- Hot Half
  - Blind Pocket
  - Direct on Flat “A” Plate (Modular)
  - Window Frame
  - Channel with Heel Blocks on Open Ends
- Ejector Half
  - Blind Pocket
  - Direct on Flat “B” Plate (Modular)
  - Window Frame
  - Channel with Heel Blocks on Open Ends

### SPECIAL EQUIPMENT SUPPLIED BY VENDOR OR CUSTOMER
- Heaters
- Probes/Nozzles
- Thermocouples
- Models/Masters/Mandrels
- Gages
- Limit Switches
- Electrical Terminal Box for Hot Runners
- Wiring Diagram for Special Plug
- Mold Electrical Controllers
- Mold Testing Material
- Other, Specify

### Comments:
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

---

Fig. 4-19 (cont.) Mold data sheet: example 2.
MOLDMAKING IMPROVEMENTS

Despite its relatively low profile, the moldmaking industry is strategically important. Because the tooling produced determines the quality limits and dimensional tolerances of molded components, the industry is customer-driven toward leading-edge production technologies. The applied technologies are frequently adopted by other industries.

The moldmaking industry is also important economically. The need to reduce costs has created incentives for adopting the most productive fabrication methods. Pursuing cost reduction is the only practical course of ensuring stability in the moldmaking industry. Alternatives that may have been acceptable in the past—ignoring the competition or imposing protective trade barriers—are no longer feasible.

AREAS THAT NEED IMPROVEMENT

To counter the pressures of low-cost competitors, moldmakers must improve performance in four areas:

1. The first of these is direct production costs, and controlling these costs is mandatory.
2. Quality is another important concern for moldmakers, who must meet increasingly rigorous customer standards.
3. Moldmakers must also work to decrease lead times. By doing so, they gain the double advantage of reducing work in progress and inventory, and increasing their flexibility to take on new work.
4. Finally, the moldmaking industry must adapt to the shrinking pool of skilled craftsmen that is available for postmachining rework and finishing operations. Because these manual skills are in shorter supply and more costly, the industry must reduce its dependence on them.

High-speed Milling

Three methods are used to fabricate dies and molds: electrical discharge machining (EDM), milling at conventional speeds, and high-speed milling (see Fig. 4-20). In comparing these methods, high-speed computer numerical control (CNC) milling now offers the best solution for reducing costs and improving productivity. The choice between EDM and milling is often governed by habit or available equipment. Technical considerations favor EDM for material removal when small, deep molds with small radii are produced or in cases where low workpiece machinability has traditionally made milling difficult. Poor workpiece machinability will continue to require EDM, regardless of the degree of high-speed milling implementation.

However, when permitted by the workpiece, high-speed milling offers important advantages over EDM. It dramatically cuts lead times (EDM requires electrode fabrication time), eliminates surface metallurgical damage common to EDM, provides better dimensional accuracy, and reduces hand polishing and rework time—which can add 30–40% to production costs.

Modern mold milling is performed with CNC machines that provide continuous five-axis milling or intermediate, more user-friendly variants such as 3 + 2 axis control. In either case, the milling is performed with tungsten-carbide or cermet cutting materials at conventional operating speeds and feeds.

A simulated cost structure for in-house operations based on conventional-speed milling of a medium-size mold is shown in Table 4-8.

The relative costs are more important than the absolute values. (A vehicle dashboard mold, for example, may require more than 1000 hours of milling time.) In comparing costs, the semifinishing and finish milling operations represent 50% of the total, and hand polishing, rework, and fitting are another 38%. In addition, more complex configurations and tighter tolerances boost the impact of finishing operations.

The data in Table 4-8 shows that reductions in mold finishing requirements result in major cost savings. High-speed CNC milling offers these savings by eliminating semifinish milling and reducing (sometimes eliminating) hand polishing and rework requirements. Overall, the process provides the following productivity advantages:

- Process simplification. High-speed milling uses a highly abrasive cutting material that can machine preheat-treated steel, thus eliminating intermediate heat treatment.
- High metal-removal rates, resulting in reduced machining cycle times.
- Improved dimensional accuracy. The inherent in-process heat treatment created by conventional-speed milling is eliminated. The extreme dimensional accuracy of the high-speed process generally eliminates subsequent rework.
- Improved surface finish, reducing or eliminating hand-polishing requirements and costs.

Applications. High-speed milling applications are governed by the following parameters:

- Workpiece materials. Cast iron and alloy steels, are preheat-treated to a tensile strength of 145–232 ksi (1000–1600 MN/m²) (R, 30–45).
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• Speeds and feeds. The heat-treated materials are machined at peripheral cutting speeds of 1640–3280 fpm (500–1000 mpm). The high surface speeds allow higher feed rates of up to 390 in./min (10 mpm) for shorter machining cycles, and tighter lateral feeds without compromising cycle time.

Advantages. There are two principal advantages of high-speed milling. Since the universal moldmaking tool is the ball-nose end mill (especially when making convex forms), the tighter lateral feed of high-speed milling permits a smaller peak-to-valley height and thus a finer surface finish. This action in turn shortens or eliminates the final polishing cycle. Since tighter lateral feeds mean slower metal removal, a tradeoff is required between finish cycle times and costs versus final polishing costs. Figure 4-21 schematically represents this tradeoff. A similar model can be developed for each family of molds, classified according to size, complexity, and precision.

One test situation showed that, for a typical mold shape, high-speed milling reduced rough-milling cycle times by a factor of three and finish-milling cycles by a factor of five to ten. In addition, the semifinish operation, usually required with conventional-speed milling, was eliminated.

Cutting speeds of 1640 fpm (500 mpm) and higher provide better tool life because of the modified chip formation. Both the tool and workpiece remain cold, eliminating cratering.

Tool life is also increased by using a highly abrasive polycrystalline cubic boron nitride (PCBN) cutting material. In test applications on preheat-treated mold and die steel, the PCBN cutting edge, combined with higher peripheral speeds, maintains surface finish values approaching those of a ground surface for the equivalent of the surface area of a mid-sized mold. PCBN cutting tools, in high-speed production milling applications, have achieved the following results:

• $2.15 \text{ ft}^2/\text{hour}$ ($0.66 \text{ m}^2/\text{hour}$)
• $R_s$ surface finish: $0.3–0.7 \mu\text{m}$
• Tool life: 5–6 hours

---

### TABLE 4-8

<table>
<thead>
<tr>
<th>Operation</th>
<th>Time (Hours)</th>
<th>Hourly Rate, ($/h)</th>
<th>Total Cost, ($)</th>
<th>Total Cost, (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough milling</td>
<td>30</td>
<td>95</td>
<td>2,850</td>
<td>12</td>
</tr>
<tr>
<td>Semifinish milling</td>
<td>60</td>
<td>95</td>
<td>5,700</td>
<td>25</td>
</tr>
<tr>
<td>Finish milling</td>
<td>60</td>
<td>95</td>
<td>5,700</td>
<td>25</td>
</tr>
<tr>
<td>Hand polishing</td>
<td>75</td>
<td>50</td>
<td>3,750</td>
<td>16</td>
</tr>
<tr>
<td>Rework/fitting</td>
<td>100</td>
<td>50</td>
<td>5,000</td>
<td>22</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>23,000</td>
<td>100</td>
</tr>
</tbody>
</table>

---

Fig. 4-20 Comparison of metal-removal processes. (Courtesy GE Superabrasives)
Cutting Tool Material and Design
Cutting speeds are limited by the cutting-tool material’s abrasion resistance. Modern PCBN materials significantly extend tool life, making high cutting speeds economically feasible.

Figure 4-22 compares the tool life of a P25 cemented carbide tool to that of a PCBN tool as a function of the peripheral cutting speed. The two cutting materials have complementary operational cutting-speed ranges. The carbide tool is used on heat-treated
steels at speeds of 330–650 fpm (100–198 mpm). Above 980 fpm (299 mpm), its performance declines. By using the PCBN tool at this and higher speeds, the higher initial tool cost easily justifies its ten- to fifteen-fold life extension.

Work conducted in Japan (see Fig. 4-23) shows the advantages of using PCBN in place of a cermet cutting material. In the U.S., PCBN ball-nose end mills operating at 2300–3400 fpm (701–1036 mpm) were tested against a similar cermet tool running at 3400 fpm (1036 mpm). Flank wear for each tool was plotted against cutting length. The cermet tool reached 0.004 in. (0.10 mm) flank wear after 490 linear feet (149 linear meters). In contrast, the PCBN tools displayed flank wear of only 0.0012–0.0016 in. (0.03–0.04 mm) after more than 1640 linear feet (500 linear meters).

At one time, PCBN cutting tools were also recommended for cutting speeds of 330–650 fpm (100–198 mpm) and for exclusive use on workpiece materials that were heat treated in excess of Rc 45. More recent testing demonstrates that much higher cutting speeds are needed to optimize tool life, and at these speeds, good tool life is obtained even on softer materials.

PCBN cutting-tool materials are manufactured by a high-temperature, high-pressure process. This process imparts the very high mechanical and thermal properties necessary for high-performance cutting tools.

PCBN cutting-tool materials—which are used for most developmental work in Europe—are available in a variety of formulations. Table 4-9 summarizes the typical physical properties of two PCBN grades: one contains 93% cubic boron nitride (CBN), and the other is a composite CBN/ceramic grade designed for higher thermochemical resistance.

Both grades are used commercially in high-speed mold-milling applications. Cutting-tool manufacturers continue to optimize PCBN tool design.

Tool developers are also investigating the relative merits of PCBN brazed-tip and indexable insert designs. Brazed-tip inserts may offer somewhat better surface finish, since they can be manufactured to closer tolerances. However, the relatively small cost and flexibility advantages of the indexable design may preclude the use of the inserts.

To date, most PCBN tool testing has used 0.787 in. (20 mm) diameter ball-nose end mills. This does not represent a limit but rather reflects the size compatible with most finish-machined surface areas. Ball-nose end mills as small as 0.157 in. (4 mm) in diameter are available; even smaller tools are in development. The size reduction of PCBN tools may only be limited by the maximum available spindle speed.

Testing to optimize operating parameters. A collaborative test program was conducted to investigate the influence of operating parameters and tool design characteristics on surface finish. The test material was heat treated to 232 ksi (1600 MN/m²), frequently used for plastic injection molds. The test machining blocks are defined in Fig. 4-24; machining was done on a 45° inclined plane.

The test tools were 0.787 in. (20 mm) diameter, single-tooth ball-nose end mills. The cutting-tool material was a 93% cubic boron nitride composition. The test program, shown in Table 4-10, evaluated the influence of seven operating parameters, each at three levels.

All other variables, such as cutting-tool material and inclined angle of the workpiece, were kept constant.

All machining was performed without cooling. Furthermore, a single-tooth ball-nose end mill was selected to limit runout disturbances between edges. In production, a minimum of two teeth would be used to optimize the tradeoff between surface finish, tool life, and feed rates.

The influence of each parameter was analyzed and processed according to the Taguchi design of experiments model. An accurate

---

**TABLE 4-9**

<table>
<thead>
<tr>
<th>PCBN Material</th>
<th>Structure</th>
<th>Volume % CBN</th>
<th>Binder</th>
<th>Vickers Hardness</th>
<th>TRS (kg/mm²)</th>
<th>CBN Particle Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCBN 1</td>
<td>CBN/metal</td>
<td>90</td>
<td>Metal phase</td>
<td>2700</td>
<td>200 (1380)</td>
<td>0.3</td>
</tr>
<tr>
<td>PCBN 2</td>
<td>CBN/ceramic</td>
<td>65</td>
<td>Ceramic phase</td>
<td>2400</td>
<td>200 (1380)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

(Courtesy GE Superabrasives)
analysis of the influence of each variable was obtained in a test matrix by running only 18 test combinations.

The selected parameters simulated conditions of machining preheat-treated mold steel on an inclined plane. Rotational speeds varied from 6,750–20,250 rpm. Feed rates ranged from 40–225 in./min (1016–5715 mm/min), translating to machining efficiencies of 0.15-2.60 in.²/min (1-17 cm²/min).

Test results. Each variable was studied for its influence on surface finish quality (as measured by standard Rₐ surface roughness values), both longitudinally (in the feed direction) and transversely. In the longitudinal direction, Rₐ values of 0.15–0.60 µm were obtained, with an average of 0.26 µm. In the transverse direction, the readings ranged from 0.30–1.30 µm, with an average of 0.55 µm. The analysis results are shown graphically in Figs. 4-25 and 4-26.

Although the values obtained in this analysis may not be absolute, they are valid trend indicators. Table 4-11 summarizes the influence of each variable.

The transverse Rₐ values are more sensitive to changing parameters than are the longitudinal numbers. In the latter case, most variables have little significant effect, although increasing the cutting speed and defining the tool with a sharp edge are beneficial.

In the case of transverse Rₐ values, changes in all but two of the parameters have noticeable effects. Surface finish is degraded by increasing the lateral feed rate as well as by combining upcut and downcut milling (a common feature of many machining programs). The negative effects from changes in tool geometry and edge prep suggest that vibration was generated under certain combinations. On the positive side, combining a sharp edge preparation with a machining strategy that maximizes downcutting is highly beneficial.

To determine whether operating parameters could then be selected to yield the best surface finish, a final confirmation run was programmed referencing the test results obtained. The parameters are defined in Table 4-12.

The confirmation run resulted in an average machining efficiency of 0.93 in.²/min (6 cm²/min) and Rₐ surface finishes of 0.12 µm longitudinally and 0.33 µm transversely. If similar surface finishes were reproduced on 3D parts, manual polishing would be totally eliminated from many mold and die milling applications.

None of the PCBN tools used in the testing showed any signs of wear, even in some cases after machining several test block surfaces.

Several ancillary tests were also run. One was conducted with a 0.787 in. (20 mm) diameter, two-tooth cemented micrograin-carbide ball-nose end mill. The parameters are shown in Table 4-13. In this test, good Rₐ values were obtained on the test block surface: 0.18 µm in the longitudinal direction and 0.52 µm transversely. However, after machining one test block surface, the tool showed considerable clearance-angle wear. In addition, the chips had changed from a brown to blue color, and sparks appeared near the end of the machining cycle. Normal cutting speed for a carbide tool in this material is about 260 fpm (79 mpm).

Effects of coolant. Most of the high-speed milling trials run on typical die and mold materials with PCBN cutting tools have not used coolant. Figure 4-27 summarizes the results of testing performed to evaluate tool life when wet- and dry-turning cast iron. In the context of high-speed milling, the dry Z curve is the result of two tool wear mechanisms that have proportionally differing influences as a function of speed.

The hardness of cast iron decreases rapidly at about 750˚ F (399˚ C), whereas the PCBN material softens less severely in a progressive linear relationship up to about 1832˚ F (1000˚ C). At the same time, the temperatures at the tool/material interface and in the shear zones are directly influenced by the cutting speed.

For turning, the speed range of 330–980 fpm (100–299 mpm) does not lead to cast iron softening; however, at 980–2460 fpm (299–750 mpm), the relative loss of cast-iron hardness is greater than that of the PCBN cutting-tool material, and tool life is extended. Above 2630 fpm (802 mpm), the predominant influence...
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Fig. 4-25 Transverse roughness. (Courtesy CETIM)

Fig. 4-26 Longitudinal roughness. (Courtesy CETIM)
on tool life is chemical wear rather than the relative tool/work-piece hardness, due to the much higher temperatures incurred.

Based on these observations, the addition of coolant is advantageous to tool life only at slower speeds, where there is no material softening. In the intermediate speed ranges, the coolant effectively cools the cast iron and so discourages its softening. Furthermore, in the higher speed range, coolant is not applied sufficiently to combat the effects of chemical wear.

In adapting this evaluation to high-speed milling, the effects of coolant-induced thermal fatigue cracking must be considered.

Spindle and Machine Tool Requirements

For all of its productivity advantages, high-speed milling entails a number of significant technical issues, which are best approached by the combined efforts of the machine tool builder, spindle supplier, cutting tool manufacturer, and CAD/CAM specialist.

Components of the overall high-speed milling system are linked as follows. The PCBN cutting tool depends on high-speed spindle technology to achieve its required high rotational speeds. Together, the tool and spindle assembly rely on the machine tool to hold close positional tolerances at high feed rates in a 3D form. Finally, the machine tool relies on a CNC system that can process large quantities of data rapidly enough to control tool displacements at speeds 20–30 times faster than those needed for complex nonlinear trajectories.

Although final specifications for high-speed system components are left to suppliers and the end user, some essential characteristics for the high-speed spindle and machine tool will ensure satisfactory system performance.

<table>
<thead>
<tr>
<th>TABLE 4-11 Variables and Their Influence on Surface Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Increasing cutting speed</td>
</tr>
<tr>
<td>Increasing feed rate</td>
</tr>
<tr>
<td>Increasing DOC</td>
</tr>
<tr>
<td>Increasing lateral feed</td>
</tr>
<tr>
<td>Downcut/downcut</td>
</tr>
<tr>
<td>Downcut/upcut</td>
</tr>
<tr>
<td>Upcut/upcut</td>
</tr>
<tr>
<td>Negative-edge helix</td>
</tr>
<tr>
<td>Neutral-edge helix</td>
</tr>
<tr>
<td>Positive-edge helix</td>
</tr>
<tr>
<td>Sharp-edge prep</td>
</tr>
<tr>
<td>Honed-edge prep</td>
</tr>
<tr>
<td>K-land + hone</td>
</tr>
</tbody>
</table>

Key: “+” = Beneficial effect     “–” = Adverse effect     “0” = No effect

High-speed spindle. The following electrical characteristics are required:

- A synchronous high-frequency motor.
- Constant torque.
- Instrumentation to monitor overheating, vibration, and tool clamping.

The following mechanical characteristics are necessary:

- Very high rigidity and axial and radial stability.
- Compact motor dimensions.
- Excellent dynamic balance.
- A housing with a circulating cooling system.
- Concentricity within 0.00001 in. (0.0003 mm).
- Completely leakproof.
- Quiet operation.
- 5,000–15,000 hours of operation between overhauls.

The integrity of the tool-attachment system is also important. Considering its extremely high rotational speeds, the following characteristics are necessary:

- Ability to transmit high torque and power levels.
- High precision.
- Maximum rigidity.
- Low mass to limit out-of-balance forces.
- High resistance to centrifugal forces (the female cone cannot expand unevenly).
- High tensile blocking force.
- Low noise.
- Safety.

<table>
<thead>
<tr>
<th>TABLE 4-12 Confirmation Run Test Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Cutting speed, fpm (mpm)</td>
</tr>
<tr>
<td>Feed rate, in./tooth (mm/tooth)</td>
</tr>
<tr>
<td>DOC, in. (mm)</td>
</tr>
<tr>
<td>Lateral feed, in. (mm)</td>
</tr>
<tr>
<td>Cutting direction</td>
</tr>
<tr>
<td>Tool helix (°)</td>
</tr>
<tr>
<td>Edge prep</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 4-13 Micrograin-Carbide End Mill Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>Cutting speed, fpm (mpm)</td>
</tr>
<tr>
<td>Feed rate, in./tooth (mm/tooth)</td>
</tr>
<tr>
<td>DOC, in. (mm)</td>
</tr>
<tr>
<td>Lateral feed, in. (mm)</td>
</tr>
<tr>
<td>Cutting direction</td>
</tr>
</tbody>
</table>
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High-speed machine tool. High-speed machine tool performance is maintained with the following features:

- Stable structure capable of damping vibrations.
- Slideways with a low coefficient of friction but a high level of damping; for example, hydrostatic.
- High-rigidity moving parts.
- Drive motors with high acceleration and dynamic ratings.
- A chip evacuation system.
- Ergonomic and fast part-handling system.
- Enclosed machining area for safety.
- Suitable safety instrumentation.
- A CNC system that can handle a large volume of data.

CONCLUSION

Extensive development work indicates high-speed milling technology offers a cost-effective way to fabricate plastic injection molds as well as a viable solution to increasing productivity. Mold and die industries in the United States and Western Europe cannot ignore the potential benefits of this technology in the face of increasing international competition.

References

4. Dym.
8. Witzler.
10. Dym.

Bibliography

P. Bagard, y Crapart, Palleau, Lefebvre, Padilla, Usinage a Grande Vitesse: Application aux Outillages (Senlis, France: CETIM).
Bliki, R., Economic and Technical Advantages of Utilizing PCD, PCBN and CBN Ceramic Composite Tool Materials in Metal-
REFERENCES

Injection Molding, (September 1993), pp. 15–18.
Koenig, M., New Technologies in Milling (Germany: IPT Aachen).
Moulistes: Comment Gagner en Productivite (France Defaux: Techniques et Equipment de Production).
Rigby, Auffret, and Collet, Fraisage a Grande Vitesse Pour L’industrie du Moule, Mold Expo ’92, Oyannax, France.
Tryouts, Startups and Qualifications of Injection Molds, (WJT Associates).
EXTRUSION EQUIPMENT AND PROCESSING TECHNIQUES

The extrusion process converts a solid plastic feedstock material into a molten viscous fluid, and then to a finished solid or flexible film product for practical use. Extrusion equipment consists of a plasticizing extruder, some type of tooling in the form of a die assembly, a cooling assembly, and haul-off or winding equipment. Extrusion is a continuous process, as opposed to molding, which is a cyclic process. Extrusion is suitable for many types of continuous plastic products that have a uniform outside shape and can be coiled, cut, or wound.

The transformation of a solid plastic feedstock material into a molten viscous fluid takes place in the extruder barrel, through the mechanical shearing action of a rotating screw and the heat provided by electrical resistance heaters clamped to the outside of the extruder barrel and die. The combination of the mechanical, rotating shearing action of the screw and the heat of the electrical heaters causes the solid plastic feedstock to change into a hot molten material.

There are two basic types of plastic extrusion: screw extrusion and ram extrusion. This discussion is limited to screw extrusion, because ram extrusion is suitable only for specialized plastics such as polytetrafluoroethylene (PTFE) which cannot be screw-extruded because of its low friction. In ram extrusion, a plunger goes through a barrel and pushes out the material above its melting point and puts the melt under pressure. The molten plastic material can then be forced through an orifice, commonly known as the die. This process is common to all types of extrusion.

The extrusion process can produce pipe and tubing, a variety of profiles, flat products (thin film to heavy sheet), coatings on paper or other substrates, wire insulation, cable jacketing, and monofilaments. All synthetic fibers are produced by some form of extrusion and plastic raw materials are made (compounded) by extruding strands and cutting them into pellets. Examples are blown film for bags, cast film for packaging materials, tubing for catheters, wire insulation for telephone wire, rod for glue guns, profiles for window frames, and monofilaments for fishline and sutures. In all cases, the plastic must be converted from its raw material state—pellet or powder—and melted and pressurized via the extrusion process. After that is done, the material is moved to the die and downstream equipment for completing the desired product.

Any discussion of the extrusion process should begin with the extruder itself.

EXTRUDER DESCRIPTION

Basic extruder components are:

1. An extruder screw is slid into the extruder barrel and rotated by the gear reducer, which is in turn rotated by a DC or AC drive motor coupled directly, through pulleys and/or through sheaves.
2. A feed throat section, which is attached to the gear reducer.
3. An alloy steel barrel usually having a highly wear resistant liner. The barrel is then attached to the feed throat.
4. A mechanical gear reducer with a fixed reduction ratio anywhere from 4:1–25:1, depending on its intended application.
5. A hopper over the opening at the feed end of the barrel, through which material enters, usually by gravity although sometimes force fed. The feed throat is the vertical passage between the hopper and the barrel.
6. A main control panel which contains all necessary electronic controls for temperature, process monitoring and recording, and motor controls.

The Contributors of this chapter are: Frank Goffreda, Vice President, Sales and Engineering, Filmaster, Inc.; Allan Griff, Consulting Engineer, Edison Technical Services; Larry Livinghouse, Technical Sales, Spartech Plastics; Tom Walsh, Director, The Plastics Pipe Institute; Joseph Scuralli, Operations Manager, Wayne Machine & Die Company.

The Reviewers of this chapter are: Allan Griff, Consulting Engineer, Edison Technical Services; Anthony Klusewicz, Sales Manager, Filmaster, Inc.; Ken Rood, Engineering Manager, Plastigage Corporation; Bill Spencer, National Sales Manager, Malish Brush & Specialty Company.

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CHAPTER 5

EXTRUDER DESCRIPTION

In summary, the extruder is a mechanical pump that control the mass flow of a hot pressurized molten liquid by the modulation of the extruder feed screw’s revolutions per minute (rpm), which are in turn controlled by the drive motor’s rpm through the gear reducer. The design and controlling functions of all these items will be discussed later in this chapter.

SCREW

The screw is the heart of the extruder. Just as the heart pumps blood to the body, the screw pumps the polymer through the extruder. The most common type of screw is a single-stage metering screw. The most popular version is a general-purpose screw with a 3:1 compression ratio. It consists of three sections: the feed section, the transition section, and the metering section. These screws typically have a length-to-diameter ratio (L/D) of 24:1.

The polymer is fed through a hopper and falls into the feed section of the screw. The turning screw takes away polymer with each turn and pushes it along inside the barrel. Since the barrel is heated, the polymer begins to heat up. As it goes along, the polymer enters the transition section, where the depth of the screw begins to get smaller, compressing the polymer. For a compression ratio of 3:1 in a 1 in. (25 mm) 24:1 L/D screw, the depth in the feed section might be 0.180 in. (4.6 mm). At the point where the depth of the screw stops decreasing, the metering section begins. Here, for a 3:1 compression ratio, the screw is 0.06 in. (1.5 mm) deep. By the time the polymer reaches this section, it should be melted. The melt is put under pressure in this section and is heated further and homogenized. Finally, the screw pushes the melt out of the extruder at high temperature and pressure. Other factors should be considered in addition to compression ratios: zone balance, preheating, die type, and channel depths have an effect on processing. Zone balance considers factors within the span of the screw such as the length of the feed and metering zones. This will affect the melting or decomposition of the plastic. Preheating means less feed length is needed. Other factors include the die type which determines the mixing amount needed and channel depths which affect screw performance.

Special Screw Designs

A Maddock section is a length of screw about two diameters long normally placed just a few turns before the end of the screw, with large grooves (flutes) parallel to the screw axis instead of flights. Each inlet flute has a corresponding outlet flute separated from it by a barrier ridge. The clearance to the barrel over this barrier is around 0.020–0.030 in. (0.50–0.76 mm). The melt enters the inlets, jumps the barrier through this clearance and leaves through the outlets. Unmelted pellets cannot pass over the whole, but are sheared and flattened as they finally pass through. This device keeps unmelted material out of the die, and thus provides a more uniform melt (see Fig. 5-1).

A barrier screw is a standard screw with an extra flight in the melting (compression) zone that divides it into two channels, one for melt and one for pellets. The new flight is not full diameter, so there is a gap over which the melt can pass into its channel (for example; 0.060 in. [1.5 mm]). The pellets remain in the main channel where they rub and melt more efficiently but are drained of excess melt which might over lubricate them. As the plastic moves down the screw, the pellet channel gets smaller and the melt channel gets bigger. At the end of this section the pellet channel ends and a single flight continues into the metering zone. Figure 5-2 shows a barrier screw. The length of the barrier section was shortened for clarity to four diameters; the usual length is at least 10 diameters.

Mixing pins are rings of studs projecting from the screw root to disrupt streamlined flow, thus improving mixing. Usually they are set in the last quarter of screw length.

Grooved barrels have axial or helical grooves in the feed section to improve the intake of slippery, hard plastics like high-density polyethylene. A screw with a shallower feed and deep metering zone is needed, often with no compression at all. Because a deep-metering zone gives poor mixing, an extra mixing section is needed at the output end.

For vented (two-stage) extrusion, a very long screw is needed, because the material must be melted in the first 70% of length. This first portion is a normal three-zone screw, but at its end the channel suddenly gets deep again, reducing melt pressure so that a vacuum can be applied through a hole in the barrel (the vent) to draw off moisture, air, and volatiles. The melt is then recom pressed, passes through a final metering and mixing section, and goes out through the die.

Additives can be added through a vent—notably glass fiber, which is much less abrasive if added to hot, molten material rather than mixed with hard, solid feed particles.

In a vented screw, the front stage must take away what the rear stage puts into the vent zone, so the front channel depth must be greater. Otherwise, material will come up the vent, which is what happens when the screens get clogged or the feed intake suddenly improves. The ratio of front to rear metering depths is between 1.5 and 2.0. However, deep channels cannot pump well against high pressures, so a vented screw can only work against a maximum of around 2500 psi (17,235 kPa) resistance of screens, head, and die combined. For higher resistance, only a gear pump will allow venting.

In double-flighted screws, there are two parallel paths in part or all of the screw length. This helps heat transfer in the metering zone, so a double-flighted screw is sometimes used for extrusion coating where very high temperatures are desired. The two paths may give smoother feed (less pulsing) and less bending of the screw at the end of the compression zone, but they are seldom used for these reasons. A barrier screw is double-flighted in its barrier section but the two paths are not equal, while a wave screw has a double-flighted section where melt is passed back and forth from one channel to the other, thus improving mixing.
Twin-screw extruders are used in about 10% of all extrusion. There are two screws turning in a figure-8 barrel, usually intermeshing (Fig. 5-3). The screws may turn in the same direction (corotating) or in opposite directions (counterrotating).

Some twins have slow-moving, counterrotating, deep-channel conical screws in a matching barrel; the diverging axes allow bigger bearings which can take more die resistance, as needed for rigid polyvinyl chloride (PVC) pipe and profiles. Fast corotating parallel screws are still preferred for compounding, the other big use for twins. They have shallower channels and may need intensive cooling. They may have ports for additives and venting, and some are even used as continuous chemical reaction vessels.

Twin screws mix by splitting the streams where the flights of each screw come together rather than by the less effective parallel-plane shear of the single-screw systems. There is intense shear in the nip between the two screws, but much less elsewhere, so that the total shear energy input is low. This means lower melt temperature, which is why twins are used for heat-sensitive plastics like rigid PVC. Lower melt temperature can reduce PVC material cost (less stabilizer), making up for the higher machine cost per unit output.

Twin screws give a more positive bite (intake) for easy entry of powders, and are often fed by volumetric or weigh feeders which control production rate.

THE HEAD ZONE

After the material reaches the end of the screw, it passes through the head. First it goes through woven-wire screens which trap contaminants such as bits of paper, wood, and decomposed plastic. A pack of two to four screens fits in a recess on the screw side of a heavy metal disk called the breaker plate. The coarsest screen goes up against the breaker plate and the finest screen faces the screw tip. The thickness of the breaker plate is around 20% of its diameter. It has many holes drilled through it, and can be thought of as a very coarse screen. In addition to supporting the real screens, the breaker plate is the sealing gasket between the head and the body of the extruder. All mating surfaces must be clean and smooth to avoid leakage.

A typical screen pack might be 20-40-60 square mesh (the numbers refer to wires per inch). There are sandwich packs (for example, 20-40-60-40-20) to prevent anyone from putting the pack in backward—that is, with the finest screen up against the breaker plate. In such a case, the pressure of the melt would blow the fine screen through the breaker plate, with bits of contamination and screen in the product, and possible scratching of expensive polished die and roll surfaces.

The pressure entering the screens is the pressure at the tip of the screw, and reflects the combined resistance of the screens, head, and die. It may be very high, but the screens may not blow through because it is the pressure differential across the screens that blows them, not the absolute value. Usually the pressure buildup is slow because contamination enters slowly, and can be monitored by reading the pressure gage or connecting a recorder.

Avoiding Contamination

A screen is used to reduce foreign material (see Fig. 5-4). Sometimes, however, a lot of contamination enters rapidly, such as paper, polyester tape, or perhaps a handful of stones or gravel. In such a case, the screen is blinded; pressure rises rapidly and there is danger of the head and die separating from (blowing off) the extruder. This is dangerous, as hot plastic may shoot out and injure people or damage the equipment.

To avoid this problem, some lines use rupture disks at the screw tip which relieve the melt pressure if it gets too high. Others have shear pins in the gate bolts which are designed to fail under stress and thus allow harmless leakage of the blocked material. Pressure gages can be connected to an alarm to alert operators or shut down the extruder if necessary. Everyone working around an extruder should know the pressure limits, what safeguards exist, and whether they work properly.

Screens are thrown away after use. They can be cleaned, but this is too much work and mess for the value recovered, and they may tear during removal or cleaning. Also, such reuse risks putting them in backward (with the surface that faced the screw now facing the die), in which case the extrusion pressure will push out particles embedded in the wires and contaminate the first product.

Screen changers are devices that allow changing screens without taking the head apart. This saves time and makes less scrap. With the simplest ones, the line is stopped, the head loosened, and the clean plate with screens is pushed into place—thus pushing out the old one with its dirty screens. Better models have a sealing system which allows the line to keep running during screen changes. Some have a prefilled position where the new plate and screens are filled with hot plastic just before entering the head, thus minimizing the disruption of the system—even then, the sudden pressure change may affect product dimensions.

Continuous screeners move a strip of screen or a series of screen pieces continuously across the flow path. Unlike the screen changers, they can keep pressure at the screw tip relatively constant by increasing or reducing the speed depending on the amount of contamination.

Gates

The gate is a thick steel piece that clamps the head and die assembly onto the end of the extruder barrel. The standard gate has four bolts at the corners which must be tightened evenly to avoid leakage. The bolts are attached to the barrel and swing out when their nuts are loosened. The nuts should stay on the bolts to avoid their loss.

Quick-opening gates have only one or two bolts holding the segments of the gate together. This is especially useful for PVC, where cleanup must be fast to avoid decomposition.
CHAPTER 5

EXTRUDER DESCRIPTION

Many gates are hinged on one side for easy screen changing. The hinge pin should be on the side away from the operator, and should come out completely to allow removal of the gate while still attached to the die. This is needed for big dies which have their own supports. Gates may be heated at start-up to make up radiation loss but they are seldom insulated and never cooled.

The adapter is the connecting piece through which the plastic flows, between the extruder barrel and the die.

Temperature Measurement

Temperature measurement of the head and die is done with thermocouples for each zone, set deep into the metal walls. These signals are sent to controllers which regulate the corresponding heaters. Also, a melt thermocouple projects around 0.25 in. (6 mm) into the plastic stream, usually in the adapter after the screens and breaker plate but before the die. It is not used for feedback control, but it does show steady operation and may also signal possible degradation or cooling problems. If there is no melt thermocouple, melt temperature can be determined by sticking a needle pyrometer into the emerging melt or aiming an infrared device at it.

Melt Pressure

Melt pressure is measured at the tip of the screw, just before the screens, where the pressure shows both the contamination on the screens and the resistance of the head and die. This pressure reflects melt temperature, affects the mixing, and stresses the thrust bearing. A second pressure gage may be set in the adapter after the screens; its pressure shows up surges (thickness changes), and the differential pressure across the two gages (hence through the screen pack). The differential pressure can be used to actuate an automatic screen change.

To measure pressure, a thin metal disk is set flush with the inner wall and transmits pressure to an indicator through a solid rod or a tube filled with a liquid such as mercury. It can generate an electrical signal for closed-loop control.

The first pressure gages were grease-filled tubes open to the plastic flow path. These can work if set on the underside of the adapter so that the grease does not leak into the plastic stream, but they are still troublesome and almost all have been replaced by sealed disk-type devices.

Valve

A valve is an adjustable barrier to flow which can raise pressure without clogging, unlike screens. The valve is often a steel rod with a spherical end, threaded into the adapter, and moved up and down by hand or a controlled device. Valves are often seen on vented extruders, but are quite rare on others.

Mixers

Static mixers are flow-diverting devices set between the extruder and the die which divide and redivide the melt as it is pushed through by the extruder, thus achieving better dispersion and mixing. A static mixer increases the head resistance; there is some pressure drop across it which may raise melt temperature. Some mixers are jacketed to provide more heat or cooling as needed. Some are easier to purge and clean than others, and all increase the need for die support because they lengthen the neck between the extruder and the die.

Dynamic mixers are like static mixers but are driven by their own motors, or are extensions of the screw.

Gear Pump

A gear pump (sometimes called a melt pump) may be set between the gate and the die, and takes over the job of pushing the melt through the die. A pair of intermeshing gears turn in a closed chamber, and the melt is carried around in the spaces between the gear teeth and the chamber walls. If a precise drive is used, it gives very uniform output and thus eliminates the effect of surging in the extruder. It also takes some of the load off the extruder motor, which may reduce the pressure at the end of the screw, and possibly the melt temperature. If these are production limitations, the gear pump may allow a higher output rate.
Coextrusion Feedblock

A coextrusion feedblock is another device sometimes found in the head, just before the die. Coextrusion is the combination of two or more molten streams of plastic so that they exit from a single die to give a multilayered, striped, or other multimaterial product. The flows must be similar to get uniform layers, and adhesive layers may be needed to bond incompatible plastics. The passages inside a feedblock are designed like traffic intersections for the smooth and gradual joining of materials in a common stream.

EXTRUSION DIES

The die is a steel block at the output end of the extruder and has a passage with one or more openings that form the final shape. Dies vary widely in size, from tiny wire-coating dies to huge papercoaters 8 ft (2.4 m) or more across.

Heating of a die is done with electrical resistance heaters, either mica- or ceramic-insulated heaters that clamp or bolt to outside surfaces, or cartridge heaters that fit into holes drilled in the die block.

Die heaters are needed for several reasons:

1. To allow safe start-up. Cold starts can cause substantial equipment damage and are a serious safety hazard.
2. To make up for radiation loss during operation. Insulation can serve the same purpose.
3. To control die temperature, either to keep it uniform, or to vary it to get differential flow.
4. To reduce resistance by reducing viscosity at the inner metal surfaces (hot-lips method).
5. To heat the emerging surface for more gloss, less swell, and less chance of melt roughness.

Most dies are made of steel, but lips and inserts for holes may be hardened to reduce wear, and a few dies have low-friction internal surfaces of porous metal impregnated with a fluoropolymer. The formulation of the extruded material may also reduce the friction in the die. Especially for linear low-density polyethylene, there are additives that reduce the friction and thus reduce the melt temperature. This, in turn, means easier cooling and higher production rates. Additives also help production by raising the critical speed where melt roughness would occur.

Brass adjusting bolts may be used in steel dies; they do not rust, offer less turning friction, and, if they seize or otherwise lock, fail before they distort or damage the rest of the die. Chromated interior contact surfaces may avoid corrosion (with PVC) and reduce friction, but must be a thick and adherent layer (no “flash” chrome). With good purging and cleaning, chrome plating may not be needed, even for rigid PVC. However, polyvinylidene chloride (PVDC) and a few fluoroplastics need special anticorrosive metals, not only for dies but for screws and barrels as well.

BARREL

The barrel is a cylinder that the screw goes into. There are two basic types of barrels, nitrided and bimetallic. Nitrided barrels are made of a single steel such as 4140 and are case-hardened to resist wear. Bimetallic barrels are typically 4140 cylinders with a centrifugally cast liner inside. The liner is usually about 0.06 in. (1.5 mm) thick and is made of highly wear resistant material. The type of barrel depends on the polymer compound processed. While working with the screw, the barrel’s function is to melt and pressurize the polymer. The barrel completely surrounds the outside of the screw and provides a surface for friction that the polymer encounters on its way down the extruder. As the screw flight passes, it scrapes polymer off the barrel wall and pushes it along. The barrel is a pressure containment vessel, usually rated up to 10,000 psi (68,945 kPa).

FEED THROAT

A barrel may be one-piece or two-piece. One-piece barrels have a hole in the top of the barrel. The two-piece barrel has a separate bolt-on feed throat between the barrel and the gearbox. The two-piece design is cheaper to make, but can result in barrel misalignment. Some extruder manufacturers require borescoping of the barrels before start-up. Feed throats or sections can be smooth or grooved in both one- and two-piece barrels. Grooved feed throats have straight or spiral grooves cut into the barrel. Some plastics can run at higher outputs with grooved feed throats. However, these throats are not advisable for plastics, such as PVC, that degrade easily. The same is true for frequent-changeover extruders such as those in laboratory and custom environments because material and color can get caught in the grooves and come out later as unwanted streaking and discoloration. Both types of feed throats are typically water-cooled, since the feed throat can get hot and the plastic can melt prematurely, causing a bridge. Once a bridge forms, the plastic cannot flow through the feed throat and output of the extruder stops.

DRIVE AND MOTOR

The function of the drive and motor is to provide energy to turn the screw that compresses the polymer. The drive is typically an electronic variable-speed DC drive. It converts the AC voltage of the plant to DC voltage that runs a DC motor. A potentiometer is used to electronically control the voltage sent to the motor, which is roughly proportional to the speed of the drive. Most DC motors run at 1750 rpm at full voltage. This speed must be stepped down by the gearbox.

Direct current (DC) drives and motors account for about 85% of drives installed on extruders because they offer versatility at a relatively low cost. Alternating current (AC) inverter drives are also used but are typically more costly. Brushless DC drives are also used and can offer full torque over the entire speed range.

There are various types of feedback systems. The most basic is armature feedback, where the control monitors the armature voltage and keeps it constant. Voltage may change because while under load more voltage is needed to keep the same speed. Tachometer, or tach, feedback is often used. A tach is mounted on the rear of the motor and generates a certain amount of volts per rpm. When the rpm lowers without a command from the control, such as in an increasing load situation, the drive compensates to maintain the proper speed. Typical tach feedback systems maintain speed within ±1%. Brushless DC drives go even further, and one manufacturer even offers 0% short-term speed error.

GEARBOX

The function of the gearbox is to reduce the motor speed that is acceptable for screw extrusion. Typical DC motors have a 1750-rpm top speed and typical screws have a 150-rpm top speed, although there are exceptions, like compounding extruders that run up to 350 rpm. The reduction in speed also allows for a torque increase. The best type of gearbox for a single-screw extruder is a double-reduction helical gearbox. Some machines use worm drives, but these are inefficient, generate more heat, and wear more quickly.
Some extruders are direct-drive, meaning that the motor is directly coupled to the gearbox. A more common arrangement is the use of belts and pulleys. This arrangement allows a change in speed range by changing the pulley on the gearbox. This is useful when a machine is used for multiple purposes such as running high outputs of polyethylene and then switching over to fluoropolymers, which require higher torque and typically run in a much lower speed range.

**SMOOTH-BORE EXTRUDER**

This type of extruder is the most prevalent type used today (Fig. 5-5). The name smooth bore signifies that there are no longitudinal grooves in the feed throat section of the extruder. This type of extruder is basically a pump for highly viscous materials or thick fluids. The purpose of the extruder is to deliver a homogeneous molten material at the proper flow rate, pressure, and temperature to the next piece of equipment in the production line; therefore, the plasticating extruder used in polyethylene blown-film lines serves as a melter, mixer, and flow controller.

Most commercial blown-film lines are equipped with either 2.5, 3.5, or 4.5 in. (64, 89, or 114 mm) extruders depending on the output required and the purpose for which the machine was purchased. These machines are usually “low-boy” extruders (they sit close to the floor) that have a barrel length-to-diameter ratio of 20:1, 24:1, or 30:1. Equipment manufacturers recommend machines with 30:1 ratios to give the material more time in the mixing section, especially in the case of processors running both conventional and linear blends.

Most extruders are equipped with DC drives to control the speed at which the screw turns. The size of drive will vary with extruder size. Drives can range in size from 25 hp up to as much as 600 hp (19–450 kW), depending on the size of the extruder and its intended pumping capacity. Normally for polyethylene production, drives are calculated to produce approximately 5–7 lb (2.3–3.2 kg) of product per hour, per horsepower (0.75 kW), as a free discharge from the open end of an extruder barrel. This free discharge rate can drop by as much as 25–35% when tooling is attached to the extruder and the system becomes fully pressurized.

Torque requirements and extruder rpm are a function of the processing material. For most common low-density polyethylene (LDPE) resins, extruders are geared for a top rpm of between 125–140. Generally torque requirements are calculated at final gear ratios of 10:1–14:1 reduction, supplying a maximum torque between 12,000–70,000 in.-lb (1356–7809 N-M) at their maximum rpm, respectively, for 2.5 and 3.5 in. (64 and 89 mm) extruders with 25 and 150 hp (19 and 112 kW) drives.

Other, more viscous, materials such as linear low-density polyethylene (LLDPE) will require the same or greater torque at much lower screw rpm. A typical LLDPE extruder would have an rpm range between 65–90, depending on the size of the extruder and its associated tooling.
EXTRUDER SCREW

The extruder screw determines the extruder’s performance. There are many styles of screw designs available, providing various plasticating, melting, mixing, and overall pumping capabilities, and they have gone through many stages of design improvement. However, the two most common screw designs are the single-stage metering screw and the double-flighted barrier extruder screw.

Generally, screws used for low-density polyethylene service have a constant pitch, while the depth of the channel between flights varies depending on how far down the extruder the measurement is made. The depth of the channel divides the screw into three sections (feed, transition, and metering). The feed section on the drive end is characterized by a constant channel depth. Its purpose is to convey solid pellets from the throat of the extruder to the transition section while warming the material in preparation for melting.

SCREW COMPRESSION RATIO

In the transition section of the ordinary plasticating screw, the depth of the channel decreases farther down the screw. While the outer diameter of the flights remains constant, the root diameter increases. A standard measurement of this change is referred to as the screw compression ratio. The ratio is the depth of the channel in the feed section divided by the depth of the channel in the metering section. Screws used for low-density polyethylene usually have a feed-to-metering compression ratio between 3.5:1 and 4:1. In the transition section of the screw, the solid polymer begins to melt from the rubbing action of the polymer between the screw and the wall of the extruder, and the rubbing action of the pellets on themselves. This rubbing action is referred to in the industry as shear. Figure 5-6 shows cross-sections of the melt taken from various locations of the screw.

Careful examination reveals the progress of the melt as the material moves down the screw. Depending on the operation of the extruder, some heat used to melt the product may come from the extruder wall heaters; but, usually, the walls are used to remove heat with either fan cooling or water jackets. Overheating the polymer can result in the degradation of the material and a loss of product properties. Also in this section of the screw, while the temperature of the product has been increasing, pressure is also building. At the beginning of the transition section, the melt pressure may be only 50 psi (345 kPa), but by the end of this section, the melt will develop anywhere from 3,000–9,000 psi (20,684–62,052 kPa), depending on the operating conditions.

In recent years, processors have been replacing their single-stage metering screws with double-flighted barrier screws, as shown in Fig. 5-7.

In the transition section of the screw another flight has been added with variable pitch. The additional flight creates another channel in the screw. If one were to measure the volume of the original channel in this section of the screw while moving down the screw, and compare it to the volume of the second channel forming, the volume of the second channel would be increasing while the volume of the first would be decreasing. The second flight creates a dam over which the polymer must flow to exit the extruder. Since it is easier for the melt to pass through the clearance between the dam and the extruder wall, melt moves into the second channel and exposes the remaining pellets to shearing and heating. By this operation, the barrier increases the output of the screw and helps to ensure a more uniform melt feed to the mixing and metering section.

MIXING ELEMENT

The next section of the screw may be equipped with a mixing element as shown in Fig. 5-8 to improve the uniformity of the melt, especially when scrap or regrind material is blended into the finished product. Screw manufacturers differ in opinion as to whether the mixing element should precede the metering section or follow it. The most common mixing element is the Maddock mixing head which consists of alternating linear flights and melt...
channels. The polymer is forced to pass through a narrow clearance before it leaves the extruder and roll into the channel. The Maddock head was developed to mix the melt without generating higher temperatures that could degrade the polymer.

Assuming that the mixing section precedes the metering section, the purpose of the final screw section is to meter the product into the flow transfer tube. In this area of the screw, the channel depth is minimized to ensure good contact with the extruder wall, so that output can be controlled. However, if the metering section channel is too shallow, high frictional heat occurs and lower outputs can result. Effective barrel cooling can control excessive frictional heat developed in the transition section, which otherwise might result in polymer degradation.

**COOLING SYSTEM**

The majority of all extruder screws are cored for cooling in their screw shanks up to a distance just past the feed flights. This liquid cooling system, usually a closed-loop system containing water and glycol running through a heat exchanger, increases the coefficient of friction between the feed throat and barrel, compared to the channels in the screw shank, to increase the solids conveyance characteristics of the screw. This helps to increase the extruder’s output and maintain an even, surgefree back pressure in the extruder barrel.

As solid polymer pellets are fed into the throat of an extruder, melting usually begins within a few diameters downstream of the feed inlet. The extruder barrel is usually divided into three to six temperature control zones, depending on the barrel length and diameter. Extruder barrels are also equipped with liquid or air cooling devices such as fans and shrouds, or water cooled cast-aluminum heaters. These devices remove excessive frictional heat generated by the shearing action in the extruder.

**BARREL ZONES**

The barrel zones consist of electrical resistance heaters, with each zone having a thermocouple connected to a three-position electronic temperature controller. Each temperature controller has a display window, usually digital, that will show the set point of the instrument and the actual temperature of the zone. Consequently, an operator can easily see any deviation between the desired set point and temperature for each zone.

The barrel temperature profile should be varied to find the best combination that will generate a uniform melt temperature for a particular machine. Normally, Zone 1, at the feed section, is kept the coolest to keep the material from melting too soon and blocking the feed section.

To ensure uniform heating and melting, it is best to have the zone thermocouples located slightly downstream from the heater bands if possible. All heaters must provide heat at the same rate to the melt according to the dimensions of the heated area. The heater terminals, usually areas where there is no heating strip, should be symmetrically offset from each other in each zone and between zones on a die. If terminals were located on the same side, without heat under the terminal section of a heating band, there would be a cold spot on that side of the die which would result in uneven melt flow and poor gage distribution. Loose heating bands or heating band surfaces not in direct contact with the die will also cause hot and cold spots and will reduce heater effectiveness.

Bad thermocouples can cause uneven heating and degradation of the resin. If the thermocouple is located in a cooler area with poor heat transfer, the melt can be subjected to excessive heat (burn-in) where the heater band is located. Loose thermocouples that do not bottom out in a heating zone will read the zone temperature colder than it actually is and call for too much heat. Most thermocouple manufacturers can provide a heat-transfer medium for the thermocouple well to ensure good thermocouple temperature sensing. Frequent checks of a thermocouple’s condition and connections, and semiannual calibration of both the thermocouple and the zone temperature controller will help to ensure repeatability of processing conditions and good quality control.
BREAKER PLATE

The production end of a film extruder is equipped with a breaker plate fitted with some type of filter element or screen pack. The breaker plate will usually be a flat piece of metal having several holes ranging in diameter from 0.06–0.19 (1.5–4.8 mm). The breaker plate serves to support the screen pack, straighten the spiral flow of the melt, act as a seal between the barrel and the adapter, and build back pressure to help reduce surging in the line. Surging results in nonuniform part wall thicknesses and processing instability. The filter element is usually stainless steel and may be either dutch quill or a four-layer screen pack of 20-, 40-, 100-, and 20-mesh elements. The latter has been gaining broader acceptance. The purpose of the screen pack is to trap contaminants to prevent small clearances in the die, such as the die gap, from plugging.

RUPTURE DISK

The end of the barrel screw is fitted with a rupture disk to prevent the barrel from rupturing under high pressure. If the breaker plate, screen pack, or die begins to plug or the flow becomes restricted, melt pressure will build as the extruder begins to draw more power while trying to maintain screw speed. If the extruder is unprotected, pressure can quickly build to a level high enough to burst the barrel. The disk, usually a thick piece of metal, is designed to rupture at a pressure significantly lower than the burst pressure of the barrel, to protect both the operator and the equipment. An operator who observes frequent failures of the rupture disk may be tempted to install a rupture disk set for a higher pressure; however, in no case should a disk be installed if its rating exceeds the manufacturer’s equipment specification. To do so could result in ruined equipment and serious injury to the operator and any other personnel in the work area.

Before running any type of resin through an extruder, it is of the utmost importance that a processor get a material specification sheet from the resin manufacturer. The specification shows the resin’s suggested running melt temperature, melt flow index, density, and mass flow viscosity. Only then, can a safe working heat profile be established for all the barrel zones. If there is any doubt, check with the resin manufacturer’s technical service representative.

GROOVED-FEED EXTRUDER

The smooth-bore machines and their screws are generally very efficient up to 140 rpm. At higher speeds, they frequently run into problems such as surging, overriding temperature zones, and unstable melt temperatures. High-molecular-weight high-density polyethylene (HMWHDPE), polypropylene (PP), and other materials with a low coefficient of friction are particularly difficult because at high rotation speeds they tend to remain almost static in the extruder barrel as the screw continues to rotate. The result is a dramatic reduction in output.

Various compensatory strategies have been explored, but in terms of realistic bottom-line productivity there is very little that can be done to run most polyolefin materials successfully through small-to-medium-size smooth-bore extruders at speeds above 140 rpm. Instead, processors purchase larger extruders and run them at lower rpm to achieve maximum outputs in a film-producing system; or, they purchase extruders with 28:1–30:1 L/D to increase outputs and keep the melt temperature stable.

By contrast, the grooved-feed throat extruder will produce more output at less input power for a comparable extruder size, while maintaining remarkably consistent pressures and melt temperatures throughout 95% of the operating range from 50–250 rpm. It is primarily the unique design of the feed section that is responsible for the grooved-feed extruder’s success in running various resins at high rotation speeds. The feed section incorporates a cylindrical, removable tungsten carbide liner with a series of grooves machined into its inside diameter.

These grooves run the full length of the liner, spaced equally apart. Extruder screw rotation shears the resin pellets in the grooves, creating tremendous heat and pressure which liquefy the resin while it is still in the feed section. Cooling channels in the outer alloy 4140 steel housing eliminate any excess heat buildup during the process. A typical grooved-feed section is shown in Fig. 5-9.

Of course, precise groove geometry must be achieved with respect to the pellet geometry as well as to the feed flight depth and lead, and, since the resin enters the extruder body already in a melt condition, the design and function of the barrel and screw are necessarily quite different from the smooth-bore counterparts.

Any discussion of exact groove geometry is unavoidably limited by proprietary considerations, and each application must be individually engineered. However, in a general sense, the number of grooves in the tungsten carbide liner is usually determined by the extruder L/D and diameter. In a typical situation, the starting point could be to divide the extruder bore in inches by a factor of 0.4. By this design, a 2.5 in. (64 mm) 24:1 L/D extruder would require 6.25 grooves, which can be rounded to 6. By the same design, the length of the grooves would be determined by the extruder diameter multiplied by a factor of 4.

The width and taper of the grooves are also extremely important. The width range is usually 0.18–0.38 in. (4.6–9.7 mm), and the depth range is approximately 0.12–0.44 in. (3–11.2 mm). Depending on running conditions and resins, the taper can be as much as 3° for the entire length of the groove.

In several instances, it has been observed that by increasing the number of grooves and carefully arranging their spacing, dramatic performance improvements may be achieved.

Another important design feature is the predetermined air gap situated at the juncture or connection point of the extruder barrel and the production end. The purpose of the air gap is to trap contaminants to prevent small clearances in the die, such as the die gap, from plugging.

Fig. 5-9 Typical grooved-feed section. (Courtesy Filmaster, Inc.)
Chapter 5

Grooved-Feed Extruder

This process uses an extruder to pump the molten fluid through a die head having an annular circular opening at its top, forming a 360° annular orifice. The width of this opening is usually from 0.020–0.125 in. (0.5–3.2 mm) wide, depending on the material to be processed. The blown-film process produces films that come out of the extruder in a round tube. Typical products made by the blown-film process are plastic bags of all types and certain films such as agricultural films. The plastic goes through the adapter and around a pin with spirals cut into it. This is why blown-film dies are sometimes called spiral mandrel dies. The dies are sized by the diameter of the pin at the output end. For example, a 2 in. (51 mm) spiral mandrel blown-film die would have a 2 in. pin at the output. There is a hole that runs through the mandrel completely and at an opening at the top of the die and at the bottom. This hole is kept open on the top and is connected to a compressed-air source with a shutoff valve at the bottom. There are four adjustment bolts on the die that allow the operator to adjust the thickness of the film. The outside piece or die should be concentric with the mandrel or pin. However, sometimes the material flow is not perfect and there is more pressure on one side of the die than the other. Then the operator must slightly close off one side and slightly open another to get a uniform bubble. This concept of adjusting dies is important in every type of extrusion. There is no such thing as making a fixed die that is machined perfectly that will give perfect output day after day. Adjustment of the die is part of setting up all extrusion lines.

Air Ring

At the top of the die is a device called an air ring. The function of the air ring is to cool the circular extrudate, also known as the bubble, by blowing air around the outside of the extrudate. Air rings are supplied with air by a blower. Hoses run from the blower to the air ring. The point on the bubble where the plastic turns from a liquid to a solid is called the frost line. The extrudate is cooled and then runs to the top nip, which usually consists of two rollers, one steel and one rubber-coated, and a collapsing frame. The top nip pinches off the bubble, causing two creases in the film and making it flat. The collapsing frame helps to guide the bubble as it collapses. The top nip also serves to seal the bubble. When the line is strung up, the plastic is pulled by the operator up to the top nips. Then the operator must fill the bubble with air. Like a balloon, the bubble gets larger as the operator blows more air into it. The diameter of the bubble compared to the diameter of the die is called the blowup ratio. The size of the bubble determines the layflat width of the film, which is the width of the film when it comes out of the top nip. The film is then guided by rollers to a turret winder, where it is wound on a core (see Fig. 5-11). These cores can later be put on bag-making machines, where the layflat film is sealed, serrated, and rewound on cores. Alternatively, the layflat film can be slit and unfolded, making a flat film twice the size of the layflat.

Monolayer Dies

The bottom-fed monolayer spiral die processes a molten extrudate through its feed ports and spiral channels. The key consideration is to evenly distribute the polymer and create a peak axial and tangential flow profile so that, as the melt emerges from the annular die gap, it is uniform and equal in velocity for 360° of the die opening.
Fig. 5-11 Blown-film line. (Courtesy Filmaster, Inc.)
This type of die processes only one resin, or blend of resins, and produces a single-layer structure having only the mechanical or barrier properties of the one resin or blended resin being used. This type of die is used in 85–90% of the blown-film industry and accounts for most of the trash bags, carrier bags, produce bags, and shopping bags. It also accounts for much of the individual wound sheeting film produced for use in high-speed packaging and laminating machines. In essence, this type of die is the backbone of the blown-film industry and is in use throughout the world.

The monolayer die typically processes LDPE, LLDPE, and HDPE (low-density polyethylene, linear low-density polyethylene, and high-density polyethylene), as well as almost every other common polyolefin. It also processes nylon as a single-layer structure when designed especially for this resin, as well as polypropylene.

**Heat Zones**

The dies are equipped with electrical heaters and are divided into heat zones similar to those on an extruder barrel, with each heat zone under the control of a temperature controller with feedback from a thermocouple. They also incorporate a mechanism for adjusting the die gap annular opening to control the extrudate wall thickness.

As noted, a well-designed spiral die in either monolayer or coextrusion configuration will be designed for peak axial and tangential flow profile, as illustrated in Fig. 5-12. Maintaining this

![Fig. 5-12 Spiral die designed for peak axial and tangential flow profile. (Courtesy Filmaster, Inc.)](image-url)
relationship of the two flows is extremely important, as it serves to form a homogenous melt and eliminates port lines. Port lines are vertical stripes or translucent bonds 0.250–0.375 in. (6.4–9.5 mm) wide. This effect is usually attributed to a supervelocity axial flow that does not combine with the tangential flow to form a uniform mix. The die designer must consider these two flows and design the spiral channel width, depth, lead, and total wraparound angle on the spiral mandrel to design a flow-balanced die for the best polymer distribution.

**COEXTRUSION**

So far this chapter has discussed the extrusion of monolayer products, or products made solely from one material such as LDPE, LLDPE, HDPE, and various other types of common polyolefins. Other products made from a combination of various materials forming a composite structure are known as coextruded products and require special tooling on systems to produce them.

Coextruded products combine various materials to produce products with special properties, for example, enhanced structural strength or barriers that curtail the transmission of oxygen or moisture. This applies especially to flexible films that are used for solid food, liquid packaging, or items that require a package that keeps odor out and flavor fresh. In other cases, barrier films are used to contain oils and fatty meats to prevent spoilage when these products are not refrigerated.

Examples of barrier films are those containing nylon, ethyl vinyl alcohol, or polypropylene in combination with LLDPE, LLDPE, or HDPE resins and certain ionomers used as adhesion layers, more commonly referred to as tie layers. These layers bond one material to another incompatible material in a coextrusion structure. Certain materials, such as nylon and ethylene vinyl alcohol, will not bond to LDPE, LLDPE, or HDPE without a tie layer.

**COEXTRUSION BLOWN-FILM DIES**

The coextrusion blown-film die head assembly, or any type of coextrusion tooling, combines various individual materials into one composite structure to produce either a high-strength product or a product having some type of barrier properties.

In the case of a three- or five-layer blown-film die, the die incorporates several individual spiral mandrels nested one on top of the other, all contained in a common housing known as the die body. Each spiral mandrel releases its polymer flow into a common channel that is formed by the die body assembled to the flange of the outer-layer spiral section or the first spiral section. The entire die assembly is attached to a fixed block or an oscillator assembly. In a three-layer system, there would be three fixed or oscillator blocks and three transfer tubes stacked one on top of another.

In the fixed-block arrangement, the die head is stationary, whereas in the oscillating arrangement, the last block, commonly called the top block, incorporates radial bearings and a thrust bearing to support the oscillator neck and sprocket or gear assembly, which is driven by a 1500:1 gearhead reducer and an AC electric motor. Consequently, this arrangement allows full 360° oscillation, clockwise and counterclockwise, of the die assembly at very slow speed, 1–1.5 rpm in both directions. The job of the oscillator is to randomize the extrudate so that oxygen or nitrogen is prevented from being delivered to the annular die gap opening, thereby creating a more uniform wall thickness.

Figure 5-13 illustrates a typical three-layer coextrusion die assembly and an oscillator assembly. The most common three-layer coextruded film it produces is an LDPE-HDPE-LLDPE structure. A three-layer system is also extensively used when a processor wants to use scrap pelletized material or reground fluff material in the center layer to make trash liners or garbage bags.

Flow manifold. Normally a three- or five-layer system will use an extruder for each layer, but it can also incorporate a flow manifold, in which one extruder feeds the same material to two layers of the final composite. However, because of their tortuous flow path, manifolds are useful only for materials that are not heat sensitive and do not easily degrade. Consequently, they are not used for nylons, ethylene-vinyl alcohol copolymer (EVOH), polyethylene terephthalate (PET), PVDC, and other heat-sensitive resins that must travel at a constant velocity in streamlined flow passages having no dead spots or hang-up areas where the polymer could degrade or burn up, forming carbon.

Flow usually is distributed through the connection point of the extruder to the oscillator, or fixed block, and transfer tube assembly. Each block has a vertical tube which guides and constrains the polymer as it heads toward the die assembly. These blocks and tubes are stacked on each other, and the annular clearance between the outside diameter of one tube with respect to the inside diameter of the other tube creates an annular, vertical flow channel for each layer, with flow for the inside layer being on the inside of the innermost vertical tube.

Flow distributor. At the top of each flow tube is a flow distributor which evenly distributes the polymer flow into the feed points of each spiral section. The spiral sections are insulated from each other by an annular air gap between their male and female pilot diameters to prevent or minimize heat exchange between polymers at various temperatures. These pilot diameters also ensure that the spiral mandrels are all nested concentrically to provide balanced flow.

Oscillator assembly. In an oscillator assembly, the bearings are prelubricated with a high-temperature, high-pressure lubricating grease, which is relubricated at least once a week, or more often, depending on the melt temperatures and pressures of the polymers being processed. This assembly sees tremendous pressures and heat loads 24 hours a day for over 8000 hours per year, in most cases. To say the least, they are very rugged, designed especially to withstand these hostile operating conditions.

The entire assembly, on a three- or five-layer system, comes equipped with 10–15 separate heat control zones, all individually monitored and controlled by temperature controllers or a microprocessor control system. Heat is supplied by either radiant or conduction electrical resistance heaters.

**Processing Metalloocene Resins**

Coextrusion systems are used to process a whole group of polymers much different from the common polyolefins already discussed, and it is worth briefly mentioning metalloocene resins as they are becoming more common for commercial use and for many film applications. This single catalyst resin, with its long branch chain, definitely improves processibility and greatly enhances the mechanical dart impact properties of the film. In many ways this resin process, like LLDPE, has one big advantage that current LLDPE resins do not offer—that of extremely good optics and clear film. The resin is also successfully used as a seal layer on laminations and coextruded products. It shows great promise when it is used in conjunction with conventional LLDPE as an additive to increase the impact and tear strength of the final film product.

Metalloocene resin has an extremely low melting point, 212˚F (100˚C). In its molten form it is a very viscous material similar to LLDPE fractional melt resins. Therefore, a prospective processor should take the following into account before trying to run this material on a conventional LDPE blown-film line.
Fig. 5-13 Typical three-layer coextrusion die assembly and oscillator assembly. (Courtesy Filmaster, Inc.)

1. Top pin
2. Die bushing
3. Inner pin
4. Middle pin
5. Bottom pin
6. Body
7. Diverter cone
8. Metal O-ring
9. Socket head cap screw
10. Heater
11. Heater cover
12. Bottom block
13. Middle block
14. Top block
15. Oscillator nut
16. Oscillator neck
17. Outer tube
18. Inner tube
19. Clamp ring
20. Nut seal ring
21. Inner tube seal
22. Outer tube seal
23. Lower neck seal
24. Packing
25. Radial bearing
26. Thrust bearing
27. Flat head screw
28. Die adapter
29. Sprocket
1. The die should be a typical lower pressure spiral die with either 0.500 or 0.625 in. (1.3 or 1.6 cm) diameter feed ports and spiral channels.

2. Die gaps should be anywhere from 0.060–0.090 in. (1.52–2.3 mm) and of the reverse land type, commonly found in LLDPE die lip design.

3. The extruder should have sufficient horsepower to process this more viscous melt and should be geared down to produce a maximum of 100 rpm at its highest speed. In conjunction with the greater horsepower required at the lower extruder rpm, the extruder gearbox must be checked for its mechanical and thermal efficiency at lower speeds and higher torques.

4. A barrier screw, commonly used to process LLDPE, is the preferred extruder screw to use. Single-stage metering screws can be used, but will not provide as good a melt quality or output as the barrier screw.

5. A good dual-lip air ring and AC frequency inverter control for the blower should be used. Ideal blowup ratios (BUR) for this material are 2:1–2.5:1 for bubble stability and best final film properties.

6. The extruder should ideally provide a melt temperature between 390–410˚ F (199–210˚ C). The final temperature profile can then be modified to determine best running conditions.

Typical running heat profile. As an example of metallocene processing, consider a 3.5 in. (89 mm) diameter extruder having a 24:1 L/D ratio and five extruder barrel zones, plus a 12 in. (305 mm) die, an oscillator, a screen changer, and an adapter tube. A typical heat profile to run metallocene resins to initially achieve a 390–410˚ F (199–210˚ C) melt temperature on this extruder is shown in Table 5-1. (All zones should be within 5˚ F (2.8˚ C) of set points.)

With this profile, the extruder screw speed should be zero at start-up. For a representative temperature profile and start-up procedure for nonmetallocene materials, see “Operation and Maintenance of Equipment” in this chapter. After initial warm-up of one to two hours on a cold machine, when all set points have been reached or slightly exceeded, the extruder can be started and the screw speed slowly brought up to 10 rpm. While increasing screw speed, keep monitoring the head pressure. It should not exceed 2500 psi (17,236 kPa) at 10 rpm, at 390–410˚ F (199–210˚ C) melt temperature.

Starting a cold machine. The procedure for starting up a cold machine to run metallocenes is to set all zones at 250˚ F (121˚ C) first. When the temperature comes up to the set point, increase all set points 25˚ F (14˚ C) and repeat this step until the final set point heat profile and temperatures match, or are very close to one another. By using this procedure for warm-up, a cold start and possible damage to the system’s components is avoided. In conjunction with the head pressure at start-up, the main extruder drive should be drawing under 50 amps maximum for a standard 150-hp DC drive having a 500-V DC armature and 300-V field. Excessive amperage draw may indicate an obstruction in the system or a melt too low in temperature. The temperatures, pressures, and amperage draws listed at 10 rpm at the stated melt temperature are close to the operating points required to run this resin on the described extruder. However, the processor should always check with the machinery supplier and the resin manufacturer for final confirmation before running this material, as the operating temperatures and procedures shown may not be suitable to all types of equipment.

Final film thickness. Once a bubble has been established at a desired diameter to produce the final layflat and film thickness, refinements can be made to the operating parameters such as the heat profile, haul-off speed, extruder screw rpm, and die and air-ring adjustments. Final film thickness uniformity is usually controlled by using the die gap adjusting bolts to either increase or decrease the gap, thereby eliminating high and low spots in the film. Likewise, the air-ring blower output air is also fine-tuned by either increasing or decreasing airflow through the AC inverter blower motor control to achieve the desired bubble stability and maximum cooling rate. When the die gap is set as uniformly as possible and the bubble is very stable, an even frost line will be clearly visible around the entire circumference of the bubble.

Additional changes may have to be made to the heat profile to obtain clearer film, higher outputs, lower head pressures, and lower amperage draw at any given screw rpm and throughput. This will require experimentation by making gradual changes in set point temperatures of no more than ±5˚ F (2.8˚ C) at a time, and then observing the results after 15 minute intervals. In general, raising melt temperatures by increasing extruder barrel set point temperatures will reduce the head pressure and amperage draw of the machine, but may result in lower outputs or possible degradation of the polymer, which can lead to carbon showers or inclusion of dirt in the film. Moreover, the air-ring blower output air is also fine-tuned by decreasing the gap, thereby eliminating high and low spots in the bubble.

### Table 5-1

<table>
<thead>
<tr>
<th>Zone 1, °F</th>
<th>Zone 2, °F</th>
<th>Zone 3, °F</th>
<th>Zone 4, °F</th>
<th>Zone 5, °F</th>
<th>Manual Screen Changer</th>
<th>Adapter Tube</th>
<th>Oscillator</th>
<th>Die 1, °F</th>
<th>Die 2, °F</th>
<th>Die 3, °F</th>
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<tbody>
<tr>
<td>350</td>
<td>360</td>
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Typical Metallocene Running Temperature Profile

Typical films and resin cost of metallocene. While these resins are commercially available in today’s marketplace, one must consider that they are still being developed. The metallocenes show great promise for current and future film applications and can be used in place of many common LDPE and LLDPE film products currently being sold.

However, at this point, their higher cost per pound price, versus the selling price of LDPE, LLDPE, and HDPE, makes them less competitive in the commodity film market. The metallocene resins can cost anywhere from two to three times as much per pound as the LDPE, LLDPE, and HDPE resins. Consequently, metallocene
resins are generally used for specialty film products that require higher impact and clarity properties, and for films that require very good sealability when processed through pouch machines and various other heat or impulse sealing machines. Metallocene resins have also found a niche market in coextruded films and as laminates when a good seal layer is of primary importance to the final film products. In addition, on certain coextruded films, this resin has been used as a skin coating to improve the optical qualities and clarity of the film.

The metallocenes show great promise as impact modifiers to enhance the properties of LLDPE films. The addition of metal-locene to LLDPE greatly improves the film’s puncture resistance and enhances its stress cracking properties because of metallocene’s lower density. This is especially important as more processors want to reduce the thickness of their film products without sacrificing their mechanical or optical properties.

Because of the long chain branching (LCB) associated with metallocene resins, they process at lower melt temperatures, head pressures, and amperage.

Figures 5-14 to 5-17 illustrate dies, screws, and air rings for metallocene resin processing.

**DIE ASSEMBLY**

The die assembly has temperature zones, controlled by temperature-control instruments and thermocouples. The number of zones depends on the size of the die.

The entire die assembly is mounted on the top of a right-angle transfer block that is either fixed or oscillating. An oscillating assembly turns 360˚ clockwise and counterclockwise to randomize the liquid melt as it flows from the die lips. This right-angle block and die head are mounted on a movable die cart. Protruding from the base of the right-angle block is a transfer tube and flange. The entire die cart assembly is mated to the discharge flange of the extruder barrel that is connected to a mechanical filter on the extruder size, die size, and width of the rollers, also referred to as roll face width. The system runs continuously, 24 hours a day for 365 days a year.

With the entire die cart assembly mated to the extruder, the center of the die falls in place directly in the center of a tower structure that ascends upward anywhere from 20–44 ft (6–13.4 m). A cooling ring is placed directly on the top of the die, and its cooling orifice is held concentric to the die lip orifice via a male pilot tube. Situated at the very top level of the tower structure is a pair of haul-off rolls, one roll made of hard-chrome-plated steel, the other a nondriver, rubber-covered, swing nip roll that is free-wheeling until it makes contact with the driven chrome roll through pneumatic air cylinders.

**THE BLOWN-FILM DIE AND ADAPTER**

Most conventional blown-film lines use a bottom-fed spiral die. A wheeled carriage, with adjustable casters for elevation, is normally used so that the die may be rolled away from the extruder for maintenance and so that the extruder screw may be removed. The carriage holds the die, die rotator drive, and air ring rotator drive, and may hold the air ring.

After passing through the screen pack, the polymer melt exits the extruder and passes into the adapter section, which connects the extruder to the die. It is usually at this point that the melt temperature and pressure are measured. Another melt rupture disk assembly, in addition to the one in the extruder, is usually mounted to protect the adapter, the rotator seals, and the die from overpressure. The melt passes from the adapter into the die block, which joins the die assembly to the die stand. The block diverts the polymer flow through a passage into the die. Manufacturers disagree as to whether or not a sharp 90˚ turn is acceptable. One manufacturer uses long radius elbows, another cuts the flow channel at an angle, and another cuts the flow channel at right angles, taking care to hand-polish the inside surfaces. Nevertheless, a properly designed die will have melt flow channels inside the adapter, the die block, and the die that are streamlined to prevent polymer hang-up and avoid degradation problems.

In the bottom pin of the die, the melt immediately splits into several streams, all flowing from the center of the die out to the spiral section. As the melt leaves the bottom pin, it flows between the outer surface of the bottom pin and the main die body through spiral grooves cut into the outer surface of the bottom pin. Therefore, as the melt moves up the die, it is forced to spread out evenly around the circumference of the bottom pin. The spiral section is usually designed for minimum shear, minimum pressure drop, and positive polymer distribution to ensure uniform melt around the die.

**A-FRAME ASSEMBLY**

Suspended from the haul-off assembly side frame members is a pair of matched collapsing frames that hang downward, forming an included angle that resembles the letter A, hence the name collapsing A-frame assembly. These frames can have either wooden slats or rollers equally spaced across their entire face. The apex of the A-frame is situated approximately 1–2 in. (25–51 mm) below the center of the haul-off rollers, and can be adjusted for width of opening at the top and bottom of the frame assembly to achieve the optimum included angle for bubble collapsing. At the base of the tower structure are the lower haul-off rollers plus a center turret-type winder or surface contact winder.

**SYSTEM OPERATION**

The system size and production output is determined by the extruder size, die size, and width of the rollers, also referred to as roll face width. The system runs continuously, 24 hours a day for 365 days a year.
Fig. 5-15 Typical die gap and land profile for metallocenes.

Fig. 5-16 Barrier screw for metallocenes. (Courtesy Filmaster, Inc.)
The extruder pumps a hot molten liquid under pressure to a die-head assembly through the mechanical filter, transfer tube, and right-angle block. When this molten fluid, commonly referred to as a melt, emerges from the die lips, it is gathered together and slowly pulled or drawn away by hand from the die lips. At this time the extruder screw speed is only 10–26 rpm, to provide just enough melt to create a bubble as the melt is pulled away and sealed off at the top.

A continuous controlled flow of air is introduced to the inside of the tube being pulled from the die lips. Air enters from a small hole at the top of the die; the hole diameter is smaller than the opening of the die lip itself. At this point, the gathered and sealed top portion of the tube is tied to a rope hanging down from the upper haul-off roll assembly at the top of the tower structure. As the air enters the inside of the tube, the tube increases in diameter and is gradually pulled upward by the rope into the haul-off rolls.

**COOLING RING**

For the sequence described earlier, the hot molten fluid emerging from the die lips must be sufficiently cooled to crystallize and become semirigid, or convert to a solid from a liquid. This transition point is clearly defined as a translucent, white, frosty band around the bubble. Consequently, it is called the frost line. It is at this ring that the bubble actually becomes a solid crystalline structure rather than a molten extrudate. This is the function of the cooling ring, commonly referred to as an air ring. The air ring has an upper and lower circular orifice (dual-lips) which expels a controlled volume of high-velocity air on to the outer surface of the tube produced from the die lips as the tube is slowly inflated. The dual-lip air ring is situated on the top of the blown-film die, concentric to the annular die gap opening.

Once the tube and rope have been pulled through the upper nip rolls, the swing nip is actuated against the driven chrome roll and seals off the top of the tube. The tube is now sealed at the top, and the internal air column is trapped between the upper rolls and the face of the die assembly while the air ring continues to cool and crystallize what is now an ascending bubble. As this bubble ascends and its diameter increases in size, the bubble makes contact with the A-frames and gradually changes shape from a round bubble into a collapsed tube at the apex of the A-frame prior to entering the haul-off rolls. The larger the diameter of the bubble, the wider the collapsed tube will become as it leaves the upper haul-off rolls and continues down the tower to the lower haul-off rolls and winding system.

When the proper ratio of bubble diameter versus final collapsed tube width has been achieved, the air inflating the bubble is turned off and not turned on again unless the film width has become smaller, or if a different width film is to be produced. If the frost line appears uniform and equal in width around the entire bubble, a uniform wall thickness has been established and the film is usually right on its intended target gage. If the frost line appears jagged and nonuniform, with high and low frosty spikes, it would indicate off-gage film walls because of uneven cooling of the bubble, which can be caused by a nonuniform die gap or airflow from the air ring. In either case, adjustments must be made to the die gap or air-ring airflow streams through the die bushing adjusting bolts or air-ring venturi gap openings.

![Fig. 5-17 Dual-lip air ring for metallocenes. (Courtesy Filmaster, Inc.)](image-url)
The film thickness is controlled by the speed of the upper haul-off rolls in conjunction with the speed of the extruder screw. At any given screw rpm, the faster the upper nip rolls pull the film away from the die, the thinner the tube walls of the film will be. The slower the upper nip rolls go, the thicker the tube walls of the film will be. Consequently, final film thickness is determined by the ratio of the upper nip haul-off speed and the extruder screw rpm. The faster the extruder screw turns, the more mass flow and output will be pumped through the die assembly.

The rate, or pounds (kilograms) of film per hour, that can be produced is mainly dependent on the stability of the ascending bubble and the efficiency of the cooling ring. Contributing factors are the ambient air temperature and the cooling ring air-discharge temperature. As the air discharge temperature is lowered, the entire process becomes more efficient, since the lower temperature will enhance bubble stability and heat transfer. Figure 5-17 shows a cross-sectional view of a typical dual-lip air-ring assembly. Supply air for this assembly would come from a high-pressure centrifugal blower modulated by a variable-speed drive or mechanical damper.

**INTERNAL BUBBLE COOLING**

In some cases, internal bubble cooling (IBC) systems are used to enhance film output by pumping chilled air to the inside of the bubble and at the same time exhausting the heated air that accumulates during the heat-transfer process. This can be very tricky because, while this additional cooling process takes place, the bubble diameter must remain constant to maintain the collapsed tube width. Consequently, sonar or infrared detection systems are used to feed back data to a microprocessor, which in turn will modulate the input flow of air, and also the exhaust air, to maintain a perfect balance. This feedback control function is normally used to modulate the air blower's impeller rpm through a type of variable-frequency drive such as an AC frequency inverter or a DC silicon controlled rectifier type of drive module.

The cooled air supply in a conventional cooling ring or IBC system is supplied through a central chilled-water system or, in some cases, a portable chilled-water system, where the water is chilled through a refrigeration system or evaporator tower system. It is then pumped in a closed loop through a fan coil which is encased in a sheet-metal housing. The fan coil is similar to a radiator with heat transfer fins. As forced air is blown or sucked across these fins, the ambient air is chilled and then aspirated onto the bubble.

Once the collapsed tube leaves the upper haul-off nip assembly, it travels down the tower over and under freewheeling idler rolls and enters a lower nip haul-off station. The lower nip haul-off assembly can be a free-standing unit or an integral part of the winding system. These lower nip assemblies are usually fitted with a pneumatic dancer that applies a preset web tension to the bubble. The dancer tension is maintained.

**SLITTING AND WINDING**

The lower nip contains edge-trim razor-blade slitters which are laterally adjustable on a ridged cross member. These razor blades slit an approximately 1 in. (25 mm) wide edge of film from each side of the collapsed tube so that it can be separated into two individual sheets, which are then wound into finished rolls on a dual turret winder or individual back-to-back single turret winders. As this is a continuously running process, the edge slit trim material is sucked away by a venturi vacuum system into storage bins or wound on individual bobbin winders on metal or cardboard reels. This trim can later be reground into fluff and introduced to the resin feeding hopper in small amounts of up to 15% of the total pounds per hour of film being produced.

If the razor blades were not used, the processor would then wind rolls of layflat tubing on one winder, or one station if a dual turret winder is used. This finished product of wound rolls of tubing or sheeting is then converted into a final film product off-line in the processor's converting department.

**CORONA DISCHARGE**

If the film is to be printed with various colors or graphics, it first must be treated with a corona discharge to roughen its surface and increase surface tension so that printing inks will adhere. This corona treating can be done in-line, as the film is being blown, or off-line. The corona discharge assembly consists of a bank of individual anodes, a dielectric roll, a high-voltage transformer, and a frequency transmitter. In operation, the film passes over the dielectric roll and the anodes are placed into position about 0.063 in. (1.6 mm) above the film, as an electrical current travels through the anode and emits a spark, or corona, onto the film.

**RELAXATION PLENUM**

As the melt leaves the spiral section at the upper portion of the mandrel where the spiral channels feather out to tangency with the mandrel's outside diameter, the polymer enters into the plenum area. This area is known as the relaxation plenum; its purpose is to relax the stresses in the polymer melt that have built up during extrusion and flow to this point. Polymer that flows against the walls experiences different shear than polymer that flows in the center of the melt channels. If the stresses are not relaxed before the polymer flows out of the die, the resulting film product can have weak areas and uneven gage. The length of the relaxation plenum depends on the nature of the resin being extruded. Higher-melt-index materials require a shorter relaxation plenum, but the greater effect can be seen across material types. For example, conventional low-density polyethylene needs a relaxation plenum of only 1 in. (25 mm). High-molecular-weight, high-density resins may need a length of 8–10 in. (203–254 mm).

Leaving the relaxation plenum, the melt finally passes over the mandrel or die pin and out of the die. The land length, which refers to the length or depth of the small channel around the die between the die pin and outer die ring, is the last flow restriction that the melt encounters before passing out of the die. Figures 5-18 and 5-19 show a typical blown-film die and spiral flow channel configuration.

**BLOWUP RATIO**

To produce the best physical properties in the extruded film, a proper balance between the machine direction and the transverse direction of film orientation must be achieved (Fig. 5-20). This relationship is ensured by adjusting the blowup ratio (BUR) of the film. The blowup ratio—the ratio of bubble diameter to die diameter—indicates the amount of stretching the melt is undergoing during the shaping of the film.

While all other processing variables equal, the best converter film properties are obtained from a resin when the film is manufactured using larger blowup ratios, for example, from 2:1 to 3:1. At these ratios, the best balance of machine and transverse direction orientation occurs in most polyethylene films. Most processors use blowup ratios that range from 1.5:1–3:1. Ratios greater than 3:1 are not commonly used because gage uniformity is harder
CHAPTER 5

BLOWN-FILM PROCESS

Adapter connection to die stand to suit

Streamline entry angular die feed ports


Optional internal lip heat zone to reduce melt fracture and increase clarity

Alternate lip designs available for various resin characteristics

Adjustable or nonadjustable design lip available

Main die body zone

External lip zone

All die pieces of 4340 forged steel

Fig. 5-18 A typical blown-film die. (Courtesy Filmaster, Inc.)
ratios below 1.5:1 are not commonly used because the film will be too weak in the transverse direction and split in the machine direction if impacted.

The exception to this rule is in the production of HMWHDPE film, where blowup ratios of 5:1 are common, using what is known as a high-stalk bubble where the melt emerges from the die as a tube having the same diameter as the die, then suddenly blossoms out to a larger-diameter bubble 40–60 in. (1–1.5 m) above the die’s surface and air ring. This technique is unique to HMWHDPE film blowing.

Fig. 5-19 Spiral flow channel configuration. (Courtesy Filmaster, Inc.)

Fig. 5-20 A film’s bubble and die diameter for the blowup ratio.

\[
\text{Blowup ratio} = \frac{\text{Bubble diameter}}{\text{Die diameter}}
\]

or

\[
\text{Blowup ratio} = \frac{0.637 \times \text{Film layflat}}{\text{Die diameter}}
\]
As blown film is produced, it is wound on large rolls or spools. This can be done by a haul-off assembly, surface winder, or center-type winder.

HAUL-OFF ASSEMBLIES
Haul-off assemblies consist of a driven, chrome-plated steel roll and freewheeling rubber-covered nip roll actuated by a pair of pneumatic cylinders. They are driven by variable-control DC drives and are used to haul the film away from the die before it enters the winding system. The upper nip assembly is situated at the top of a tower structure and the lower nip assembly at the base of the tower structure.

SURFACE WINDER
The surface winder is usually one of the simplest winders to design and fabricate (see Fig. 5-21). It also requires the least amount of drive horsepower, because it employs a driven winding drum which surface-drives the film and winding core on its outside diameter. This cardboard core, or in some cases a plastic or steel core, is slipped onto a winding shaft held in position by either mechanical or pneumatically actuated grippers.

At the start of the winding cycle, the film is sandwiched between the winding drum and the core, which make tangency contact with each other. The speed of the winding drum is regulated and set to maintain the same surface speed or a slightly faster speed than the incoming web speed. A slight overspeed of from 1% to perhaps as much as 10%, depending on the stretch factor of the film, minimizes web wrinkles and prevents the web from lateral wandering or telescoping.

Achieving Winding Tension
Winding tension and roll packing or hardening are normally achieved through a pneumatic dancer assembly, a load cell with a feedback loop to the drive motor, and winding shaft arms that employ pneumatic or hydraulic cylinders. The cylinders force the parallel winding arms, which hold the winding shaft and core in place against the winding drum, onto the outside diameter of the winding drum. The pushing force is controlled through a precision regulator and pressure gage to achieve the desired roll hardness and help eliminate entrapped air between the layers of wound film.

Initial web tension, when a counterbalanced pneumatic dancer assembly is used, is also controlled through precision regulators.

Fig. 5-21 Surface contact winders. (Courtesy Filmaster, Inc.)
and pressure gages. In some cases, the pneumatic dancer assembly is designed so that, as it pivots within an included angle of perhaps 20–30°, it will rotate a speed potentiometer at its pivot point to make up to 10–15% speed trim adjustments to the base speed of the winding drum. These slight speed trim adjustments compensate for an incoming web’s contraction and expansion, which can occur as ambient conditions and upstream process conditions change.

Surface winders are especially useful for winding extremely large or jumbo roll diameters, exceeding 30 in. (762 mm) or more, at film widths over 44 in. (1118 mm) wide. This is because the roll is being driven by the winding drum on its outside diameter. Consequently, the electrical drive motor does not have to overcome an ever-increasing moment-arm and supply the countertorque required to continue the winding cycle. Moment-arm is the perpendicular distance from the pivot point (center drive) to the line of force (weight to the outside of the reel). For this reason, less horsepower, at a given roll diameter and tension, is required to wind a roll than is required for a center winder. However, surface contact winders do have certain limitations and are not well suited to the winding of very slippery film such as polypropylene, nylon, and polycarbonates. Another limiting factor would be very sticky or tacky films that exhibit high degrees of surface tension and friction—films like LLDPE stretch cling film which contains additives to achieve a high cling factor. These films tend to stick to the winding drum and create air pockets and wrinkles in the roll being wound.

Uneven Winding

If a film is too slippery or stiff, a surface contact winder will not produce quality roll geometry. The rolls may telescope at their ends and produce a staggered effect which may result in ±0.125 in. (3 mm) or greater end weaving. The rolls may also be loosely wound and not packed hard enough. In extreme cases, the winding drum may not be able to produce enough surface friction to drive the roll.

Film Overfeed

Uneven winding results in a speed differential between the winding drum and the driven roll and creates an overfeed problem, where the incoming web is not being wound fast enough and accumulates in front of the roll being wound. The roll being wound cannot rotate fast enough to pick up the slack.

Film Blocking

The other severe and probably most critical problem in trying to wind these types of films on a surface winder is a condition known as film blocking. This condition occurs as a combination of tightly wound and densely packed film with pressure from the parallel winding arms. The roll’s weight and diameter increase, pushing it against the winding drum. Consequently, the winding core is crushed and the roll cannot unwind properly when processed with off-line converting machinery.

Films that contain an additive such as polyisobutylene (PIB), which gives a film its cling, are especially prone to such problems. The PIB tends to “blossom,” or migrate to the film surface, after several days, or in some cases several hours, of curing, depending on the percent of PIB additive. This migration tends to bond the various layers of film together and can cause the roll to become a rocklike solid mass of film.

CENTER-TYPE WINDERS

The turret, or cantilevered, center winder (Fig. 5-22) is probably the most versatile winder. It has found widespread acceptance in the flexible film converting market and still remains the number one choice for most domestic film producers.

Center winders are configured as either single-turret or dual-turret winders. This type of winder generally consists of a pair of parallel arms assembled between two steel side plates on a center pivoting main turnover shaft. It contains a retractable lay-on roll assembly which cycles in and out with turret rotation from the winding position to the transfer position, plus a full speed range pneumatic dancer assembly which controls the spindle speed and the amount of tension in the finished roll.

Greater Horsepower

The center winder does require greater horsepower than the surface winder because the method of winding is to rotate a shaft holding a winding core in position between the parallel winding arms. Pneumatically actuated and retractable core chucks are housed in one arm, while the other arms house individually driven winding spindles. The core chucks and driven spindles are centered on a common horizontal line between the parallel arms.

Initial speed of the winding shafts and winding core is set up to match incoming web surface speed plus a 3–7% overdraw, depending on the film stretch factor. At this point, the pneumatic dancer is normally in its most upward position, and the winding spindles are running at their maximum speed, commonly referred to as core match speed. The film is threaded over the dancer idler rolls in either a single- or double-pedestal web wrap, depending on the tension requirements and amount of web storage required for transfer onto a new core at given line speed. Web tension is regulated through precision air and pressure regulators which control the pneumatic cylinders, which in turn actuate the dancer arms. The pneumatic cylinders are usually a rolling diaphragm type to provide the least friction and smoothest cylinder stroke possible as the dancer moves through a predetermined arc of travel, which can be anywhere from 45–60°.

At the pivot point of the dancer arms is a mechanical device—a cam, sprocket, or timing pulley—which rotates a speed potentiometer as the dancer travels through its arc. The speed potentiometer in turn regulates the armature voltage of a DC motor through a silicon controlled rectifier (SCR) control board from its maximum speed setting to minimum speed at the end of the winding cycle. This is done so that two things occur continuously during the winding cycle:

1. The winding spindle drives must match the torque (turning motion) requirements of the ever-increasing arm of the roll as its diameter increases. (This is commonly referred to as constant torque, constant horsepower winding.) In other words, the drive must overcome or match the torque in the web which was preloaded by the pneumatic dancer assembly, at an ever-increasing inertia created by the weight of the film.

2. Just as important, the winding spindle speed must decrease as the roll increases in diameter to maintain the same surface speed as the incoming web. This is necessary because, as roll diameter increases, each revolution of the winding shafts accumulates more length on the roll being wound. As the roll increases in diameter and its moment-arm also increases, the net result is to slowly pull the dancer down from its up position at maximum speed to its down position to achieve minimum speed at the finish of the winding cycle.

Predetermining Counter

When the winding cycle is complete, a predetermining counter will actuate an alarm to alert the operator to index the turret to bring the finished wound roll to the unload position and present
the new core into the transfer position for the start of another winding cycle. The web is then manually cut and transferred to a new preglued core, or automatically transferred with some type of flying knife. In some cases, the predetermining counter is configured to count down to a preset amount of roll footage, and a second set of alarms will automatically index the winding turret and effect web transfer. In the more sophisticated winders, predetermining counters have been replaced with programmable sequential logic controllers.

**Lay-on Roll**

As mentioned previously, the lay-on roll also cycles in and out with the turret index cycle. The function of this free-wheeling rubber-covered roll is to ride on the roll and squeeze out entrapped air between the film layers. It is housed between a pair of parallel arms that are counterbalanced and pneumatically actuated through mechanical cams, limit switches, or photoelectric cells.

**Roll Diameter Limits**

The main limitation of a center winder, if it is considered a limitation, may be its inability to wind rolls to extremely large diameters. In general, turret winders are usually designed for a maximum of 30 in. (762 mm) diameter roll buildup at webs up to 74 in. (1880 mm) wide. Wider films are usually configured to 24 in. (610 mm) diameter roll buildup and in many cases use 6 in. (152 mm) diameter rather than 3 in. (76 mm) diameter winding cores.
Custom-designed winders have been manufactured to handle roll diameters greater than 30 in. (762 mm). However, they are of a specialty nature and do not allow sensitive control over a wide range of film thicknesses. In reality, probably the most versatile blown-film winder available today is the center turret winder with fully regulated DC drives and controls.

OTHER TERMS

The following are common names and phrases used in the flexible-film winding industry when referring to either center turret or surface contact film winders:

Pounds per lineal inch of web (PLI). This is the initial tension loaded on the web prior to and during winding by mechanical means.

\[
PLI = \frac{P}{W} \quad (1)
\]

where:

- \( P \) = pressure (in lb/in. or kg/cm)
- \( W \) = web width

For example, if a web 50 in. (127 cm) wide were loaded initially with 25 lb/in. (22 kg/cm) of force, the PLI would be 25 \( \div 50 = 0.500 \) lb/in. (22 \( \div 127 = 0.17 \) kg/cm).

Roll buildup (RBU). The ratio between the outside diameter of the winding core and the maximum diameter of the finished wound roll.

\[
RBU = \frac{F}{W} \quad (2)
\]

where:

- \( F \) = finished roll
- \( W \) = winding core

For example, for a 3.5 in. (89 mm) diameter winding core and a 24 in. (610 mm) diameter maximum finished wound roll, RBU = 24 \( \div (89) \) = 6.86:1 (610 \( \div 89 = 6.85:1 \)).

Web width. The width of the web being wound on the winding core.

Foot per minute (fpm). The usual unit of measure of web winding speed.

Speed range (SR). The ratio of the maximum to minimum speeds a winder must cover.

\[
SR = \frac{S_{\text{max}}}{S_{\text{min}}} \quad (3)
\]

where:

- \( S_{\text{max}} \) = maximum winding rpm
- \( S_{\text{min}} \) = minimum winding rpm

For instance, an application may require a winder to operate as slow as 30 fpm and as fast as 300 fpm. The speed range would be 300 \( \div 30 = 10:1 \). This means that the winder must operate at 30 fpm, 300 fpm, and all speeds in between. In some cases, this can become very difficult to ensure because of the speed range limitations of the SCR controllers and DC motors frequently used in film winders. Most standard SCR controllers are not true linear devices for regulating DC motor rpm from maximum to minimum speed.

Therefore, on a winder rated for 30–300 fpm, speed tracking and total motor rpm regulation may only be in the range of 100–280 fpm, or somewhere around a 2.8:1 speed range, for best results. Slower speeds such as 30 or 40 fpm may cause erratic winding and not accomplish a full roll buildup, unless the winder is re-speed-tracked, or a mechanical transmission is used.

By using a mechanical transmission with a speed ratio variable from 2:1–4:1, wider winder speed range is allowed from any initial speed, and the full motor rpm, torque, and hp curve are utilized. For example, a 30–300 fpm winder tracked at 100–280 fpm by a 4:1 gear transmission would now handle four winding speed ranges (keep in mind that the original tracking was over a 2.8:1 speed ratio): 300 fpm \( \div 4:1 = 75 \) fpm, and 75 fpm \( \div 2.8:1 = 27 \) fpm, or a range of 27–75 fpm in low gear; 300 fpm \( \div 3:1 = 100 \) fpm, and 100 fpm \( \div 2.8:1 = 36 \) fpm, or a range of 36–100 fpm in higher gear. The same holds true for the 2:1 ratio, and the 1:1 ratio gets back to the original tracking of 100–280 fpm. Much of the same can be accomplished through the use of very sophisticated electronic drives, especially digital and DC frequency vector drives, as well as proportional integral derivative (PID) semicon-ductor-controlled rectifier (SCR) control systems with tachometer or encoder feedback. However, these systems are very expensive and extremely complicated to maintain in the field, unless a processor has a full-time electrical engineer on the staff.

Horsepower (hp). The power required to wind a maximum roll diameter at any given range of winding speeds. There are many ways to calculate hp for a center winder. The basic calculation is

\[
\text{hp} = \frac{\text{FPM} \times \text{web width} \times \text{PLI} \times \text{RBU}}{29,700} \quad (4)
\]

In using this formula, it is absolutely critical to know what PLI to use, depending on the characteristics of the web—stiff or stretchy, thickness, etc. If the PLI is not known, experimentation will be required to find the correct value. For most flexible films 0.0005–0.010 in. (0.013–0.254 mm) thick, a range of PLI from 0.125–0.500 is common. The number 29,700 is an efficiency factor representing 90% of the usable inch-pound value equated with one horsepower.

An example of hp calculation for an LDPE film, 84 in. (2134 mm) wide \( \times 0.002 \) in. (0.05 mm) thick, wound at 250 fpm to a 24 in. (610 mm) maximum roll diameter on a 3.5 in. (89 mm) OD core, is as follows:

\[
\text{hp} = \frac{250 \times 84 \times 0.500 \times 6.9:1}{29,700} \quad (5)
\]

= 2.4 hp (1790 W)

Select a three hp motor to allow for thermal and mechanical losses.

Roll hardness or packing. The hardness of the roll after winding to its maximum diameter. A tightly packed roll may cause unwinding problems and a loose roll will lead to uneven roll edges. Telescoping. Found in a roll where insufficient tension leads to uneven roll edges and web weaving. Telescoping can also be caused by entrapped air or a misaligned idler roll on the winding cores. Gage bands. Circular bumps in the roll’s outside diameter caused by nonuniform film thickness. Crushed core. The result of too much winding tension where the roll being wound crushes a cardboard or plastic core and the winding shaft cannot be removed.

WINDER DESIGN CONSIDERATIONS

The first consideration is, of course, to determine the type of winder needed for the web, maximum roll diameter, and minimum and maximum speeds. Once these factors have been decided, the winder can be designed according to the principles previously discussed in this chapter. The key considerations are:

1. All rotating members should be balanced, preferably dynamically. Usually static balancing will be acceptable for speeds
CHAPTER 5

FILM WINDERS

no greater than 300 fpm (90 m/min), but speeds greater than 300 fpm must be dynamically balanced.

2. Critical rotating speeds of all members must be calculated with respect to their mass, wall thickness, and overall length to avoid any potential injury to an operator. These speeds are calculated by the classic engineering formulas.

3. Precision ball and roller bearings should be used on all rotating members. These are bearings with as little run-out as possible. They need not be aircraft-quality bearings, but should be at least good machinery bearings having true indicated reading (TIR) run-outs of 0.001 in. (0.025 mm) or less.

4. Winder side frames should be manufactured and ground for stiffness and final parallelism during assembly. Side frames are usually 0.875–1.00 in. (22.2–25.4 mm) thick after grinding.

5. SCR controllers with at least a 30:1 speed range or better should always be used for best results in a DC drive system.

6. Direct current motors should have at least a 40:1 speed range from their base speed of 1750 or 2500 rpm. They should be shunt-wound instead of permanent-magnet motors.

7. Gear reducers and mechanical transmissions should have at least a 1.25:1 safety factor and a thermal rating of 0.8–0.9 if possible.

8. Although chains and sprockets are commonly used in film winders at speeds up to 300 fpm, it is preferable to use timing belts and pulleys. At speeds of 400 fpm (120 m/min) and higher, timing belts and pulleys are absolutely necessary.

9. Tension-controlling pneumatic cylinders for air dancers, etc., should be of the rolling diaphragm type rather than the piston type. The diaphragm cylinders create less friction and offer a greater surface area to develop the forces required for proper tension.

10. All mechanical fasteners should have a generous application of some type of coating to preclude loosening up during machine operation.

11. All electrical components should be Underwriters Laboratories (UL) or Canadian Standards Association (CSA) rated and preferentially carry both ratings.

Perhaps most important, keep in mind the speed range of the winder and the speed tracking that can be expected from normal stock SCR controllers and DC motors. If these factors are not initially taken into consideration, the winder may not perform to its original design specifications.

DRIVE CALCULATIONS

To determine shaft speeds and gearing, first calculate the maximum core speed at start of winding:

\[
\text{Core speed} = \text{LS} \div \mathcal{C}
\]  

where:

\[
\text{LS} = \text{line speed} \\
\mathcal{C} = \text{core circumference}
\]

(Both are in a consistent system of units.)

Assume that \( \text{LS} = 400 \text{ fpm} \times 12 \text{ in./ft} = 4800 \text{ in./min} \) (122 m/min) and the core radius is 3.5 in. (0.09 m). Then \( \mathcal{C} = 3.5 \text{ in.} = 11 \text{ in.} \) (0.279 m).

The core speed is therefore \( 4800 \div 11 = 436 \text{ rpm} \) at the start of winding.

For a 5:1 speed reducer and 1750 rpm DC motor, the speed at the reducer output shaft is \( 1750 \div 5 = 350 \text{ rpm} \). The ratio of the 436 rpm needed at the core to the 350 rpm shaft speed is 1.26:

The required 1.2:1 speed increase can be provided by a timing belt that engages a 24-tooth sprocket on the output shaft of the reducer and a 20-tooth sprocket on the drive shaft of the winding spindle.

ELECTRONIC CONTROLLERS AND FEEDBACK LOOPS

Turret winder electronic control systems are available in several models, each performing a specific function for its intended use. The most simple and common drives in the past have been AC torque motor drives. Probably the most common electronic drive used in turret winders is the DC analog drive with either a full speed range or a self-centering PID dancer controlling the winding speed. If a speed control dancer is not used, some sort of load cell device to monitor tension and speed is substituted.

TENSION CONTROL SYSTEMS

There are two types of tension control systems: constant and taper tension.

Constant Winding Tension System

Tension, expressed as PLI (pounds per lineal inch of web), is the predetermined load placed on the full width of the web prior to winding at the winding shaft. This load is normally produced by regulating the pressure to the air cylinders which actuate the air dancer assembly. This assembly is forced up and against the incoming web so that the web and winding speed must pull the dancer from an up position to its lowest position under the preload.

The up position of the dancer denotes maximum winder speed at the current speed range. The down positions indicate and control the minimum speeds of the winding shaft to the point of actually reducing the signal output to the drive board to zero and stopping the winding spindle completely. This transition of speed from maximum to minimum is achieved as the dancer assembly travels through its arc and its pivot shaft gradually rotates the sprocket, which in turn is connected by a chain to the sprocket on the input shaft of a speed potentiometer.

This type of speed control is called constant tension, constant horsepower control with no tension taper. While this is acceptable for most polyolefin films, certain films, especially thin, sticky films such as stretch LLDPE, will not wind well with this tension system. If starting tension is the same as finishing tension at the end of the winding cycle, the film may be wound too tightly and stick to itself so that it cannot be easily unrolled. On the other hand, excessive tension may be so great that it can crush the card-board winding core, making it impossible to remove from the winding shaft.

Taper Winding Tension System

Taper winding is automatically adjusted from the tension initially preset into the web, lessening, or tapering off, as the roll increases in diameter. As an example, if 20 psi (138 kPa) were used for the initial pressure setting and the operator adjusted the taper tension potentiometer to a 50% setting, the system would initially start winding at 20 psi and gradually reduce this pressure setting by 50%, or 10 psi (69 kPa), by the end of the winding cycle at the maximum roll diameter buildup that was selected. If a higher percent setting were used, the pressure would be reduced proportionately. For example, if 100% were used as a setting to
taper from 20 psi, the winding cycle would start at 20 psi and finish at zero pressure at the end of the winding cycle.

**Self-centering Dancers**

A self-centering dancer system uses a sophisticated electronic circuit board that counts and knows at every point of the winding cycle what the roll diameter is. Basically, the system works on a plus and minus voltage arrangement, with the center position of the dancer being a null zone and all points above or below the center being speed increase or decrease factors. The feedback signal from the dancer potentiometer is transmitted to the silicon controlled rectifier (SCR) drive board which regulates the DC motor rpm.

The self-centering dancer does not move from its center horizontal position during winding. Consequently, the initial setting for tension is maintained throughout the entire winding cycle unless the system has a taper-regulated tension system. The overall benefit is that the dancer does not move through an arc to achieve maximum and minimum speeds. Since it does not move through an arc, the dancer does not change the tension setting as does a standard dancer.

Because the PID (proportional integral derivative) loop precisely controls the DC motor rpm from start of winding to finish, all the available speed range of the motor is used, plus all available horsepower at any rpm. This effect extends the ability to wind larger diameters on a turret winder.

**Microprocessor-controlled Winders**

Perhaps the greatest impact on winders has been that of microprocessors. They have made programmable logic controllers (PLCs) possible, replacing relays, cams, timers, and other associated electrical ladder logic. Microprocessors have also automated such winder functions as film cutoff, transfer, tension, and speed adjustment.

With a microprocessor-based computer and its associated software, data on previous runs on the winder can be stored (product, speed, RBU, and tension, for example). The operator can match a run to a production sheet and merely recall the previous program recipe that is best suited for the new winding application. Once triggered, the computer will automatically control all the winding functions required.

Microprocessor-based systems are usually equipped with a cathode-ray tube (CRT) screen and can be operated from a keyboard or touch screen. In many cases, they also employ a loop feedback system for production control; a production manager can see what products have been run or are going to be run for any specific time period.

### BLOWN-FILM EQUIPMENT AND OPERATING COST

An extrusion system is a substantial investment; purchasers naturally want to know what kind of return they can expect on their investment. The following is a sample payback calculation cost analysis for a blown-film extrusion line that can produce layflat tubing or individual wound sheeting up to 50 in. (1.3 m) wide, using a 3.5 in. (89 mm) \( \times \) 24:14 L/D extruder, 12 in. (305 mm) die, oscillator, air ring, tower, upper nip, lower nip, and back-to-back center turret winders. A system like this can sell anywhere from $390,000–$425,000 depending on its final configuration. The payback calculation will be predicated on equipment cost of $400,000, with LLDPE film to be produced at an average thickness of 0.001 in. (0.025 mm), and an average rate of production cost of $400,000, with LLDPE film to be produced at an average thickness of 0.001 in. (0.025 mm), and an average rate of production of 340 lb (154 kg) per hour for an average of 8000 hours per year.

<table>
<thead>
<tr>
<th>1. Investment Capital</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>a. Machinery investment including all optional items</td>
<td>$400,000</td>
</tr>
<tr>
<td>b. Installation cost, estimated at 6% of machinery investment</td>
<td>24,000</td>
</tr>
<tr>
<td>c. Total investment</td>
<td>$424,000</td>
</tr>
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<table>
<thead>
<tr>
<th>2. Capacity Calculation Using Virgin Material</th>
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</tr>
</thead>
<tbody>
<tr>
<td>a. Operating hours per year at 24 hour/day, (including downtime)</td>
<td>8000 hours</td>
</tr>
<tr>
<td>b. Output of LLDPE (for one line), estimated</td>
<td>340 lb/h (154 kg/h)</td>
</tr>
<tr>
<td>c. Gross output per year</td>
<td>2,720,000 lb (1234 metric tons)</td>
</tr>
<tr>
<td>d. Output at 95% efficiency</td>
<td>2,584,000 lb (1172 metric tons)</td>
</tr>
<tr>
<td>e. Minus scrap (1%)</td>
<td>25,840 lb (11.7 metric tons)</td>
</tr>
<tr>
<td>f. Net production per year</td>
<td>2,558,160 lb (1160 metric tons)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Polymer Cost</th>
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</tr>
</thead>
<tbody>
<tr>
<td>a. Price of LLDPE, approximate</td>
<td>$0.41/lb ($0.90/kg)</td>
</tr>
<tr>
<td>b. Total annual polymer cost (0.41 ( \times ) 2,558,160 lb gross)</td>
<td>$1,048,846</td>
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<tr>
<th>4. Fixed Cost</th>
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</tr>
</thead>
<tbody>
<tr>
<td>a. Overhead for factory space, one year at $9.50/ft(^2) (5000/ft(^2)); $102/m(^2) (465 m(^2))</td>
<td>$47,500</td>
</tr>
<tr>
<td>b. Freight charges and placement of machinery</td>
<td>$15,000</td>
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<tr>
<td>c. Total fixed cost</td>
<td>$62,500</td>
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<table>
<thead>
<tr>
<th>5. Variable Cost (based on three workers running one line, for each of three shifts per day)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>a. Wages per hour, including benefits:</td>
<td></td>
</tr>
<tr>
<td>• Extruder operators</td>
<td>$8.25</td>
</tr>
<tr>
<td>• Fringe benefits (36% of hourly wage)</td>
<td>$2.97</td>
</tr>
<tr>
<td>• Total wages per hour</td>
<td>$11.22</td>
</tr>
<tr>
<td>b. Total annual wages</td>
<td>(3 ( \times ) 8000 h ( \times ) $11.22/h)</td>
</tr>
<tr>
<td>c. Production manager, annual salary and benefits</td>
<td>$45,000</td>
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<tr>
<td>d. Energy at ($0.10/kW-h ( \times ) 250 kW ( \times ) 65% ( \times ) 8000 h)</td>
<td>$130,000</td>
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<tr>
<td>e. Total variable cost</td>
<td>$444,280</td>
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<thead>
<tr>
<th>6. Manufacturing Cost</th>
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</thead>
<tbody>
<tr>
<td>a. Total fixed cost</td>
<td>$62,500</td>
</tr>
<tr>
<td>b. Total variable cost</td>
<td>$444,280</td>
</tr>
<tr>
<td>c. Total polymer cost</td>
<td>$1,048,846</td>
</tr>
<tr>
<td>d. Manufacturing cost, first year</td>
<td>$1,555,626</td>
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<table>
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<tr>
<th>7. Conversion Cost</th>
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<tbody>
<tr>
<td>Manufacturing cost = net output = $1,555,626 – 3,558,160 lb</td>
<td>$0.61/lb ($1.35/kg)</td>
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<table>
<thead>
<tr>
<th>8. Gross Profit Before Taxes</th>
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</tr>
</thead>
<tbody>
<tr>
<td>a. Sales price per pound for converted products (estimated)</td>
<td>$0.90/lb ($1.98/kg)</td>
</tr>
<tr>
<td>b. Turnover = net output ( \times ) sale price = 2,558,160 lb ( \times ) $0.90/lb</td>
<td>$2,302,344</td>
</tr>
<tr>
<td>c. Minus manufacturing cost</td>
<td>$1,555,626</td>
</tr>
<tr>
<td>d. Gross profit before taxes</td>
<td>$746,718</td>
</tr>
</tbody>
</table>
CAST FILM AND SHEET

The cast-film process (Fig. 5-23) uses many of the assemblies mentioned previously, such as haul-off nips, winders, and ancillary equipment. However, it is a horizontal process that extrudes material through a flat, slotted die onto a large, rotating, chrome-plated steel roll.

The flat, slotted die has flexible lips that can be adjusted for a precise die gap by machine bolts equally spaced along the entire length of the lips. The flat die is attached to the extruder discharge flange by a transfer tube.

The extruder centerline height from the floor to the center of its barrel is usually 40–60 in. (1–1.5 m). The extruder is situated behind the chill roll stand, a unit that contains one or more large chrome-plated rolls. These rolls are cooled internally by chilled water. The flow and temperature of the water depend on the speed of the line, the amount of heat to be removed from the film, and the film thickness. The chill roll stand also contains an air knife and a pair of driven haul-off rolls.

As the molten extrudate flows downward onto the chilled roll, it immediately changes from a liquid to a crystallized film. The function of the air knife is to aspirate a high-velocity, low-pressure air stream onto the film and pin the film to the chilled roll. The haul-off rolls then pull the film from the driven chill roll and carry it off to the winding system. Sometimes an oscillating web guide is used to keep the film tracking perfectly into the winder. In some cases, the web guide assembly contains a corona treatment station.

The web guide uses a proximity sensor to detect the film's edge. The signal from this sensor is fed back to a hydraulic or pneumatic proportioning valve assembly, which directly controls a hydraulic or pneumatic cylinder attached to a movable frame assembly that can oscillate laterally. Consequently, it can steer the film web into the winder to maintain proper web alignment, and keep uniform edges on the film as it is wound. The winder can be either a contact surface winder or a center turret winder, depending on the material being processed.

Cast film and sheet are grouped together because the processes by which they are made are very similar. The end products are the same, except cast films are typically less than 0.010 in. (0.25 mm) thick and sheet is greater than 0.010 in. thick. The dies used to produce these products are known as flat film and flat sheet dies. They are often called coathanger dies because the melt is forced through a hole that opens into a coathanger-shaped cavity cut into the bottom plate of the die. The top plate of the die is flat and is bolted to the bottom plate. The coathanger fill the cavity and comes out of the slit on the other side of the "coathanger." Sheet dies are dimensioned by the width and the gap of the slit. For example, a 12 in. sheet die with a 0.040 in. (305 × 1 mm) gap would produce a sheet that is 12 in. wide and 0.040 in. thick. The machine bolts on the flexible lips adjust the die gap by either pushing the lips together or pulling them apart, ensuring uniform, proper thickness of film or sheet and flatness all the way across the die. Figure 5-24 shows a sheet extrusion assembly.

Although both cast film and sheet dies operate the same way, the take-off systems are different.

The most prevalent configuration for cast-sheet lines is the three-roll stack, where three rolls are stacked over each other in a vertical configuration or, in some cases, an inclined geometry. The rolls are driven and have internal water cooling.

As in the cast-film process, the molten extrudate travels downward from a flat die, making tangent contact with the outside diameter of the top chill roll. The crystallized web, or wheet, is then threaded through the middle roll and bottom roll in an S-shaped web path between the three rolls. The rolls can be precisely moved up or down on their vertical axes to form a highly precise gap between them. This gap determines the final sheet thickness. Adjustments are made by electrically-driven gear-head reducers and fine-pitched lead screws. The gear ratio, in conjunction with the pitch of the lead rotating screw, determines the amount of linear roll travel per screw turn until micrometer-type gap adjustment takes place. From the three-roll stack, the web is pulled away by a pair of driven haul-off nips and conveyed to the winding system.

The winding system is usually a center turret winder using either DC variable-speed drives or AC torque motor drives. These lines usually produce thicker webs or sheeting, from 0.020–0.060 in. (0.5–1.5 mm) thick. Because of the thicker webs, winder speeds are usually slow, as is the overall line speed of the three-roll stack. Typical products made on these lines are styrene, polyethylene, and thermoplastic sheeting, used in various types of vacuum- or thermal-formed products, as well as mechanical die-cut plastic products.

CHILL ROLLS

Cast film is usually extruded directly onto a chill roll. The function of the chill roll is to cool the extrudate into a solid and transport it from the die. Chill rolls are typically mirror-finish chrome-plated rolls. Most have spiral baffles inside that force water from one side, helically around the surface of the roll, and out the other side. This ensures a uniform cooling action across the extrudate. An air knife blows the extrudate against the chill roll and keeps it pinned to the roll. By the time the extrudate goes around the roll, it is cooled and goes to the nip rolls. The function of the nip rolls is to give the desired tension and supply the film to
Fig. 5-23 Cast-film extrusion system. (Courtesy Filmaster, Inc.)

Notes:
1. All dimensions are approximate.
2. Appearance of finished unit may vary from drawing.
3. (m) Indicates dimension in meters.
CAST FILM AND SHEET

ADVANTAGES AND DISADVANTAGES

Perhaps the main advantage of the cast-film versus the blown-film process is greater production output. This is because of its more efficient cooling system. A cast-film line usually will produce more per hour of film than a blown-film line. Cast-film lines also produce better uniformity of film thickness or gage, usually ±5% or less, depending on the type of material as well as the overall line speed. They are also better suited to processing crystal-clear films, because they quickly quench the molten extrudate and crystallize it into a film.

The main disadvantage of a cast-film line is that it is not as versatile as a blown-film line. The cast-film flat die can produce film of only one specific width, that of the die face. Some very sophisticated flat dies have deckling devices that, when actuated equally from both ends toward the center of the die, can reduce the length of the die opening and produce narrower films within limits. However, these devices can cause extended periods of residence of the molten polymer in the die because of a reduced flow area, and can cause the polymer to degrade or burn, forming carbon.

Cast-film lines are usually preferred over blown-film lines when a processor wants to produce a dedicated film width at one specific thickness, having excellent optical characteristics, at high yearly production outputs. Blown-film lines are selected when a processor wants maximum versatility in producing various types of film products, such as tubing to make trash liners, garment bags, carrier bags, or shopping bags, as well as various widths of individual wound sheeting products at various film thicknesses.

PROFILE EXTRUSION

Profile extrusion (Fig. 5-25) is a horizontal process where an extruder pumps a molten extrudate through a die head having an annular gap in the shape of the product to be extruded. The profile is extruded into a long horizontal tank or cooling trough filled with water. The water crystallizes the extrudate as it exits the die. At the end of the cooling tank, driven haul-off rolls pull the profile away from the die head at a uniform controlled speed. As the profile is being pulled through by the haul-off assembly, a cutting knife severs it into equal lengths, dropping them onto a stacking table or other collection device.

Typical products are rigid shapes such as channels, moldings, pipe, and various other structural shapes. These products are usually made from such materials as polyethylene, polypropylene, polystyrene, and polyvinyl chloride.

POLYETHYLENE PIPE AND FITTINGS MANUFACTURING

This section describes the production of extruded solid- and profile-wall polyethylene pipe and the molding and fabrication of fittings. Quality assurance and control tests that are required under typical American Society for Testing and Materials (ASTM) specifications will also be discussed.

Introduction

The principle of pipe and fitting production is to melt and convey polyethylene into a particular shape and hold that shape during the cooling process. This is necessary to produce solid- and profile-wall pipe as well as injection-molded fittings. The smaller diameters of solid-wall polyethylene pipe are continuously extruded through an annular die. For large-diameter profile-wall pipes, the profile is spirally wound onto a mandrel and sealed along the seams.

Solid-wall polyethylene pipe is produced in sizes ranging from 0.50–63 in. (1.3–160 cm) in diameter. Spirally wound profile pipe may be made up to 10 ft (305 cm) in diameter or more. There are several specification standards that govern the manufacturing processes for polyethylene pipe, but the main standards for solid- and profile-wall pipe include:
• ASTM D2239: Standard specification for polyethylene (PE) plastic pipe, standard inside dimension ratio-pressure rated (SIDR-PR) based on controlled inside diameter.
• ASTM D2447: Standard specification for polyethylene (PE) plastic pipe, schedules 40 and 80 based on outside diameter.
• ASTM D2513: Standard specification for thermoplastic gas pressure pipe, tubing, and fittings.
• ASTM D3035: Standard specification for polyethylene (PE) plastic pipe, standard dimension ratio-pressure rated (SDR-PR) based on controlled outside diameter.
• ASTM F714: Standard specification for polyethylene (PE) plastic pipe (SDR-PR) based on outside diameter.
• ASTM F894: Standard specification for polyethylene (PE) large diameter profile-wall sewer and drain pipe.

Generally, thermoplastic fittings are injection-molded, fabricated from sections of pipe, or machined from molded plates. Injection molding is used to produce fittings up through 12 in. (30.5 cm) in diameter, and fittings larger than 12 in. are normally fabricated from sections of pipe. The main ASTM specifications for injection-molded fittings include:

- ASTM D2683: Standard specification for socket-type polyethylene fittings for outside diameter-controlled polyethylene pipe and tubing.
- ASTM D3261: Standard specification for butt heat fusion polyethylene (PE) plastic fittings for polyethylene (PE) plastic pipe and tubing.
- ASTM F1055: Standard specification for electrofusion-type polyethylene fittings for outside diameter-controlled pipe and tubing.

Currently, there is not an ASTM specification for fabricated fittings. The industry recognizes the need for this new specification due to the rapid growth of demand for large-diameter pipe and plans to develop one.

All these standards specify the type and frequency of quality control tests that are required. Several steps during the manufacturing process are closely monitored to ensure that the product complies with these rigorous standards. Some of these steps are discussed in this chapter under “Quality Control/Quality Assurance Testing.”

**Pipe Extrusion**

The principal aspects of solid-wall polyethylene pipe manufacturing are presented in Figs. 5-26 and 5-27. This section describes the production of solid-wall pipe from raw material handling, extrusion, sizing, cooling, printing, and cutting, through finished product handling. Details concerning profile-wall pipe are also discussed in the appropriate sections.

**Raw materials description.** The quality of the starting raw material is closely monitored at the resin manufacturing site. A battery of tests is used to ensure that the resin is of prime quality. A certification sheet is sent to the pipe and fitting manufacturer documenting important physical properties such as melt index, density, environmental strength crack resistance (ESCR), stabilizer tests, and tensile strength. The resin supplier and pipe manufacturer agree on the specific tests to be conducted.

The raw materials used to manufacture polyethylene pipe are generally supplied as pellets. The resin is stabilized as required in ASTM D3350 against thermal oxidation. The resin is supplied in either the natural state (milky white) or in a precolored form. In the United States, the most common colors are black, tan, yellow, and orange. The choice of color depends on the intended application and the requirements of the pipe purchaser. Carbon black is the most common pigment used for water, industrial, sewer, and aboveground uses. All of the colors mentioned are used for gas distribution and oil gathering.

All ASTM and many other industry standards specify what compounds shall be used to produce pipes and fittings. A compound is defined as the blend of natural resin and color concentrate and the ingredients that make up each of those two materials. The pipe producer must not change any of the ingredients in the listed compound, such as substituting a different color concentrate, which could affect the long-term strength of the pipe. These stringent requirements ensure that only previously tested and approved compounds are used.

If the resin is supplied as a natural pellet, the pipe producer will blend a color concentrate with the resin prior to extrusion. To obtain a Plastic Pipe Institute (PPI) listing, a manufacturer producing pipe in this manner is required to submit data, according to ASTM 2837, to the PPI Hydrostatic Stress Board. A careful review of the data is made according to PPI Policy TR-3 to assess
the long-term strength characteristics of the in-plant blended compound. When the policy requirements are met, the compound is listed in PPI Publication TR-4, which lists compounds that have satisfied the requirements of TR-3. Producers of potable-water pipe are usually required to have the approval of the National Sanitation Foundation (NSF), or an equivalent laboratory. NSF conducts unannounced visits to verify that the correct compounds are used to produce pipe that bears its seal.

Raw materials handling. After the material passes the resin manufacturer’s quality control tests, it is shipped to the pipe manufacturer’s facility in 180,000–200,000 lb (81,648–90,720 kg) capacity railcars, 40,000 lb (18,144 kg) bulk trucks, or 1000–1400 lb (454–635 kg) boxes.

Each pipe-producing plant establishes quality control procedures for testing incoming resin against specification requirements. The parameters that are typically tested include melt index, density, tensile strength, and ESCR. Many resin producers utilize statistical process control (SPC) on certain key physical properties to ensure consistency of the product.

Resin is pneumatically conveyed from the bulk transporters to silos at the plant site. The resin is then transferred from the silos to the pipe extruder by a vacuum transfer system. Precolored materials can be moved directly into the hopper above the extruder. If a natural material is used, it must first be homogeneously mixed with a color concentrate. The resin may be mixed with the color concentrate in a central blender remote from the extruder or in an individual blender mounted above the extruder hopper. The blender’s efficiency is monitored on a regular basis to ensure that the correct amount of color concentrate is added to the raw material.

Color concentrate is important for protecting the pipe from the effects of ultraviolet radiation that can cause degradation. Black concentrate alone is very effective in absorbing ultraviolet radiation, whereas nonblack concentrates use an ultraviolet stabilizer to provide protection.

Drying. Polyethylene is not hygroscopic, but for ease of processing and to ensure finished product quality, the resin and black concentrate should be dried prior to extrusion. The drying step
ensures that the pipe quality will not be affected by voids caused by water vapor trapped within the pipe wall. The resin manufacturer is the best source of specific recommendations for drying times and temperatures.

Extrusion principles. The function of the extruder is to heat, melt, mix, and convey the material to the die, where it is shaped into a pipe. The extruder screw design is critical to the performance of the extruder and the quality of the pipe. The mixing sections of the screw are important for combining natural and concentrate blends thoroughly to produce a homogeneous melt.

There are many different types of screw designs, but they all have features in common. Each screw is designed specifically for the type of material being extruded.

The extruder screw operates on the stick/slip principle. The polymer needs to stick to the barrel so that, as the screw rotates, it forces the material forward. The polymer is subjected to heat, pressure, and shear (mechanical heating). The extent to which the material is subjected to these three influences is a function of the screw speed, the barrel temperature settings, and the screw design. The design of the screw is important in the production of high-quality pipe. The wrong screw design can degrade the resin by overheating and shearing it, which will degrade the physical properties of the pipe.

If a natural resin and concentrate blend are used, the screw will also have to incorporate the colorant into the natural resin. Various mixing devices are used for this purpose, as shown in Fig. 5-28. They include mixing rings or pins, fluted or cavity transfer mixers, blister rings, and helix-shaped mixers, which are an integral part of the screw.

The pipe extrusion line generally consists of the extruder, die, cooling systems, puller, printer, saw, and take-off equipment. These items are addressed in the following sections.

Extruders. The single-screw extruder is generally used to produce polyethylene pipe. An extruder is usually described by its bore and barrel length. Pipe extruders typically have an inside diameter of 2–6 in. (5.1–15.2 cm) with barrel lengths of 20–32 times the bore diameter. The barrel length divided by the inside diameter is referred to as the L/D ratio. An extruder with an L/D ratio of 24:1 or greater will provide adequate residence time to produce a homogeneous mixture.

The extruder is used to heat the raw material and then force the resulting melted polymer through the pipe extrusion die. The barrel of the machine has a series of four to six heater bands. The temperature of each band is individually controlled by an instrumented thermocouple. Most of the heat supplied to the polymer is provided by the motor. This supply of heat can be further controlled by applying cooling or heating to the various barrel zones on the extruder by a series of air or water cooling systems. This is important since the amount of heat that is absorbed by the polymer should be closely monitored. The temperature of the extruder melted polymer is usually between 390–450˚ F (199–232˚ C), and it is under high pressure, 2000–4000 psi (13,788–27,579 kPa).

Breaker plate/screen pack. The molten polymer leaves the extruder in the form of two ribbons. It then goes through a screen pack which consists of one or more wire mesh screens, positioned against the breaker plate. The breaker plate is a perforated solid-steel plate. Screen packs prevent foreign contaminants from entering the pipe wall and help develop a pressure gradient along the screw to homogenize the polymer. Many extruders are equipped with a screen changer device, which removes a dirty pack while it inserts a fresh pack without removing the die head from the extruder.

Die design. The pipe extrusion die supports and distributes the homogeneous polymer melt around a solid mandrel, which forms it into an annular shape for solid-wall pipe. The production of a profile wall pipe involves extruding the molten polymer through a die shaped to the pipe profile.

The die head is mounted directly behind the screen changer unless the extruder splits and serves two offset dies. There are three common types of die designs for solid-wall pipe: spider, annular breaker, and screen basket (Egan system). The names refer
Pipe sizing operation. The dimensions of the pipe are set during the sizing and cooling operation. For solid-wall pipe, the process consists of drawing the hot material from the die through a sizing sleeve and into a cooling tank. Sizing may be accomplished by either vacuum or pressure techniques (Fig. 5-29). Vacuum sizing is generally limited to pipe diameters of 8 in. (203 mm) or less. Pressure sizing is the preferred method for larger-diameter pipe, although some manufacturers use vacuum sizing.

During vacuum sizing, the molten extrudate is drawn through a sizing tube or rings while its surface is cooled enough to maintain proper dimensions and a circular form. The outside surface of the pipe is held against the sizing sleeve by vacuum. After the pipe exits the vacuum sizing tank, it is moved through a second vacuum tank or a series of spray or immersion cooling tanks.

In the pressure sizing system, a positive pressure is maintained on the inside of the pipe by attaching a plug to the die face by a cable or, on very small bore pipe, by closing or pinching off the end of the pipe. The pressure on the outside of the pipe remains at ambient and the melt is forced against the inside of the calibration sleeve with the same results as in the vacuum system.

The production of large-diameter profile pipe, up to 10 ft (305 cm) in diameter, uses mandrel sizing. In one form of this process, the extruded profile is wrapped so that each turn overlaps the previous turn. In some other techniques, the turns are not overlapped.
Fig. 5-29 External sizing systems. (Courtesy Hoechst Celanese Corporation)
Cooling. For either the vacuum or pressure sizing technique, the pipe should be cool enough to maintain its circularity before exiting the cooling tank. Various methods of cooling are utilized to transfer the heat out of the polyethylene pipe. Depending on the pipe size, the system may use either total immersion or spray cooling. Spray cooling is usually applied to large-diameter pipe where total immersion would be inconvenient. Smaller-diameter pipe is usually immersed in a water bath. Cooling water temperatures are typically in the optimum range of 40–50˚ F (4–10˚ C). The total length of the cooling baths must be adequate to cool the pipe below 185˚ F (85˚ C) to withstand subsequent handling operations.

Stresses within the pipe wall are controlled by providing annealing zones. These zones are spaces between the cooling baths that allow the heat, contained within the inner pipe wall, to warm and anneal the entire pipe wall. Proper cooling bath spacing is important in controlling pipe wall stresses. Long-term pipe performance is improved when the internal pipe wall stresses are minimized.

Pullers. The puller must provide the necessary force to pull the pipe through the entire cooling operation. It also maintains the proper wall thickness control by providing a constant pulling rate. At the rate at which the pipe is pulled in combination with the extruder screw speed determines the wall thickness of the finished pipe. Increasing the puller speed at a constant screw speed reduces the wall thickness, while reducing the puller speed at the same screw speed increases the wall thickness.

Standards of the American Society for Testing Materials (ASTM) and other specifications require that the pipe be marked at frequent intervals. The markings include nominal pipe size, type of plastic, SDR and/or pressure rating, and manufacturer’s name or trademark and manufacturing code. The marking is usually ink, applied to the pipe surface by an offset roller. Other marking techniques include hot stamp, ink jet, and indent printing. If indent printing is used, the mark should not reduce the wall thickness to less than the minimum value for the pipe or tubing, and the long-term strength of the pipe or tubing must not be affected. The mark should also not allow leakage channels when gasket or compression fittings are used to join the pipe or tubing.

Saw equipment and bundling. Pipe 4 in. (10.2 cm) or more in diameter is usually cut into specified lengths for storage and shipping, unloading, and installation. Precautions should be taken for specific recommendations.

Injection-molded fittings. Injection-molded polyethylene fittings are manufactured in sizes through a 12 in. (30.5 cm) nominal diameter. Typical molded fittings are tees, 45˚ and 90˚ elbows, reducers, couplings, caps, flange adapters and stub ends, branch and service saddles, and self-tapping saddle tees. Very large parts may exceed common injection molding equipment capacities, so these are usually fabricated.

Equipment to mold fittings consists of a mold and an injection-molding press. The mold is a split metal block machined to form a part-shaped cavity in the block. Hollows in the part are created by core pins shaped into the part cavity. The molded part is created by filling the cavity in the mold block through a filling port, called a gate. The material volume needed to fill the mold cavity is called a shot.

The injection molding press has two parts: a press to open and close the mold block, and an injection extruder to inject material into the mold block cavity. The injection extruder is similar to a conventional extruder except that, in addition to rotating, the extruder screw also moves lengthwise in the barrel.

Injection molding is a cyclical process. The mold block is closed and the extruder barrel is moved into contact with the mold gate. The screw is rotated and then drawn back, filling the barrel ahead of the screw with material. Screw rotation is stopped and the screw is rammed forward, injecting molten material into the mold cavity under high pressure. The part in the mold block is cooled by water circulating through the mold block. When the part has solidified, the extruder barrel and mold core pins are retracted, the mold is opened, and the part is ejected.

Typical quality inspections are for knit line strength, voids, dimensions, and pressure tests. A knit line is formed when the shot flows around a core pin and joins together on the other side. Voids can form from material shrinkage during cooling, particularly in heavier sections. Voids can be detected nondestructively by x-ray scans. If this is not available, samples can be cut into thin sections and inspected visually.

Fabricated fittings. Fabricated fittings are constructed by joining sections of pipe, machined blocks, or molded fittings together to produce the desired configuration. Components are joined by heat fusion, hot gas welding, or extrusion welding techniques. It is not recommended to use either hot gas or extrusion welding for pressure service fittings, since the joint integrity is significantly less than that of a heat fusion joint.

Fabricated fittings designed for full-pressure service are joined by heat fusion and must be designed with additional material in areas subject to high stress. The common commercial practice is to increase wall thickness in high-stress areas by using heavy-wall pipe sections. This is similar to molding fittings with heavier body walls. If heavy-wall pipe sections are not used, the conventional practice is to reduce the pressure rating of the fitting. The lowest-pressure-rated component determines the operating pressure of the piping system.

Various manufacturers address this pressure derating process in different ways. Reinforced overwraps are sometimes used to increase the pressure rating of a fitting. Encasement in concrete is also used for the same purpose. Contact the fitting manufacturer for specific recommendations.

Very large diameter fittings require special handling during shipping, unloading, and installation. Precautions should be taken to prevent bending moments that could stress a fitting during these periods. Fittings are sometimes wrapped with a reinforcement material, such as fiberglass, for protection.

Thermoformed fittings. Thermoformed fittings are manufactured by heating a section of pipe and then using a forming tool to reshape the heated area. Examples are sweep elbows, swaged reducers, and forged stub ends.

The section to be shaped is placed in a hot liquid bath and heated to make it pliable. Then, it is removed and reshaped in a forming tool. The new shape is held until the part has cooled.

Fittings Overview

Polyethylene fittings may be injection-molded, fabricated, or thermoformed. The following section briefly describes each technique.

Injection-molded fittings. Injection-molded polyethylene fittings are manufactured in sizes through a 12 in. (30.5 cm) nominal diameter. Typical molded fittings are tees, 45˚ and 90˚ elbows, reducers, couplings, caps, flange adapters and stub ends, branch and service saddles, and self-tapping saddle tees. Very large parts are manufactured by heating a section of pipe and then using a forming tool to reshape the heated area. Examples are sweep elbows, swaged reducers, and forged stub ends.

The section to be shaped is placed in a hot liquid bath and heated to make it pliable. Then, it is removed and reshaped in a forming tool. The new shape is held until the part has cooled.

Saw equipment and bundling. Pipe 4 in. (10.2 cm) or more in diameter is usually cut into specified lengths for storage and shipping. Typical lengths are 40–50 ft (1219–1524 cm), which can be shipped easily by rail or truck. The pipe is usually bundled before it is placed on the truck or railcar. Bundling provides ease of handling and safety during loading and unloading.
Quality Control/Quality Assurance Testing

Quality is engineered into the pipe product during the entire manufacturing process. The three phases of quality control for the pipe manufacturer involve the incoming raw material, the pipe or fitting production, and the finished product. The combination of all three areas ensures that the final product will fulfill the requirements of its specification.

Testing the incoming resin is the first step in the quality control program. It is usually checked for contamination, melt index, density, tensile strength, and ESCR. Any resin that does not meet the raw material specification is not used for the production of specification-grade pipe. During the manufacturing step, the pipe producer routinely performs quality assurance tests on samples. This verifies that proper production procedures and controls were implemented during production. Once the product has been produced, it undergoes a series of quality control tests to ensure that it meets the minimum specifications as required by the appropriate standard.

The manufacturing specifications for piping products list the tests that are required. Several quality control tests are common in most ASTM polyethylene standards. For gas service piping systems, refer to PPI Technical Report TR-32 for a typical quality control program for gas system piping, or to the AGA Plastic Pipe Manual for Gas Service. The typical quality control/quality assurance (QC/QA) tests found in most standards are as follows:

- Workmanship, finish, and appearance. According to ASTM product specifications, the pipe, tubing, and fittings shall be homogeneous throughout and free of visible cracks, holes, foreign inclusions, blisters, and dents or other injurious defects. The pipe and fittings shall be as uniform as commercially practicable in color, opacity, density, and other physical properties.
- Dimensions. Pipe diameter, wall thickness, ovality, and length are measured on a regular basis to ensure compliance with the prevailing specification. All fittings have to comply with the appropriate specification for proper dimensions and tolerances. All measurements are made in accordance with ASTM D2122, "Standard Test Method of Determining Dimensions of Thermoplastic Pipe and Fittings."

Pressure tests. Three pressure tests are used to detect defects in the pipe manufacturing process. They are the quick burst, sustained pressure, and elevated temperature tests. The details of these test methods are presented in ASTM D1596, "Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure", and ASTM D1599, "Standard Test Method for Short-time Hydraulic Failure Pressure of Plastic Pipe, Tubing, and Fittings."

In the quick burst test, the PE pipe sample is pressurized at a temperature of 73.4°F (23°C) and a constant pressure to obtain a burst failure within 60—70 seconds. The burst pressure measured in the test must exceed the minimum burst pressure requirements in the applicable product specification. This test is used to determine, in a very short time period, if the pipe production has any serious problems.

The sustained pressure test requires that the pipe samples are maintained at a constant pressure for a minimum of 1000 hours at a temperature of 73.4°F (23°C) without failure. Again, this test will indicate if there are any malfunctions in the pipe production.

The elevated temperature test is conducted at 176°F (80°C) using pressurized pipe samples. The failure time must exceed the minimum value as listed in the applicable pipe specification. This test accelerates the failure time due to the higher temperature. It is more sensitive to changes in processing conditions or resin formulation than the other two pressure tests.

Physical property tests. Several tests are conducted to ensure that the final pipe product complies with the applicable specification. Depending on the specification, the type and frequency of testing will vary.

The following tests, with reference to the applicable ASTM standard, are generally required in many product specifications, such as those for natural gas service. Table 5-2 shows a list of tests and is an example of typical tests for gas piping systems.

Other tests are used that are not ASTM test methods. They are accepted by the industry since they further ensure product reliability. One such test is the bend-back test, which is used to indicate inside surface brittleness under highly strained test conditions. In this test, a ring of the pipe is cut and then subjected to a reverse 180° bend. Any signs of surface embrittlement, such as cracking or crazing, constitute a failure. The presence of this condition is cause for rejection of the pipe.

Summary. Through the constant updating of industry standards, the quality performance of the polyethylene pipe and fitting industry is continually evolving. Each year, PPI and ASTM work to improve standards on plastic pipe by calling for the latest test methods and recommended practices. Resin producers, pipe extruders, and fittings manufacturers incorporate these revisions into their own QA/QC practices to ensure compliance with these standards. In this way, the exceptional performance and safety record of the polyethylene pipe industry is sustained.

TUBING AND HOSE

Plastic tubing ranges from soda fountain hoses to precision medical tubing used in catheters and intravenous applications. Tubing can be flexible or rigid. It can be as small as a human hair or as large as a garden hose. A tubing die is similar to a blown-film die in that it surrounds a mandrel with an air hole through its middle. There are usually four adjustment bolts that can be tightened or loosened to obtain a uniform tube wall thickness. Usually an operator can adjust the tube wall thickness by pulling off the tube as it is being extruded and watching the new extrudate coming out. If the emerging tube bends up, there is too little extrudate coming out of the top of the die and too much on the bottom. The operator then adjusts the bolts to have less extrudate flowing through the bottom and more through the top.

Straight and Crosshead Dies

There are two types of tubing die, straight and crosshead. Straight dies are the simplest and are much like bottom-fed blown-film dies. The plastic comes into the back of the die, flows through a device called a spider, which is a series of holes or slots in a ring. The spider is necessary to support the inside pin. The material flows straight through, hence the name. Crosshead dies are fed from the side. The plastic must then flow around the pin and the two flows meet on the opposite side. Instead of air blowing through the hole in the pin of the die, a wire, fiber-optic
CHAPTER 5

PROFILE EXTRUSION

strand, or cord is inserted. As it goes through the die, it gets coated. Crossheads typically have only one knit or weld line. These lines are formed when the material flows in the die, meet each other, and weld or knit together. Straight dies may have many knit lines. These lines are sometimes undesirable in the end product because they can be seen and felt. Crosshead dies are used wherever there is a reason to change pins quickly, because the pin can be removed and another size put in without taking the entire die apart. They are used for wire coating, fiber-optic sheathing, and explosive cord covering.

Two Sizing Methods

In tubing extrusion, there are two types of sizing to hold the final product within dimensional tolerances: free extrusion and vacuum sizing. Free extrusion is the simpler type of sizing and involves a process called drawdown. For example, the outside diameter of the final tube might be 0.250 in. (6.4 mm). The outside diameter of the die might be 0.250 in. (6.4 mm). This represents a 2:1 drawdown ratio.

The speed of the puller determines how much the extrudate is stretched. The stretching of the tubing orients the tube and gives it some desirable characteristics such as strength. Furthermore, using larger tooling allows more flow through the tube; this results in greater output per unit time. For this reason, puller speed is critical in obtaining the proper size in free extrusion.

Once the extrudate leaves the die, it goes into a water trough for cooling. The water trough is typically made from sheet metal and has a hole in its side, through which the tubing enters. The tubing is kept underwater by guide rollers and exits on the other side. Water troughs can be as short as 2 ft (61 cm) for small tubing and as long as hundreds of feet (meters) for large pipe and hose applications.

In vacuum sizing, the vacuum tank is a water trough with a sealed top, typically a hinged cover. A vacuum is created inside the tank by a vacuum pump. Inside the tank are rows of sizing rings, usually made from sheet metal and containing precision-honed holes. As the extrudate enters the tank, the vacuum causes the extrudate to expand to the limits of the sizing rings. Since the rings are immersed in water, the extrudate freezes inside the rings as it travels along. The size of the rings directly influences the size of the tube. For this reason, the machining of these rings is highly critical.

The alignment of the sizing rings is also critical because, if one is out of line, it can cause a flat spot on the tube. The entire gang of sizing rings must also be straight, otherwise the tube can come out bent. Bending can also be caused by improper die alignment.

After the extrudate leaves the water trough, it passes through an air stripper. The function of the air stripper is to strip the water from the tubing before it enters the puller. The air stripper can be fed via compressed air or with its own blower. The puller consists of two rollers or belts that pull the tube along. The rolls or belts are typically adjusted with a hand wheel to match the outside diameter of the tube with enough space to grab the tube without crushing it.

Cut or Wind

Another choice in tubing extrusion is whether to cut the tubing to length or to wind it. If the choice is to cut, the tubing enters a device called a cutter. The cutter can be an integral part of the puller or a separate unit. The cutter is typically a flying knife, controlled by a clutch and brake or a servo motor, that is usually tied to a counter with an encoder on the puller belt. The counter determines the distance that the tube has traveled and sends a signal to the cutter to activate when a predetermined length has been reached.

The other option is to feed the tubing into a winder for winding on spools. Dual turret winders allow the operator to wind the tube continuously. When one spool fills up, the line is switched over to the other spool and winding continues.

WIRE COATING AND FIBER-OPTIC SHEATHING

Wire coating and fiber-optic sheathing are very similar to tubing extrusion. These processes use crosshead dies exclusively because a wire, fiber-optic bundle, or cord must be fed through the back of the die and through the crosshead. This is not possible with a straight die. The sizing of the extrudate is also determined by the free extrusion technique, because vacuum sizing requires that air be able to flow into the extrudate. The substrate (wire, cable, fiber, cord, or other material) is usually fed from spools by a payoff, which maintains proper tension. Because of the stiffness of wire, a pulling device, or capstan, is used instead of the belt or roll puller used in tubing extrusion. Capstans have a series of sheaves that the wire goes through to maintain tension. The capstans are necessary because the torque required to pull the wire along is much higher than that required for tubing.

MATERIAL CONSIDERATIONS

Material processing should include considerations for:

- Compounding and pelletizing.
- Powder and pellets.
- Abrasive thermoplastics.
- Corrosive polymers.
- Tolerances.

Compounding and Pelletizing

Compounding brings together different materials for making new substances that have enhanced, synergistic properties (the materials offer better properties together than they would by themselves). For this reason, engineers are always developing new plastic compounds. For instance, mixing polypropylene with calcium carbonate (limestone) makes it much more resistant to impact. Imagine a lawn chair on which a rock is dropped. If it were plain polypropylene, the chair would probably fracture; if it were combined with calcium carbonate, it probably would not.

An extruder is used to produce compounds by mixing. In this case, the extruder is not making a final product, but rather modifies raw materials before they are finally processed into products.

Powder and Pellets

Thermoplastic raw materials are typically supplied as a powder (granules) or as pellets. Pellets are typically 0.125 in. (3.2 mm) round or have a 0.125 in. diameter by 0.125 in. long. Most extruders 1 in. (2.5 cm) and above have no trouble running pellets. Powders are required for very small extruders under 0.75 in. (1.9 cm), because the feed depths of the extruder screw are typically less than 0.125 in. This makes feeding pellets impossible. Powder thermoplastics are typically less costly than pellet thermoplastics.
because one step in the production process—pelletizing—is eliminated for the raw material supplier.

Powders encounter feed problems in large extruders because they tend to “bridge” and stop flowing. Vibrators or stirrers are often used to prevent bridging. Twin screw extruders of the counter-rotating type are often used for powder because they have a positive displacement action that single screws do not have. This makes them perfect for processing low-cost powders with minimal problems. Most processors find the added cost of the twin screw of little concern when compared to the savings in raw material costs over the life of the machine.

ABRASIVE THERMOPLASTICS

Abrasive thermoplastic compounds are a major concern to the processor and machine builder. Thermoplastics are often filled with glass fiber for strength, mineral fillers like talcum or calcium carbonate for impact resistance, or fillers like barium to make them radiopaque. All of these fillers are abrasive and cause premature wear to barrels and screws. For this reason, the barrels and screws must be made from special wear-resistant materials. Screws are often surfaced with hard cobalt- or nickel-based weldments or made with special tool steels that can be case- or through-hardened. Barrels with bimetallic liners of abrasion-resistant alloys are available. The machine supplier can recommend the best materials for the plastic compounds to be processed.

CORROSIVE POLYMERS

Mildly corrosive polymers like PVC can corrode typical screws and barrels over time. Severely corrosive polymers like fluoropolymers can corrode screws, barrels, and dies in minutes, damaging them irreparably. For this reason, special materials must be used for screw and barrel construction when these corrosive polymers are to be processed.

The main problem with corrosive polymers is that acids and gases are produced when melt temperature is reached. The acids attack the machine components and the gases attack any other noncorrosion-resistant materials—including the human operators, who must steer clear of any fumes. Nickel-based alloys must be used for screw construction. Nickel-based alloys are not subject to corrosion when they come into contact with these acids. However, nickel alloys are costly and difficult to machine. This means that nickel-based screws, barrels, and extruders are typically two to three times the cost of polyolefin-grade screws, barrels and extruders.

TOLERANCES

Maintaining tolerances in extrusion is often critical. Customers often demand that extrusions meet certain tolerances for performance reasons. Another reason to maintain tolerances is to save raw materials. If a given extrusion contains 2% more plastic than is required, then at the end of the year, raw material costs are 2% higher than necessary. On large jobs, 2% can be a fortune. This is especially true in film extrusion, where jobs are lost over fractions of a penny. It is important to remember that all extrusion parameters—temperature, motor speed, and so forth—have an effect on the final product. Only when these parameters are kept in tolerance can the output of the extrusion line remain in tolerance.

Control technology allows for precise control at low cost. For the large majority of extrusion applications, the controls supplied with the basic models of extruders are suitable. Most are supplied with temperature controllers and motors with some type of feedback control system. A basic improvement is the addition of melt pressure control. However, marginal improvements in control of parameters come at a premium price. In fact, the controls supplied with sophisticated extrusion lines often exceed the cost of the extrusion equipment itself by 100–200%.

AUXILIARY EQUIPMENT

An extruder is a versatile machine and can be outfitted to make many different types of products. This section describes the accessories that extruders need to do their job.

PROCESS CONTROL

To precisely control the transformation from a solid to a fluid, the extruder barrel heaters are divided into equal-length zones, each zone having its own temperature controller and thermocouple or resistance temperature detector (RAD) to maintain a preset temperature. Depending on the diameter of the extruder and the length of the barrel, there can be as few as two zones and as many as six or more.

Control Panel

The control panel on a typical extruder houses the controls, loose switches, meters, and other indicators that serve as the man/machine interface. The control panel usually includes:

Screw rpm meter. This meter shows the screw speed in revolutions per minute. The number of revolutions per minute of the screw is roughly proportional to the output.

Motor ammeter. This meter shows the load on the motor in amperes or percentage of full load. This is an important quantity because it indicates the amount of power the screw is demanding to turn at the preset rpm. The more viscous the material, the more current will be required. An operator must take care to watch this meter, because too much torque can break a screw. Also, overloading can cause permanent damage to the motor.

Heater ammeters. These meters indicate the amount of current going to each heater. This is an important indication because, if a heater burns out, the subsequent cold zone condition could cause screw breakage and will most definitely cause adverse melt quality. If the temperature control indicates that it is sending power to the heater and no current is indicated, then there is clearly a relay or contact failure, or a burned-out heater. Most advanced temperature controllers have a heater break alarm feature; a digital ammeter in each temperature controller turns on an alarm light if the heater current does not go up when power is sent to it.

Melt temperature indicator. This indicator tells the operator what the temperature of the melt is, as measured by a temperature probe in the head of the extruder that touches the melt. Barrel heat zones measure only the temperature of the barrel, not the melt temperature.

Melt pressure indicator. This meter tells the operator what the pressure of the melt is in the head of the extruder. Usually, the pressure should not exceed 6000 psi (41,368 kPa). Pressures
above this level can be dangerous because they can blow dies off and release flying particles of hot plastic and metal.

Melt pressure controller. Some extruders have a melt pressure controller that keeps a relatively constant melt pressure by varying the screw speed. The operator gives the control a certain set point. The control then compares the present value of the melt pressure with the set point value. If the pressure is too high, the control sends a signal to the motor to slow down, thereby reducing the melt pressure. Conversely, if the melt pressure is too low, the control sends a signal to the motor to go faster, increasing the melt pressure. The melt pressure controller helps to achieve a stable output. This is especially important when precision products such as medical tubing are being produced.

Temperature control system. The temperature control system's function is to maintain the precise temperatures required at different stages of the extrusion process. The system consists of heating devices, cooling devices, and a feedback control system. A typical extruder would have cylindrical ceramic electrical heaters placed around the barrel, one for each of the temperature control zones. Fan cooling is often used on barrel zones, but water and oil can also be used. The temperature is controlled by temperature controllers, which are devices much like a thermostat in a home heating unit. The temperature controllers sense the temperature in the zone by a thermocouple that is placed inside a blind hole in the barrel wall. The temperature control then sends electrical current to the heaters until the desired temperature is reached and maintained. Fan cooling is also needed in many cases because once the plastic is being forced along the screw, frictional heat can build-up and drive the temperature of the barrel higher than is desired. In that case, the temperature control turns on a fan and uses air cooling to bring down the temperature. This is important because many plastic materials are temperature sensitive and can degrade severely when they are overheated.

Programmable logic controller. Advanced extrusion lines are usually controlled by programmable logic controllers. These controllers run the entire line, controlling temperatures, motors, pressures, and all critical operating parameters. There are many advantages to using a PLC to control the whole line.

Recipe storage is a key benefit. The entire setup parameter schedule can be saved in a single recipe for future use. If a successful product run must be repeated in the future, an operator need only call up its recipe number or name to set up every parameter of the entire machine. With standard controls, the operator would have to go to each temperature, pressure, and motor controller to enter each set point. On a sophisticated line, there may be 30 or more set points. The recipes save time and eliminate operator error.

Data acquisition is another benefit of PLC control. PLCs are typically controlled by computers which use a test-based or graphical-user interface (GUI) system. Data acquisition software can generate statistical reports and trend charts for any parameter and can perform statistical process control and quality control (SPC and SQC) procedures on the data. It can provide X-bar diagrams, R charts, and histograms. The operator can generate complete statistical data for the entire extrusion run and deliver it to the quality control manager or ultimately to the customer. Remote control of single or multiple extrusion lines is available when PLCs are linked on a network. One person can supervise multiple lines with the right combination of hardware and software.

Perhaps the most significant improvement to the extrusion process is complete control by microprocessors. The microprocessor, equipped with a CRT monitor and keyboard, is used extensively for the complete control of the entire extrusion line, whether it is a blown, cast, sheeting, or profile line. Microprocessor systems can be purchased outright from several reputable control system manufacturers or can be put together by a competent electrical engineer from purchased subassemblies. If the person configuring the system can create software programs, these systems can control all the heating and cooling zones, the extruder screw speed, and haul-off and winder speeds. Not only do they control and display what they are controlling on the CRT monitor, but they also record data on all the ongoing functions of the system, which can be printed out on a printer for hard copy records, or stored on a magnetic disk for use at a later time.

SCR controller. The silicon controlled rectifier (SCR) controller converts AC power into DC power and regulates the DC voltages to the armature of the DC motor. Consider a 1750 rpm DC motor having an armature voltage of 180 V DC and a field voltage of 200 V DC. By changing the armature voltage, the motor's rpm can be regulated. This is done by modulating the DC control voltage built into the SCR drive board with a 2–5 kΩ speed potentiometer so that it ranges from 0–10 V DC.

Locked-up four-quadrant drive. SCR DC drives come in two standard versions: nonregenerative and regenerative, the latter being more desirable. The regenerative version, commonly referred to as a locked-up four-quadrant drive, will not let the motor reverse itself or slip back when countertorque exceeds the drive torque being supplied by the DC motor. On the other hand, the nonregenerative SCR controller can be overcome by excessive countertorque and can slip back or slightly stall. This is normally not a problem if the motor horsepower and speed range are correctly calculated.

Master reference speed control. If the SCR drive board's internal regulating signal were used, a speed potentiometer would be needed for each drive board in the system to control each DC motor. This, in fact, did occur in the past where lines with multiple drives had multiple speed potentiometers that were gang-stacked together or clustered and actuated by a spur gear drive.

This has changed on turret winders with the advent of master reference speed control. Master reference control uses an electronic board, called a quad inverter that has four or sometimes six channel outputs. It is powered by a 24 V DC power supply. The output channels are filtered through an isolation card before going to the individual drive boards.

Quad inverter board. The function of the quad inverter board is to create a 0–10 V DC signal output. This signal is connected to the SCR drive board terminals, which bypass their own internal modulating signal and instead use the quad board's signal to regulate the DC motor armature voltage, which regulates the DC motor's rpm to control line speed.

Besides having four or six buffered channel outputs, the quad inverter board has potentiometers adjacent to each signal output that are used to fine-tune the signal to each drive board. Consequently, all the drives can be speed-regulated and slightly overdriven as required. Thus, all the drives of the system can be controlled from one master speed potentiometer located at the operator's control panel.

Electronic thickness monitor. This is a unit that uses a sensing head in the form of a capacitance sensor, gamma back scatter sensor, or other device to monitor a product's wall thickness. It monitors and records all motion lines, thickness as an ongoing function of the line, and also helps control thickness when connected to a microprocessor that regulates either haul-off speed or extruder screw rpm. These are generally the two most important variables in maintaining thickness in film, piping, and sheet lines. Many units incorporate a CRT monitor and printer for displaying and producing hard copies of data. They are sometimes integrated directly with complete computer control systems.
Tubing lines are typically controlled for two parameters: outside diameter and wall thickness. Usually, a laser gage monitors the outside diameter and reports to a controller that adjusts puller speed. When the outside diameter of the tube is too large, the puller speed is increased to make a more intense drawdown. The tube then becomes smaller. Conversely, if the outside diameter of the tube is too small, the puller is slowed to decrease the drawdown action. This type of control is suitable only for free extrusion of tubing, not vacuum tank extrusion. Vacuum sizing is a process that sizes the tube mechanically by drawing it through sizing rings. The size of the tube is directly limited to the size of the rings; the rings must be machined to effect a change in the tube size. The puller speed does not directly affect the size. The wall thickness might change some, but actually this is determined primarily by the die gap when vacuum sizing is used. Vacuum sizing is reliable after setup but is not as flexible as free extrusion.

Wall thickness control in free extrusion is typically monitored and not directly controlled. Ultrasonic gages are put underwater in the tank and measure the thickness at four points aligned with the die bolts. When the wall is too thick at a point, the operator adjusts the die bolt to thin that side. Conversely, the die gap can be made wider to make the tube thicker at that point. Usually heaters are not used to adjust the die gap as they are in film dies or sheet dies because there is not enough room for them. The same type of wall thickness and outside diameter control systems apply to wire and cord insulation, fiber-optic sheathing, and any crosshead application.

Film width and thickness controllers. Blown-film lines have different types of advanced controls. Width is controlled by a laser gage that measures the outside of the bubble. Since the size of the bubble is controlled by the amount of internal air pressure, the laser gage is tied to a controller that adjusts the damper for the internal air pressure. If the layflat is too big, the controller reduces the internal air pressure and the width is reduced. Conversely if the layflat is short of tolerance, the internal air pressure is increased. Thickness of the film is controlled by a rotating nuclear or backscatter gage that reports points of thickness around the bubble to a controller. The controller is connected to heat zones around the die lip. If the film is too thick, the zone is made cooler, thereby shrinking the die gap. Conversely, if the film thickness is too little, the heat is increased at that point to increase the die gap. There are many variations of this technique. Cast-Film and sheet lines also use the die lip heat control system for thickness control. Each die bolt area has its own heater and the control measures the thickness with the same type of gage that traverses the sheet or film.

**GENERAL EQUIPMENT**

**Blender**

Most feed to the extrusion hopper is made up of mixtures of resins, colors, and other additives. To provide a uniform mix in the sheet, a blender may be required before the hopper. This might be a batch ribbon blender, a conical blender, or in some cases, an automatic metering device which feeds multiple streams of material to the hopper in precise amounts.

**Screen Changer**

This is commonly used after the material exits the extruder barrel to filter the plastic melt and remove the occasional foreign particles, and break up conglomerates of color. The changer is usually automatic so the process need not be shut down to change dirty screens for clean ones.

**Melt Pump**

This device is used where a variety of different resin types are extruded. The melt pump ensures positive, uniform flow to the die. Otherwise, each polymer would require a special screw for optimum throughput. The melt pump also eliminates the need for fine tuning of temperatures, reduces gage variation in the machine direction, and compensates for screw wear.

**Static Mixer**

This is used to improve distributive mixing in single-screw extruders. It is well suited for color mixing and melt temperature homogenization of a broad range of thermoplastics. Additional benefits include uniform product density, elimination of melt lines in the machine direction, and reduced time to change colors. Add-on mixing units provide compounders a low-cost means to increase extruder productivity, achieve higher yield from raw materials, and improve physical characteristics of the product.

**Textured Rolls**

When the melt leaves the die and enters the roll nip, it is soft enough to take the finish off the rolls it is in contact with. Thus, textured or grain rolls impart a mirror image of their finish to the sheet. This can give both functional and aesthetic qualities to the sheet. There are as many different grains as the imagination can conjure up. Some of the most popular in the custom sheet industry are: haircell, colonial grain, levant, and saddle.

**Grinder**

One of the many advantages of thermoplastic sheet products is that they can be recycled and processed directly back into sheet after they have been ground. Since thermoplastics can be recovered and reused so easily, grinding equipment has become one of the most important auxiliary pieces in the industry.

**Dryer**

Many resins are hygroscopic (moisture absorbing). Thus, they must be dried before being fed to the extruder. The most common dryer uses hot dehumidified air that passes through and around the resin particles in a tall cylindrical hopper.

**Gravimetric Feed System**

A gravimetric feed system stores resin and automatically dispenses it into the extruder at a controlled rate of feed. A microprocessor monitors and controls the feed rate according to how the unit was programmed for a particular product. The system can be connected to a pressure feedback loop. As conditions change because of higher pressures due to a dirty screen pack in the filtering device, the system will sense this and gradually increase the extruder screw rpm to maintain a constant output at a higher back pressure up to a setting that will alert an operator that it is time to change the screen packs. These units also keep a record on tape of how much resin has been used over a preset period of time.

Gravimetric feed systems are being used in both monolayer extrusion and coextrusion. They are especially useful when a processor is using three, four, or five extruders to make a multilayer composite structure. They provide the only accurate way of controlling individual layer thickness by percent or weight.

**Scrap Reclaimers**

This equipment usually comes in the form of a granulator, grinder, or a type of pelleting line that remelts the scrap and processes it up to a certain percent with virgin material. In its sim-
Extruders can last 20 years with good care, and should certainly be producing after 10 years. Proper maintenance means a regular schedule to check the machine. Read the owner’s manual carefully; if it is gone, get another copy. Here are some important aspects of extruder maintenance.

### BASE

Everything must be bolted tight, leveled and aligned.

### MOTOR

Most DC motors are exposed to the air; the inside must be kept clean and the brushes must be checked for wear. Make sure the fan is blowing in the right direction; otherwise it will draw dirty air into the motor rather than keep it from entering. The air filter may need replacing. The motor ammeter and the screw speed indicator should be calibrated frequently. The alignment and condition of all couplings, belts, and pulleys should be checked.

### REDUCTION GEAR

Make sure there is always enough lubricant in the system, and change it at regular intervals. Seals on the shafts should be inspected and leaks observed and repaired if necessary. If there is an oil filter, change it often and inspect the old one to see what is in the oil system; for example, metal bits indicate that something is wrong inside. Monitor temperature and pressure of lubricant.

### THRUST BEARING

Determine age, model, and replacement procedure, and calculate the expected life of the bearing. While the bearing is running, look for an overheated housing and listen for vibrations and unusual noise; take it apart for inspection if noise, high temperature, or metal bits so indicate.

### HEATING/COOLING

Calibrate controllers and thermocouples and check heating and cooling devices for tight contact with the outer barrel surface. Some types of heaters do not need close contact, while others do. All electrical contacts and water connections should be tightened. Look for rust; water leaks may not be visible, but rust is evidence of previous leakage. Replace frayed wiring and guard against future fraying. Flush the cooling system and descale if necessary.

### BARREL

If the screw is pulled, shine a light down the barrel and look for cracks and scores. If wear is suspected, use an accurate instrument to measure the diameter from one end to the other. Inspect the powder seal at the feed end. Look at all the sealing surfaces at the output end and refinish/replace gaskets or breaker plates as necessary.

### SCREWS

Measure flights for wear; repair only when justified—for example, when lower output per revolution is combined with overheating. Sometimes wear does not make any difference. Keep screw pusher threads clean. If the screw has water cooling, inspect the rotary union for leaks, frayed hoses, grease connections, and rough turning. Make sure the cooling finger that enters the screw bore is not plugged or otherwise damaged. Keep all screws clean, including spares, which should be wire-brushed clean and anti-rust-treated when put in storage. When it is back in the extruder, measure tolerances and concentricity of the screw (remember that the extruder will sag in the barrel, so turn it a little, then measure; turn, etc.).

### HEAD

Keep breaker plates clean, rustproof them if they are stored, and check their sealing surfaces for smoothness, because nicks and carbonization will mean slow leakage during operation. Calibrate the temperature and pressure gages. Test the alarms, if any. Lubricate valve threads. Check supply of screens and see that spare shear pins or rupture disks are available when needed.

### DIES

Keep them clean, inspect for damage at the lips and store with protection against damage and rust. See that all bolts are in place and move freely; lubricate if needed. Calibrate controllers and thermocouples. Inspect heaters for damage, poor contact, frayed wires, or improper grounding.

### TAKE-OFFS

Flush and descale cooling systems, refinish chrome rolls as needed. Rubber rolls are often neglected more than chrome rolls and may need refinishing if they are glazed, chipped, or slipping. Roll stacks should be kept level. Water tanks should be checked for leaks, especially at hose connections. While they are running, check all pullers for speed, tension consistency, and worn belts.

### SPARE PARTS

Take regular inventory of spare parts; every system needs a different set, so make a list to be sure replacement parts are on hand—for example, screens, breaker plates, heaters, thermocou-
OPERATION AND MAINTENANCE OF EQUIPMENT

CLEANING SMALL PARTS

It is sometimes necessary to clean small parts covered with plastic. This is best done while the part is hot and the plastic is still melted. If the part is cold, reheat it in an oven to melt out as much plastic as possible; such heat soaking is good for hot parts as well. Steel cleaning tools can scratch delicate die lips and flow-path surfaces. Use brass, wood, and similar materials instead, especially where sealing surfaces are involved, because if these surfaces are damaged, leakage may occur. If a vise is used, avoid marks on sealing surfaces. For breaker plates, clamp horizontally rather than vertically, to prevent such marks and make melt-out easier. Direct an air hose at the plastic-metal contact line; the air causes shrinkage and clean separation when the plastic is slowly pulled away with long-nose pliers (wear gloves and eye protection).

Burnout with torches may warp or damage metal parts and is also dangerous. If it must be done, do it slowly and safely.

Use solvents with caution, only in ventilated areas and only as a last resort. A solvent soak is effective, but do not put hot parts in solvents. Keep containers covered but vented. Molten salt baths clean tiny holes effectively, but they are dangerous. Hot fluidized beds of alumina particles burn off the plastic with no harm to the part. High-temperature ovens, with or without vacuum, remove plastic from metal parts like a self-cleaning home oven. With all these devices, remember to vent the exhaust safely.

WARM UP

Any extrusion system requires a warm up period, or heat soak time, before material can be processed through it. This can take anywhere from two to five hours after the heaters have been turned on, depending on the size of the line. The warm up of a clean machine, without any polymer or associated tooling in its extruder barrel, should take place in incremental temperature setting steps over the entire warm-up period until the proper operating temperatures have been achieved. In other words, temperature controllers should be set at proportionate, incremental steps, higher and higher until operating temperatures reach the proper running profile.

Consider a representative blown-film line with a 3.5 in. (89 mm) extruder having four barrel zones, a manual screen changer, an adapter tube, and a 12 in. (305 mm) die plus oscillator assembly producing LLDPE film at a melt temperature of 425°F (218°C). In this example, the initial heat setting for all zones should be 250°F (121°C). When these temperatures are reached in each zone, the second setting of 300°F (149°C) should be entered for all control zones. When this temperature is reached in all zones, reset the die, oscillator transfer tube, and manual screen changer zones to 375°F (191°C), but leave all the extruder barrel zones at their previous setting of 300°F so that the die and oscillator assembly, transfer tube, and screen changer, which have more mass than the extruder barrel, have time to warm up. Meanwhile, some of the heat from the higher settings will transfer into the extruder barrel. Consequently, the critical barrel zones are the last to be set at their intended operating temperatures.

Reset Zones

When the die, oscillator, transfer tube, and screen changer have reached their set point of 375°F (191°C), it is time to reset all zones to the final operating temperature profile required to run the intended resin. In this case, an LLDPE hexene-based material having a melt flow index (MFI) rating should have the set points and temperature profile (shown in Table 5-3).

When all the set points are reached and the temperatures are at the set point, or very close to it (±5°F or ±27°C), the process is ready to run. For a representative temperature profile and start-up procedure for metallocene resins, see “Processing Metallocene Resins” earlier in this chapter.

INITIAL START-UP STAGE

During warm up, the extruder screw and drive are turned off and the speed control is set at zero rpm. Now, start the extruder drive, open the storage hopper feed chute, and slowly increase the screw speed to five or six rpm to allow material to come through the die and associated tooling. This may take 10–15 minutes, depending on the size of the system.

All through this initial stage of start-up, the operator must observe the head pressure in the barrel and the current drawn by the extruder drive. Both these readings are displayed on the main control panel. Start-up current should never exceed 25–35% of the full-load motor rating for amperes, and barrel head pressure should never exceed 1500–2500 psi (10,342–17,236 kPa) at start-up, as screw speed is slowly increased to 8–10 rpm. If the head pressure and current draw exceed these limits at 10 rpm or less, something is wrong with the system’s drive or the melt is still too cold. If the melt is too cold, gradual incremental increases in the barrel zones will alleviate this problem.

Once polymer starts flowing through the tooling, gradually increase screw rpm to reach the desired output. Always watch the

<table>
<thead>
<tr>
<th>TABLE 5-3</th>
<th>Heat Profile for 425°F (218°C) Melt Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Zone 2</td>
</tr>
<tr>
<td>Set Point, °F</td>
<td>380</td>
</tr>
<tr>
<td>Set Point, °C</td>
<td>193</td>
</tr>
<tr>
<td>Actual, °F</td>
<td>380</td>
</tr>
<tr>
<td>Actual, °C</td>
<td>193</td>
</tr>
</tbody>
</table>
current draw and barrel back pressure, making sure they are both in the safe operating range as specified by the manufacturer.

**SYSTEM SHUTDOWN**

The proper shutdown of an extrusion line is just as important as proper start up. To avoid carbon formation and/or possible damage to the system's components, the extruder should never be shut off by lowering the screw rpm to zero and then shutting off the drive and turning the heaters off at their running temperatures. This will lead to carbon formation as the material burns up in the system while it is not moving. It is also bad practice to run the tooling and barrel dry, without adding any material to the system, as this will eventually lead to oxidation of the residual material; it will combine with the ambient air and form carbon—the real enemy of any extrusion process.

It should be remembered that carbon formation and heat degradation are functions of time and temperature in an extrusion process. Simply stated, polymer must be kept moving while it is under heat and pressure to prevent degradation. Consequently, there are two preferred ways to shut down an extrusion process.

**With Purging Compound**

The first method calls for evacuating all the virgin material from the hopper and filling the hopper with a purging compound that can be run at a wide range of temperatures and is less sensitive to heat degradation. The purge material is run through the system at the existing heat profile at low rpm (10–15) for 10–15 minutes, then the machine screw is slowly turned to zero rpm and the machine is shut off, with the purge material still in it.

Purge compounds come in two versions. One version is a chemical reagent that chemically cleans and prevents the degradation of the virgin resin. The other type is a very viscous material that can be run at a wide range of temperatures and is less sensitive to heat degradation. It should be performed only by an experienced operator, however, because the extruder current draw and head pressure must be carefully monitored; as the melt gets colder, the current and pressure will increase because of the greater viscosity of the material.

Consider a system running LLDPE under the conditions given in Table 5-3. The procedure for shutting down this system without purging compound is as follows.

1. Reduce the screw speed from 50–40 rpm and lower all the temperature control zones as shown in Table 5-4.
2. Continue to slowly reduce the screw rpm from 40–30 and run the machine until the actual zone temperatures are close to the new set point temperatures, making sure that the current draw does not exceed 70–80 A and the pressure does not exceed 5000 psi (34,473 kPa). When the lower temperatures have been reached, reduce the screw speed to 25 rpm and reset the temperature profile as shown in Table 5-5.
3. Wait until all zones are at or close to their new set points, then lower the screw speed from 25–10 rpm, still watching the current and pressure. With the screw running at 10 rpm, extrudate will dribble from the tooling. Periodically remove it with a brass or copper tool while wearing goggles and high-temperature gloves to protect the eyes and hands from burns.
4. Put in the final temperature settings in preparation for shutting the system off. This step is the most critical with regard to current and pressure. If for any reason the extruder drive current or barrel pressure surges to 80 A or 5000 psi, immediately shut the drive off to avoid damage to the system or injury to staff. The final set points are shown in Table 5-6.
5. Lower the screw speed from 10–5 rpm and continue to run the machine, closely watching the amp draw and barrel pressure as the temperatures drop. When the new set points are reached, or the current draw and pressure get very high, turn the screw speed down from five rpm to zero and shut off the extruder drive and the entire system, including all electrical heaters. In any case, never run the machine at more than 60% of its full nameplate ampere rating or at more than 5000 psi barrel pressure.

Keep in mind that this procedure is used for a resin and heat profile producing a 425˚ F (218˚ C) melt extrudate. Resins that run at a lower temperature can also be shut down this way, but a modified incremental lowering of temperatures must be used.

<table>
<thead>
<tr>
<th>TABLE 5-4 Reduced Temperature Control Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
</tr>
<tr>
<td>Set Point, º F</td>
</tr>
<tr>
<td>Set Point, º C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 5-5 Lower Temperatures Achieved: Temperature Profiles Reset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
</tr>
<tr>
<td>Set Point, º F</td>
</tr>
<tr>
<td>Set Point, º C</td>
</tr>
</tbody>
</table>
When a producer configures an extrusion process or solicits a proposal from a manufacturer, the following considerations must be evaluated and/or stipulated to achieve the highest success for any given project. Although some of the following points may seem basic and elementary, they are of prime importance in selecting an extrusion process.

The first consideration is the type of product to be made. Will it be film? Will it be sheeting or a solid profile? The second consideration is how much product is to be made on an annual basis. The third is how much will the equipment cost and is the budget sufficient to cover initial purchasing and installation of this new equipment. Once all three of these determinations have been made, the selection process can begin.

A representative example is a five-layer coextrusion line to produce a nylon barrier layer film consisting of HDPE-tie-nylon-tie-LLDPE. In this example, the HDPE resin is the outer layer, the nylon is the barrier layer, and the LLDPE film is the inner layer for heat sealing purposes. The outer HDPE layer adds strength and stiffness to the final film product.

Specifications for the line are:
1. Film thickness: 0.002–0.003 in. (0.05–0.07 mm).
2. Film width (layflat tubing): 40 in. (1 m).
3. Total output: 2,000,000 lb (907 metric tons) per year calculated on 8000 hours/year operation.
4. Extruders: five extruders consisting of 1.5 and 2 in. (38 and 51 mm) sizes.
5. Product: tubing layflat or single wound sheeting.
6. Composite structure to make 0.003 in. (.076 mm) thick, 40 in. (1.1 m) wide tubing, 250 lb/h (113 kg/h).

In this case, the A outer layer would require a grooved-feed extruder for the HDPE, while all other extruders would be smooth-bore type with the appropriate screw design. For sufficient cooling at the stated output, a 28 ft (8.5 m) high tower structure would be sufficient for proper cooling, using refrigerated air at 40˚F (4.4˚C), no internal or internal bubble cooling (IBC) system required.

The roller face width for the upper nip, lower nip, and winders plus all idler rolls would be 44 in. (1.1 m), with line speed covering a range of between 20–100 fpm (6–31 m/min) to cover the range of film thicknesses. While gravimetric feeding and computer control are not necessary, they should be the first choice and are strongly recommended to maintain layer thickness and total output, and to control and monitor the entire system to include data logging, magnetic recipe disk storage, and hard copy printout for record keeping purposes.

Also, an automatic profiler type thickness measurement system should be incorporated, with a feedback loop to monitor and control the upper nip haul-off line speed to ensure film thickness is maintained and recorded. The cost for a system like this would be between $850,000 and $1,250,000 with installation, depending on the supplier and the type of ancillary equipment. Final extruder screw design should be left to the vendor, unless a processor has a tried and proven design or has a special preference for a particular design.

### GEAR PUMPS

In some cases, a processor may wish to consider gear pumps for each extruder. These are true volumetric devices driven by a variable-speed motor that precisely controls the amount of extrudate being supplied by each extruder. They are usually tied into a feedback loop that monitors the pressure differential across the screen pack to maintain a preset output as the screen pack becomes more contaminated.

With a gear pump system, a gravimetric hopper feed system is not required unless a processor wants to keep a running tare of poundage used on a daily or monthly basis, or is blending one or two additional components with a primary resin in the individual extruder.

### GROOVED FEED COMPARED TO SMOOTH BORE

Know when to use a grooved-feed extruder or a smooth-bore extruder. Remember that the smooth bore extruder is not suited to pump materials with poor solids conveyance characteristics. Grooved-feed extruders would be a poor choice when running very heat sensitive, shear sensitive resins such as PVDC and EVOH. A grooved-feed extruder is a relatively surge-free pump and will produce a minimum of pulsations in the melt, which can cause problems in the tooling. This surge problem can also be handled in the smooth-bore extruder if gear pumps are used; these pumps tend to be surge-free when used at the end of an extruder barrel with a feedback loop tied into the screen pressure differential.
CHAPTER 5
TROUBLESHOOTING

TROUBLESHOOTING

Discussion of troubleshooting will cover:

• Materials.
• General processing.
• Film extrusion problems.
• Polyethylene film extrusion.

MATERIALS

Some of the many problems that can occur during extrusion are traceable to the processed raw material; that is, the raw material is not up to specification. Regardless of any quality assurances by manufacturers of raw materials and countless programs such as ISO 9000, reengineering, and just in time (JIT) manufacturing, plastic batches and even bags or boxes within batches have their idiosyncrasies. With all extrusion parameters the same, the tubing or sheet will have a different look, bend, color, or texture. While this may sound unscientific or preposterous, these problems do occur on the floor. Despite all the computer programs and hardware designed to keep the quality constant, there will be variations.

Some materials such as polyurethane, nylon, EVOH and others, are hygroscopic (they absorb moisture from the air). This moisture is undesirable and can cause bubbles in the melt and, in the case of EVOH, can decrease barrier properties. For this reason, the polymer should be kept sealed in nitrogen-purged bags and stored in a dry place. The nitrogen gas prevents moisture from forming. Some materials such as polyethylene, and can be eliminated by running the melt or the die lips hotter, using a longer or more streamlined die, or trying a different grade or source of material. Additives may help greatly in this regard.

Other problems include contamination with foreign materials such as metal chips, screws, bolts, nuts, cardboard, rodents, and rodent droppings. Even so-called medical grade plastics are often contaminated. Of course, the contaminant will end up in the melt, so every precaution must be taken to avoid contamination by closing bags, covering hoppers, keeping a clean area around the extruders, and similar measures.

GENERAL PROCESSING

Common processing troubles are:

• Surging.
• Poor mixing.
• Melt toughness or fracture.
• Overheating.
• Moisture release.
• Trapped air.
• Contamination.
• Applesauce.

Surging

Surging is a cyclical product thickness variation in the direction of extrusion. The surge cycle time is typically between 30 seconds and 3 minutes, and the cause can be inside or outside the extruder. Outside causes are easier to see and correct. For example, the take-off pull may be irregular; in this case the screw rpm and ammeter readings remain steady. Sometimes screw motor speed varies because its regulation is not working properly. This is rare and will show up as unsteady rpm. Sometimes the feed is uneven because of particle size, light weight, or bridging in the hopper and throat. With very small extruders, the feed channel depth is not much bigger than the feed particles, and they may feed erratically for this reason alone.

• If none of these outside causes are observed, it is probable that the surging originates inside, typically at the beginning of the compression zone, where the solid bed—the mass of pellets—may be locking and breaking up irregularly. Screw rpm is steady but the ammeter shows variations of ± 5% or more. Sometimes this can be cured by increasing the temperature of the feed to promote earlier melting. Raising the rear barrel temperature may help, too. Make big changes, 25–50˚ F (14–28˚ C), and see what happens. Sometimes raising the barrel temperature at the beginning of the compression zone will help by getting better sticking of the pellets to the wall there.

• If these actions do not help, try running slower or faster by at least 10%. If the problem still remains serious, consider altering or replacing the screw, or installing a gear pump between the extruder and the die.

Poor Mixing

• This often sets the upper limit for output. The screw cannot be run any faster because the material is coming out with an “applesauce” surface, with streaks, parabolic ridges, and perhaps particles of undispersed additive. Screw modifications, such as pins or separate mixing heads will help, but may raise melt temperature. Running more slowly will always help, as it provides more residence time. A screw with internal cooling mixes better because it has the effect of a shallower channel in the metering zone. The output per rpm drops 30, but may be regained by increasing the screw speed, unless melt temperature gets too high or the drive system cannot safely run faster. High pressure is good for mixing. A valve will do this, or a gear pump pressure control that can serve as a valve. Cooler dies increase the resistance and thus raise the pressure in the system. Finer screens will raise the pressure, but as they keep clogging, pressure is inconsistent.

Melt Toughness or Melt Fracture

• This refers to fine ridges or rough surface seen when the melt comes too fast out of a narrow die. It is most common with polyethylene, and can be eliminated by running the melt or the die lips hotter, using a longer or more streamlined die, or trying a different grade or source of material. Additives may help greatly in this regard.

Overheating

• Overheating may limit the rate if the take-off cooling is limited, or it may produce degradation or make dimensional control and sizing difficult. In such a case, stop all barrel heat except in the rear zone as needed for bite (input) control and cool the barrel if necessary. (In a few cases, more barrel heat will yield a cooler melt.) There is a temperature below which the melt will not go at a given screw speed, even if all the barrel heaters are turned off.

• See if the controller around 70% down the barrel is overriding. This means overpacking of the metering zone—overbite—with much heat generated at the entry to that zone. In
that case, reduce the bite by changing the feed temperature, rear barrel temperature, or particle size.

- Grooved barrels with the appropriate screws will keep the melt temperature lower because they need less rpm to extrude the same output. For all extruders, raw material choice is critical; often, one material will run cooler than another even if properties are similar and they have the same melt index. Test the melt flow at extruder speeds with a small extruder, a melt indexer run at high loads, or a torque rheometer, to show up differences at extrusion shear rates.

Moisture Release

- Moisture is absorbed by some plastics. It passes through the extruder and boils when the pressure is relieved at the die lips. The result is a pattern of dotted lines, long bubbles, and pits. To remove moisture, the material must be predried, or a vent must be used in the extruder, or both. A moisture level of 0.1% is usually low enough to avoid such visual problems.
- Some plastics, such as PET, the nylons, and polycarbonate, can degrade and weaken if even a tiny amount of moisture is present when they are melted. For these, dehumidifying dryers are used to get moisture down to 0.01% or less.

Trapped Air

- This is not common in pelletized material used with long extruder barrels. However, some old machines have short barrels, and even a long machine can be pushed so fast that the air is carried forward into the product. A trapped-air surface shows bubbles and pits, but little, if any, dotted lines. Such a surface will improve if run more slowly if moisture is not the problem. A cooler head and die may help. Vents and vacuum hoppers will eliminate trapped air and are essential for powders, where passages between the particles are much smaller; the air cannot escape back through these passages and is carried forward instead.

Contamination

- Contamination of all kinds causes spots or dimples, often called fisheyes, in an otherwise smooth surface. Test the raw material before accusing the supplier, as oxidized or cross-linked bits of plastic may be produced in the extruder itself, in slow moving or stagnant areas. Use a microscope to detect fibers and colorants. Oxidized bits glow in ultraviolet light. Neither oxidized nor cross-linked particles dissolve in solvents that dissolve the raw material.
- Another source of contamination is the dust that gets blown around by unfiltered conveyer air or that is attracted by static electricity. Fibers from sacks of material can get into the product. Do not cut paper bags and dump them, but pull the seam threads off and empty them carefully, clean them off before pouring or, best of all, get the material out of the bags with a vacuum loader. If possible, buy material in bulk or boxes to avoid bags altogether.
- Fine particles may be left in transport lines from silos or in the silos themselves, especially when a silo or transport line is used for two different types of plastic that do not mix when melted (incompatible plastics). Incompatible plastic dropped in open scrap drums, cigarette butts, ashes, paper cups, and other trash will be shredded in granulators and may end up as contamination. Finally, bits of undispersed colorant or other additive may look like contamination. Static mixers may help here.

- Fine screens—100 mesh or more—can filter out some of the contamination, but they clog quickly and contribute to changing pressure unless there is automatic control to compensate. Continuous screeners can keep pressure constant while using very fine screens. Cross-linked polymers (gels) are particularly difficult because they are elastic and can get through most screen openings.

Applesauce

Causes and solutions for this common extrusion problem are given below.

- Cause: Poor mixing. Solution: Use water cooling in screw to improve mixing. Increase screen mesh to increase back pressure within allowable limits.
- Cause: Extrusion temperature too high or too low. Solution: Gradually adjust temperature.
- Cause: Poor resin quality, poor screw design, wrong L/D, bad heaters. Solution: Check resin homogeneity and correct accordingly.

FILM EXTRUSION PROBLEMS

Common film extrusion problems are:

- Blocking.
- Chatter in film or bubble.
- Clarity of the film is poor.
- Die lines or bubble tears in the film.
- Droop on the film edges.
- Gauge variations.
- Gel and fisheyes.
- Sag in the film.
- Stretches in the film.
- Splitting of the film.
- Strength of the film is poor.
- Uneven width of film.
- Wrinkles in film.

Blocking

- Cause: Insufficient amount of antiblock additive. Solution: Check amount of ant-blocking additive.
- Cause: Winding tension too high. Solution: Adjust winding tension.
- Cause: Frost line too high, resulting in a higher film temperature at collapse, which may increase take-up nip roll temperature, thus applying more pressure on film from roll expansion. Solution: Check frost line level. Adjust temperature.
- Cause: Inadequate cooling or too high ambient temperature causing inner surfaces to block as they pass through nips. Solution: Reduce output, raise main nip rolls, or use refrigerated air or other means of cooling. Check and control environmental temperatures which may cause this condition.
- Cause: Overtreatment. Solution: Avoid overtreatment.
- Cause: Excessive static electricity in film web. Solution: Check and control static electricity.

Chatter in Film or Bubble

- Cause: Air ring velocity excessive. Solution: Decrease air rate.
- Cause: Friction in the collapsing frame. Solution: Modify the surface to decrease friction or decrease melt temperature.
Clarity of the Film is Poor
- Cause: Poor resin quality or wrong resin grade. Solution: Check resin.
- Cause: Extrusion temperature too high or too low. Solution: Gradually adjust extrusion temperature.
- Cause: Inadequate film cooling. Solution: Check cooling system.
- Cause: Low blowup ratio. Solution: Check and adjust blowup ratio.
- Cause: Poor mixing due to low shear extruder and die. Solution: Check extruder and die.

Die Lines or Bubble Tears in the Film
- Cause: Oxidation of the polymer on die lip (caused by polymer resting on lip for prolonged periods after shutdown). Solution: Stop the screw. With a copper pad, clean die lip to a bright finish. Carefully scrape edges of lip with a piece of brass or copper shim stock. (Do not penetrate into die land more than 0.5 in. (13 mm) Apply a light coat of silicone grease for protection.
- Cause: Insufficient blending of molten polymer as it flows around die, leaving a weld line in its path. Solution: Increase mixing in extruder. Increase adapter and die temperatures and/or increase screen mesh to increase back pressure.

Droop on the Film Edges
- Cause: Normally associated with film edges rolling before the nips due to uneven cooling of edges by uneven collapsing. Solution: Adjust gap on top of collapsing frame. Adjust side collapsing boards.

Gage Variations
- Cause: Die gap uneven. Solution: Check die gap.
- Cause: Nonuniform air velocity in air ring. Solution: Adjust volume of air through air ring.
- Cause: Uneven temperature on die ring. Solution: Adjust temperature.
- Cause: Extruder surge. Solution: Check extruder drive speed for fluctuations in rpm. Check temperature of feed section housing; it may be too hot. Check temperature controllers (TC) for shorts.
- Cause: Improper nip drive speed. Solution: Check nip drive speed controls and SCR board.
- Cause: Loose chain drive. Solution: Adjust chain drive.
- Cause: Bubble not popped by air ring. Solution: Increase air volume or change die lip gap.

Gel and Fisheyes
- Cause: Poor mixing. Solution: Check mixing.
- Cause: Contaminated resin. Solution: Clean resin silos, transfer system, and hopper feeder periodically, especially when resins of different characteristics are extruded consecutively.
- Cause: Flaking from dirty screw or barrel. Solution: Clean screw and barrel.
- Cause: Excessive use of recycled film or off-grade pellets with virgin grade material. Solution: Reduce the ratio of regrind and off-grade pellets to virgin material.
- Cause: Burnt polymer which results from faulty start-up or shutdown. Solution: Check for burnt polymer.
- Cause: Poor resin quality. Solution: Check resin homogeneity.

Sag in the Film
- Cause: Bubble geometry wrong. Solution: Reduce nip height to collapse film at a higher temperature before nips.
- Cause: Bubble cooled unevenly. Solution: Check iris contact. Check side collapsing boards.

Splits in the Film
- Cause: Nips set too tight (especially if old and hardened rubber nip rolls are used). Solution: Check and adjust nips. Check old and hardened nip rolls.
- Cause: Die lines or bad weld lines from die. Solution: Decrease temperature to build-up pressure to reduce die or weld lines. (Note: This will reduce output.)
- Cause: Scratches from splinters in collapsing frame or other sharp objects. Solution: Eliminate source of scratches.
- Cause: Degraded particles of resin or dirt lodged under or in die lips that make film split at weld. Solution: Check and clean the die lips.

Strength of the Film is Poor
- Cause: Not enough blowup ratio. Solution: Increase blowup ratio.
- Cause: Thin spots in film. Solution: Check for gage variations.
- Cause: Extrusion temperature too high or too low. Solution: Gradually adjust temperature.

Uneven Width of Film
- Cause: Tension changes or is too high. Solution: Check tension and try to taper it as roll builds.
- Cause: Air leakage from bubble. Solution: Check for air leakage at air inflating point on die.
- Cause: Bubble pumping or breathing. Solution: Check collapsing frame and ensure it is not too tight. Check for too much velocity in air ring.
- Cause: Web wanders in line ahead of the winding station. Solution: Check web tension.
- Cause: Variable tension in edge trimming or slitting station. Solution: Check tension.

Wrinkles in Film
- Cause: Wide gage variations across web. Solution: Make adjustments to ensure uniform die opening, air velocity around air ring, and die temperature.
- Cause: Insufficient cooling or high frost line. Solution: Use cooler air, if possible, to increase bubble cooling. If this is not possible, lower extrusion temperature.
- Cause: Bubble bounce. Solution: Ensure a smooth bubble collapse to keep bubble from sticking to guide rolls or forming tent. Eliminate air drafts around bubble.
- Cause: Poor alignment of tent and primary nip rolls with center of die. Solution: Align tent and primary nip rolls to provide uniform take-up tension and smooth film track.
• Cause: Excessive tension or unbalanced idlers. Rough surfaces in collapsing area. Solution: Check tension and speeds of downstream rolls. Eliminate rough surfaces.
• Cause: Collapsing and cooling of bubble are uneven, producing wrinkles on edges after nips. Solution: Adjust the gap at top of collapsing frame and side collapsers. Also minimize bubble movement by reducing stalk height.

POLYETHYLENE FILM EXTRUSION
The following are activities to avoid or to follow:

Don’ts
• Don’t permit the resin to become moist or contaminated.
• Don’t remove the hopper cover while the extruder is operating, except for feeding the hopper.
• Don’t increase output at the expense of film quality.
• Don’t stop the screw before all the resin has been moved out of the screw flights visible from the hopper.
• Don’t run the extruder without a screen pack.
• Don’t use copper screen packs.
• Don’t permit the bubble in blown-film making to vibrate.
• Don’t use a tool to guide the bubble into the nip.
• Don’t permit drafts to hit the bubble.
• Don’t touch a charged treater electrode.
• Don’t let rolls get dirty or rusty.
• Don’t neglect to clean screw, barrel, adapter, breaker plate, and die periodically.
• Don’t place hands near revolving nip rolls.
• Don’t neglect repairing damaged electrical insulation immediately.
• Don’t lack electrical insulation.
• Don’t neglect cleaning the die lands if impurities have accumulated.
• Don’t watch the frost line for height and uniformity.
• Don’t maintain uniform air distribution from the air ring in blown-film making.
• Don’t keep the water temperature uniform across the film-casting roll.

Dos
• Measure the film gage periodically.
• Watch that the barrel zone temperatures stay within narrow, predetermined ranges.
• Check the thermocouples regularly for tight seating in the cylinder wall.
• Check regularly for burned-out or loose heaters.
• When cleaning the die, watch for inside surface irregularities.
• Hand-hone and polish the die lands if impurities have accumulated.
• Watch the frost line for height and uniformity.
• Maintain uniform air distribution from the air ring in blown-film making.
• Keep the water temperature uniform across the film-casting roll.
• Keep the take-off equipment well lined up.
• Always keep fuses in stock, also reserve screen packs, breaker plates, thermocouples, band heaters, bolts, etc.
• Constantly watch the film roll for good appearance and absence of wrinkling.
• Check all the extruder controls constantly.
• Keep a record of all important extruder controls in a log book.
• Watch the pressure gages to know when it’s time to clean the breaker plate and change the screens.
• Let periodic extruder checkups and regular maintenance programs become a habit.
• Follow faithfully all manufacturers’ instructions and recommendations regarding lubrication of machinery, etc.
• Be on a constant lookout for resin and water leaks.
• Keep the extrusion shop clean—for the sake of health and film.
• Keep all equipment in a high state of maintenance.
• Use only good resins, free of fines and other contaminants.
• Use the resin most suitable for the desired film type and the film-making process used.

MECHANICAL
• The most important mechanical concern in extrusion is screw and barrel wear. Depending on the polymer, a screw and barrel can last 30 years or 30 minutes. For example, a 4140 steel flame-hardened screw running polyethylene has been known to last for up to 40 years, but the same screw running fluropolymer lasts only 30 minutes because it corrodes. Any plastic that produces an acid requires a nickel-based screw. Special screw materials must be used for special plastics. It is best to read the processing guide of the particular resin you plan to run before making a screw choice.
• Screw wear and barrel wear eventually will happen. When they do, surging or variations in pressure will occur. Also, for the same rpm, the output will be less. It is then time to replace the screw. The original equipment manufacturer or a screw building shop can assist in determining the proper way to remedy the problem.
• Surging can also be caused by slipping drive belts. Belts should be checked for proper tension on a monthly basis. Motor brushes should be checked quarterly.

ELECTRICAL
• The electrical system can be divided into the temperature control and the drive system. Most electrical problems are with the temperature control, heater, or fan. If the temperature control is turning on the heat and the zone remains cold, this means the relay is faulty, the fuse is blown, or the heater is burned out. Usually, there is an ammeter for each heat zone. If the temperature control turns on the heat and no amperage shows on the meter, then there is no power going through the temperature control, heater, or fan. If the temperature control turns on the heat and no amperage shows on the meter, then there is no power going through the heaters. Fans can usually be visually checked for operation.
• The drive system problems typically occur within the drive. In today’s drives, maintenance is as easy as changing printed circuit boards. If the motor does not operate, first check if there is AC voltage going to the drive. Then, check the drive output for voltage. If it is a DC drive, DC voltage should come out and, at full speed, the voltage should be the same as the voltage on the motor nameplate. If this is not the case, the drive must be adjusted or repaired. If the voltage is correct, the problem is with the motor. The motor brushes should be checked. Any motor shop can handle this type of problem.
MAINTENANCE

- Extruder cleaning schedules vary according to the process the extruder is being used in. For example, in medical tubing extrusion, it is best to clean the extruder after each run and not less than once each shift. In recycling cases, the extruder can be cleaned on a monthly or quarterly basis. In any situation where precision is required, the extruder should be cleaned after each run or change of material to prevent cross-run contamination. The screw should be removed and cleaned of all plastic while hot. A brass brush should be used to avoid scratching. The same goes for the barrel. All tooling should be taken apart, cleaned, and coated with antiseize compound, then reassembled.
- Antiseize compounds should be used on all bolts and threaded parts as well as the back of the screw to prevent seizure when the parts are exposed to heat. If these compounds are not used, the bolts will not come out and it will be impossible to take the extruder apart.
- A spare extruder screw should always be kept on the shelf. Screws can break or be damaged, and delivery of a new screw can take up to three months, depending on the manufacturer's workload. A spare screw is a worthwhile investment when the alternative of three months of downtime is considered. Extruder manufacturers often change screw designs because gearboxes change, engineers come and go, new managers use different suppliers, etc. All of these changes mean that it is impossible for an extruder manufacturer to keep every type of screw for every type of polymer on the shelf. Always have a spare screw on hand. It can be considered low-cost insurance.

SAFETY

Safety includes proper management of:
- Heat.
- Electricity.
- Moving parts.
- Weight.
- Inside the extruder.
- Outside the extruder.
- Pressure.
- Procedures.

The following discussion of safety is strictly meant to heighten the operator's awareness of potential hazards. Proper and complete evaluation of the workplace will help determine appropriate safe practices.

HEAT

The head and die are hot and seldom insulated, so wear gloves while working with them. Antiburn materials should be available at all times. A pail of water is useful for burnt hands, but chain it down so no one throws it on electrical fires. Do not touch plastic or metal parts until they are cool enough to touch. Plastic that has just hardened is especially treacherous, as it may look like the cold product, but can burn just like the melt.

ELECTRICITY

Keep all wiring protected and repair where needed, including thermocouple leads. Avoid plastic leaks that could push wires together. Guard all heater contacts, ground everything, and check the integrity of the grounds from time to time. Fix all water leaks and mop up water spills immediately. Be very careful with high-voltage devices like film treaters and insulation spark testers. If film is being rolled up, watch out for built-up static.

MOVING PARTS

All roll nips should be shielded and guarded. Check often to see if the safety cords work. Never wear ties, loose clothes, hanging hair, or jewelry near moving parts. Guard all shears and be careful in changing or adjusting slitter blades. Be careful around fast-moving wire, which may be almost invisible. When taking apart a screen changer or anything else hydraulically driven, first relieve any oil pressure in the changing system.

WEIGHT

Many objects around an extruder are very heavy. Lift them with care and use hoists when necessary. Wear steel-tipped shoes. Keep hands high when rolling a drum and never stack things too high.

INSIDE THE EXTRUDER

Know the pressure and safety limits of the machine; know what pressure may be expected and watch out for excess. Avoid plastic leaks in the head area. Never look into a vent when the system is hot without face protection and never stand in front of a hot extruder, even if the screw is not moving, because gases may form in the barrel and suddenly blow melt out the vent or the die. Have a plastic, wood, or brass rod on hand to poke into hoppers and vents; never use your hands.

OUTSIDE THE EXTRUDER

Keep the workplace clean. Clean the floor often, avoid clutter, and hang nothing heavy overhead. Keep ladders and catwalks clean and sturdy with high-friction surfaces. Wear shoes that don’t slip even when oily, as there may be oil leaks on the floor. Avoid air hoses, as they can force air into skin breaks and blow dust particles into eyes. Use eye protection, and in some environments, ear protection and even nose-mouth air filter masks. Know where the nearest fire extinguisher is and check it periodically. Sheet-metal guards should be kept around the barrel to prevent injury from burns and electrical shock. All nip points should be guarded to prevent injuries.

PRESSURE

The hot plastic in the barrel end and the die exists in a highly dangerous mix of high pressure and high temperature that can cause serious injury or death. Dies can blow off the end of an extruder and shoot across the room like a bullet and go through walls and people. A safety rupture disk should be put in all barrel output ends. It is a small device with a standard 1/2 in.-20 thread that screws into a port at the end of the barrel. It is typically rated at 6500 psi (44,815 kPa). When pressure exceeds 6500 psi, the rupture disk will blow and the pressure will be released. This helps prevent die blowoffs and injuries. No one should ever stand close to the output end of the extruder while it is operating, except when necessary. Pressures should be kept as low as possible.
Hot dies and barrels can cause serious burns. It is best to rope off the area near hot dies to prevent injuries, especially to personnel who may be unaware of the dangers of extrusion machinery.

**PROCEDURES**

Safety glasses must be worn at all times by all personnel. Heat-resistant gloves should be worn while handling hot dies. Ties should not be worn, especially around nip rollers in take-off systems for blown film, sheet, and cast film, as well as pullers used in tubing, profile, wire, cable, and rod production. If a tie gets caught in a roller, it will draw the body into the rolls and cause injury. Long hair should be tied back. Loose clothing such as open shirts and unbuttoned shirt sleeves are also dangerous for the same reasons. Hands should be kept out of all nip points. Steel-toed safety shoes should be worn to prevent injuries from falling dies and tooling. Screw tips have been known to fall and penetrate the top of the foot. Extrusion often involves water and always involves electricity. Water can spill on the floor and people can be subject to electrical shocks. All water spills should be dried up immediately for this reason.

Each piece of equipment should have a red emergency-stop mushroom-type push button that will shut down the equipment in case of emergency. If such a button does not exist, it should be put in.

**NEW DEVELOPMENTS**

Most new developments in extrusion will probably be small improvements in existing technology rather than major innovations that involve a technological leap. These improvements occur constantly in all phases of the extruder business, including materials, controls, and mechanical and electrical components. For example, new screw materials are being developed for high-temperature corrosive materials, and new materials are also being used for small screws under 0.75 in. (19 mm) to prevent twisting and breakage. New control technologies allow for very close control of extrudates, and new mechanical transmission products and drives are allowing less electricity usage for the same amount of horsepower. This adds to productivity and efficiency.

**References**


**Bibliography**

In 1868, John Wesley Hyatt entered a contest. A billiard ball manufacturer was offering a $10,000 prize for a replacement material for pure ivory, which was becoming expensive and hard to obtain. Through a literature search, Mr. Hyatt found that a material called cellulose had been invented by Alexander Parkes, but no one had found a way of processing it effectively. As a result, John and his brother, Isaiah, refined the cellulose formula and designed a machine that could inject it into a mold shaped to produce a billiard ball. The Hyatt brothers won the grand prize and opened the door to a new industry. Injection molding became a viable process for producing additional items such as hair combs and shirt buttons.

**EVOLUTION OF THE INDUSTRY**

During the 1940s, the injection molding industry exploded as World War II created a demand for inexpensive, mass-produced products. New materials were invented for the process on a regular basis, and technical advances resulted in more successful applications.

The machine that the Hyatt brothers invented was primitive but did the job. It was simple; it acted like a large hypodermic needle and contained a basic plunger to inject the plastic through a heated cylinder into a mold. In 1946, James Hendry began marketing his recently patented screw injection machine. This auger design replaced the conventional plunger device and revolutionized plastics processing. Screw machines now account for approximately 95% of all injection machines.

**Evaluation of Screw Versus Plunger**

The auger design of the screw creates a mixing action when preparing new material for injection. The screw is inside the heating cylinder and, when activated, mixes the plastic, creating a homogenized material blend. This is especially useful when colors are molded or when regrind is mixed with virgin material. After mixing, the screw stops turning, and the entire screw pushes forward, acting like a plunger in injecting the material into a mold.

Another advantage of using the screw technology is a reduction in energy requirements. The injection cylinder, which holds the plastic for the next cycle, has a series of surrounding electrical heater bands. These bands heat the cylinder to soften the plastic. Because the screw generates friction when it turns within the cylinder, heat is generated. Thus, less heat is required from the electrical heater bands to soften the plastic.

Although the screw machine is the most popular, plunger-type machines are still used. A plunger does not rotate; it simply pushes material ahead and retracts for the next cycle. It also resides within a heated cylinder. Because there is no rotating, there is no mixing action. Therefore, if two colored materials are placed together in the heated cylinder, they are not blended. The plunger simply injects the materials concurrently. If the two colors are, for instance, white and black, the resultant molded part takes on a marbled appearance, with swirls of black and white throughout the part. This may be a desired finish for a product, such as lamp bases or furniture, and the use of a plunger machine allows molding the finish into the product. In a similar situation, the use of a screw machine would result in a single color (gray) molded product, because the two colors would be well mixed prior to injecting. In a plunger machine, the necessary heating action is provided solely by the external heater bands.

From its birth in the late 1800s to recent developments and applications, the injection molding industry has grown quickly. It has evolved from producing combs and buttons to molding products for automotive, medical, aerospace, and consumer goods as well as toys, plumbing, and packaging.

**Comparison to Other Processes**

Injection molding offers many advantages when compared to other methods of processing thermoplastic materials, but each process has its place in the variety of modern production requirements. Some of the benefits of each process are as follows.

Casting. This process consists of pouring softened plastic into an open mold, with zero pressure applied, and allowing the plastic to cool at room temperature. Molds are often made from low-quality steel, aluminum, epoxy, wood, or plaster. The process incorporates low tooling costs and minor (if any) equipment costs but usually requires secondary finishing, is time consuming, and is best suited for low volumes (less than 25 units).

Thermoforming. Thermoforming consists of heating a plastic sheet until it becomes soft enough
to drape. The sheet is then formed over a wooden, plaster, latex, silicone, aluminum, soft steel, or epoxy mold. The mold has small holes drilled throughout, and a vacuum is applied to these holes. This action draws the softened sheet tightly against the mold, causing it to take the shape of the mold. In some cases, the vacuum is replaced with a blower; this is referred to as pressure forming. The process incorporates low tooling costs and minimal equipment costs, and is most efficient for quantities of approximately 25 pieces from a single mold.

Blow molding. This process, a combination of injection molding and thermoforming, is most efficient and economical for hollow objects such as bottles, trash cans, and balls. The softened plastic is allowed to drop between two mold halves, which close on the plastic. A blast of gas (usually nitrogen) is blown into the closed mold, forcing the plastic against the mold walls. The mold is made of aluminum or soft steel, and the process takes longer to complete than injection molding. In addition, there is usually at least one secondary (trimming) operation required. This process is not capable of producing tight tolerances, but the tooling is inexpensive despite the high equipment costs. Blow molding can be performed for low and high quantities. For further comparisons of these processes, see Chapter 3 of this handbook.

THE MOLDING MACHINE

Injection molding is the most popular process for manufacturing thermoplastic products. The process consists of injecting molten plastic material from a reservoir (heated cylinder) into a closed mold, allowing the plastic to cool and solidify, and ejecting the finished product from the mold. The machine consists of an injection unit, which introduces the material, and a clamping unit, which holds the mold closed during the injection phase. This process is shown in Figs. 6-1 and 6-2.

The basic components of the machine are the injection unit and the clamp unit. Each serves a primary purpose and complements the other, although a machine may be purchased and built with virtually any combination of injection and clamp unit; each is

![Fig. 6-1 Plastic injection unit set-up. (Courtesy Texas Plastic Technologies)](image1)

![Fig. 6-2 Finished product ejected from the mold. (Courtesy Texas Plastic Technologies)](image2)
There are several basic guidelines regarding which injection/clamp combination is correct for specific applications.

**Sizing the Injection Unit**

The injection unit is normally sized so that it contains two cycles of material. In other words, 50% of the injection cylinder’s capacity is emptied during each cycle. This is referred to as the amount of “shot” a machine takes for each cycle. The 50% rule is ideal, but the shot size should never be less than 20% nor greater than 80% of the injection unit’s capacity.

A material’s heat sensitivity is critical, because it determines the amount of time that the material can reside within the heated injection cylinder before it begins to degrade. The 50% guideline noted earlier ensures that no material, regardless of its residence time, will degrade during molding. The 20% rule applies to materials with low-heat sensitivity, and the 80% guideline applies to materials that are extremely heat sensitive.

Note that machine injection units are rated in terms of their polystyrene capacity. A conversion is therefore required, using specific gravity values, to determine capacities of other plastics.

**Purpose of the Injection Unit**

The injection unit performs multiple duties and contains many components that contribute to the performance of these duties. Figure 6-3 shows several components.

- **Barrel.** The heart of the injection unit is the heated cylinder called the barrel. This unit, manufactured as a long, round tube, is made of an inexpensive steel grade. The tube is lined with a thin sleeve of high-quality, hard tool steel that can withstand the abrasive nature of the injection process. This sleeve normally has a high chromium content.

- **Heater bands.** These bands, electrically operated, are placed along the length of the barrel with gaps between them. Note that there are three heater zones, as shown in Fig. 6-3: rear, center, and front. Each zone contains three or more heater bands (depending on the size of the injection cylinder), and each zone is controlled by an electrical unit located in the control panel of the machine.

  Each temperature control unit is fed information by a thermocouple. The thermocouple is placed in the wall of the heating barrel in the zone it is controlling. There, it acts like a thermometer to sense the temperature of the zone, and it sends that information back to the control unit. This unit then decides whether more heat is required and, if so, energizes the heater bands in that zone. When the selected temperature is reached, the thermocouple informs the control unit, and this unit de-energizes the heater bands until the temperature drops again.

- **Control unit.** Minimum and maximum temperature limits are set on the control unit. These limits are the numbers used by the control unit to determine when the heater bands are energized. Note that a single control unit and thermocouple are assigned to a single heating zone, but there are three or more heaters in each zone, so each control unit controls three or more heaters concurrently. Because all of the heaters in a zone are wired together, the control unit’s actions affect all of the heaters in that zone.

- **Hopper.** A hopper is shown in the upper right section of Fig. 6-3. The hopper is where raw plastic pellets are stored before they are introduced to the heating cylinder. This unit has tapered sides to facilitate dropping fresh material (via gravity) into the barrel. The hopper holds approximately two hours’ worth of raw material for a given machine. This is based on normal cycles and average part weights typically produced on that machine.

  A magnet is placed at the base of the hopper. This may be an external drawer magnet, which is removed and cleaned while the machine is running, or a loose magnet, which is placed inside the hopper. The latter is cleaned by removal from the hopper while the machine is inoperable. While the latter is less expensive, the for-
TRADITIONAL INJECTION MOLDING

The Screw

The screw is an auger-shaped rod that is placed inside the heating barrel. The primary function of the screw is to move fresh material from the hopper area into the heating area of the barrel. A secondary function of the screw is to start the heating action that is required to raise the plastic to the proper operating temperature. This is accomplished due to the friction created by the screw flights. The friction is created by a slight clearance between the surface of the screw flights and the inside of the barrel wall; the clearance is usually only 0.003–0.005 in. (0.08–0.13 mm).

The material is brought forward in the screw auger along the screw flights, and the plastic is continually squeezed tighter. The friction that is created causes the heat that prepares the plastic. The external heater bands supply the majority of the heat that softens the plastic. The screw, however, does provide an additional source of heating, and this reduces the electricity required to completely heat the plastic. The squeezing action caused by the screw is called shear. Too much shear can destroy the plastic molecules and degrade the material, making it inferior or even useless. That is why the screw itself cannot be used to impart all the heat required.

There are many different screw designs. Changes are made to the flight shapes, the distance between flights, the amount of shearing action, the design of the screw tip, and shutoff method.

Metering screw. Figure 6-4 shows a typical metering screw design for an injection molding machine. Note that the rear section (the feed zone) has a smaller diameter than the front end (the meter zone); the middle area (the melt zone) is a transition area between the meter and feed zones. Therefore, there is a smaller gap through which the plastic must flow. This results in a shearing action, which fosters the frictional heat mentioned earlier.

Figure 6-5 shows how a typical screw tip mounts on the face of the injection screw. The tip itself is inserted through a check ring and seat (or similar nonreturn device) and is threaded into the face of the screw, usually with a left-hand thread to counteract the natural turning motion of the screw. The screw tip angle and length are determined by the viscosity of the molded plastic. In some cases, a general purpose screw and tip can be used for a variety of similar materials, but it is better to use a specific design for a specific group of materials.

Nonreturn valve. The standard injection machine uses a reciprocating screw. In this design, the screw is pushed forward and pulled backward (reciprocated), acting as a plunger to inject the molten plastic.

The purpose of the nonreturn valve mechanism, shown in Fig. 6-5, is to keep molten plastic from escaping, or drooling, through the front of the heating barrel when the screw returns to prepare for the next cycle. The valve action is as follows:

1. The screw pushes forward, injecting a charge of molten material into the mold.
2. The check ring is forced against the screw tip and seals against it.
3. Molten plastic flows through channels that are machined into the check ring.
4. The screw stops pushing and begins to turn (bringing new material forward).
5. The check ring slips backward due to the pressure buildup.
6. The check ring seals against the seat and keeps material from moving through.

Ball type. There are many different nonreturn mechanisms. The check ring style is the most common, but the ball-type device shown in Fig. 6-6 is also popular.

In this design, the shutoff ball travels back and forth between the stop pin and the flow hole. When the plastic is augered forward (plasticized), the ball moves forward and allows plastic to flow from the hole, along the inside of the screw tip, and into the machine nozzle (not shown). During injection, the shutoff ball moves backward against an angled seat in front of the flow hole and forms a seal, which keeps plastic from flowing back over the screw.

In both cases, the plastic material is restricted, even when the nonreturn devices are in the open, flow position. With high-viscosity or heat-sensitive materials, this restriction may cause degradation of the plastic. Therefore, nonreturn mechanisms are generally not used when molding these materials.

Nozzle. A final item completes the injection unit. The nozzle of the machine is a two-piece, tube-shaped component that bolts to the face of the injection barrel, as shown in Fig. 6-7. The nozzle cap has an internal taper that matches that of the screw tip. There is also a tapered hole through the nozzle tip itself. The radius on the face of the nozzle tip fits against a matching radius in the sprue bushing of the injection mold. A heater band is also shown on the nozzle tip. Called the nozzle heater, it is controlled much like the other heater bands on the injection barrel.

![Fig. 6-4 Injection screw, showing the meter, melt, and feed zones. (Courtesy Texas Plastic Technologies)](image-url)
There are some nozzle designs that incorporate shutoff devices such as needles, springs, sliding balls, or combinations of these. Their purpose is much the same as the nonreturn valve in the screw tip: they stop the flow of plastic for those materials that have lower viscosity (such as nylon), which can drool from standard nozzles.

**Shear Rate**

Shear rate is defined as the surface velocity of the plastic at the heating barrel wall divided by the depth of the screw flight channel; the value is typically listed in ft/min (m/min). One shear rate formula is as follows:

\[
SR = \frac{DN}{h}
\]

where:

- \(SR\) = shear rate
- \(D\) = screw diameter
- \(N\) = rate of screw rotation
- \(h\) = depth of channel

---

Fig. 6-5 Screw tip mounted on the face of the injection screw. (Courtesy Texas Plastic Technologies)

Fig. 6-6 Ball-type nonreturn mechanism. (Courtesy Texas Plastic Technologies)
An average shear rate is approximately 150 ft/min (46 m/min), but each plastic has a shear rate beyond which it will degrade. Heat-sensitive plastics, such as polyvinylchloride (PVC) have a lower shear rate (approximately 100 ft/min [30 m/min]), while nonsensitive materials may have a shear rate of 175 ft/min (53 m/min) or higher. Shear rate values have a direct effect on the screw rotational speed.

**Screw Output**

The amount of material that an injection machine can process is rated in lb/h (kg/h). It is determined by the horsepower the machine has available to turn the screw. A 2-ft-diameter (0.6 m diameter) screw can normally withstand a maximum of 15 hp. A 4.5 ft. diameter (1.4 m diameter) screw, however, can handle up to 150 hp. For output, molding materials range from 5–15 lb/h (2.3–6.8 kg/h) for each horsepower applied. Therefore, a 15 hp system (2 ft. diameter [0.6 m diameter] screw) is capable of producing from 75–225 lb/h (34–102 kg/h) output of plastic, depending on the viscosity (which affects the shear rate).

**Injection Pressure**

The average screw injection machine is capable of producing 20,000 psi (138 MPa) injection pressure in the heating barrel. This full pressure is available at the nozzle of the machine just before the material enters the mold. In most cases, the highest injection pressure in combination with the fastest injection speed minimize molded-in stresses and minimize the overall cycle time. While 20,000 psi (138 MPa) may be available, it is prudent to use only the highest pressure required for a specific material and application. Normal practice is to begin molding at 7,000–8,000 psi (48–55 MPa). Lower numbers are used for high-flow materials, and the material vendors supply this information on their material data sheets. These index numbers may range from 5 to 20. The lower numbers signify that the material flows with difficulty and is classified as low flow. Higher numbers signify a material that flows easily.

It is less important to remember a specific flow number than it is to know whether the material is considered high, average, or low flow. Then, understanding that it requires more injection pressure to inject a low-flow material, the clamp force is determined.

A comparison of two materials shows the difference. A product molded of polycarbonate (a low-flow plastic) may require an injection pressure of 15,000 psi (103 MPa), while that same product molded of polypropylene (a high-flow plastic) may need only 5,000 psi (35 MPa). Therefore, the polycarbonate product requires a mold clamp force that is approximately three times that required for the polypropylene product.

The method used to determine the required clamp force is to consider the projected area of the molded part and multiply that number by a factor of 2–8 tons/in.² (28–110 MPa). The projected area of this part is found by multiplying the L dimension by the W dimension (see Fig. 6-8). The D dimension, only important if greater than 1 in. (2.5 cm), is explained later. For the product shown in Fig. 6-9, the projected area is 6 × 6 = 36 in.² (15 × 15 = 225 cm²).

Clamp force requirements are now calculated by multiplying the 36 in.² (225 cm²) value by a factor of 2–8 tons/in.² (28–110 MPa). Lower numbers are used for high-flow materials, and the higher numbers are appropriate for low-flow (stiff) materials.

For this example, polycarbonate was selected as the molding material. Polycarbonate is fairly stiff and a lower-flow material, so the clamp factor used must be toward the high side. Experience has shown that a clamp factor of 5 tons/in.² (69 MPa) is adequate for polycarbonate. As a result, the 36 in.² (225 cm²) projected area is multiplied by the clamp factor of 5 tons/in.² (69 MPa), resulting in a total clamp tonnage requirement of 180 tons (1.6 MN). With a 10% safety factor added, the final clamp force needed is 198 tons (1.8 MN). The machine with the closest rating for this product is a 200-ton (1.8-MN) machine.
D dimension. The D dimension only becomes important if the plastic part is more than 1 in. (2.5 cm) deep. This is not the wall thickness but the total depth of the part. For every inch (2.5 cm) of depth, the total clamp force is increased by 10%. So, if the part shown in Fig. 6-9 were 2 in. (5 cm) deep, the required clamp force would increase by 18 tons (161 kN) (10%) to a total of 198 tons (1.8 MN). Adding a 10% safety factor to this value increases the required mold clamp force to 218 tons (2.0 MN).

Consequences of incorrect clamp force. If too little clamp force is used, the mold will not stay closed when the plastic material is injected into it. The result is flash on the parts or nonfilled parts. Flash is material that squeezes out of a closed mold. Although flash is sometimes planned, it is normally undesirable, because control of injection pressure becomes difficult. Flash removal is also required prior to shipping the finished product.

Nonfilled parts can be caused when the mold opens slightly under insufficient clamp force. This keeps the prescribed amount of plastic from flowing into the cavity.

Excessive clamp force can damage the injection mold. This damage usually takes the form of collapsing or crushing the mold material. Crush damage is difficult and expensive to repair, and in some cases it cannot be repaired.

Another factor to consider is damage to the molding machine itself. Figure 6-10 depicts a mold mounted in a molding machine. Each mold half is mounted to a press platen; one platen, retaining mold half A, is normally stationary, while the other, fixturing mold half B, moves to open and close the mold. The moving platen is connected directly to the clamp mechanism.

MOLDING PROCESS PARAMETERS
Identifying the Parameters
Many parameters affect the injection molding process. A practical approach to understanding these parameters is appropriate, and those parameters that have the greatest effect on the quality and cost effectiveness of the molded product are targeted.
Figure 6-11 shows that the parameters involve one or more of four basic categories: temperature, pressure, time, and distance. A category’s importance priority is shown by the relative size of its circle.

**Temperature**

Melt temperature control. Melt temperature is that temperature at which the plastic material is maintained throughout the flow path. This path begins when the material is transferred from the machine hopper into the heating cylinder of the injection unit. It is then augered through the heating cylinder and into the machine nozzle. From there, the material is injected into the mold, where it travels along a runner system (if one exists), through gates, and into the cavity. Control of the melt temperature is essential all along that path. It begins with the heating cylinder.

Figure 6-12 shows a heating cylinder wrapped with heater bands. These are electrical heaters that are shaped like hinged bracelets and mounted around the outside of the heating cylinder. There are three main heating cylinder heating zones: the rear, the center, and the front. In addition, there is at least one heater band fastened around the machine nozzle; that area is referred to as the nozzle zone.

When heating plastic for the injection process, the material is gradually raised to the proper temperature. The material drops from the hopper into the heater’s rear zone, where the heat begins to soften the material. It is then augured forward by the screw, which takes it into the center zone, where the temperature is generally 10–20˚ F (5.5–11˚ C) higher than in the rear zone. As the material travels to the front zone, the temperature is again increased by 10–20˚ F (5.5–11˚ C), and the material is ready for injection into the mold. It is held at this point until the previous molding cycle is complete. The mold then opens, parts are ejected, the mold closes, and the next cycle begins. At this point, the preheated plastic charge is injected into the mold.

In addition to absorbing heat from the externally mounted heater bands, the plastic material gains considerable heat from the friction caused by the augering action of the injection screw. The screw rotates, bringing fresh material into the heating cylinder and preparing it for the upcoming cycle.

Table 6-1 shows the melt temperature of common plastics.

The temperature is measured at the nozzle as the plastic exits the machine. It is measured by taking an "air shot" and plunging a probe from a measuring instrument with a fast response time (1 sec is acceptable) into the plastic melt. An air shot is made with the injection sled pulled back so that the injection unit does not touch
TABLE 6-1
Suggested Melt Temperatures for Various Plastics

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature, °F (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetal (copolymer)</td>
<td>400 (204)</td>
</tr>
<tr>
<td>Acetal (homopolymer)</td>
<td>425 (218)</td>
</tr>
<tr>
<td>Acrylic</td>
<td>425 (218)</td>
</tr>
<tr>
<td>Acrylic (modified)</td>
<td>500 (260)</td>
</tr>
<tr>
<td>ABS (medium impact)</td>
<td>400 (204)</td>
</tr>
<tr>
<td>ABS (high-impact and/or flame retardant)</td>
<td>420 (216)</td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>385 (196)</td>
</tr>
<tr>
<td>Cellulose acetate butyrate</td>
<td>350 (177)</td>
</tr>
<tr>
<td>Cellulose acetate propionate</td>
<td>350 (177)</td>
</tr>
<tr>
<td>Ethylene vinyl acetate</td>
<td>350 (177)</td>
</tr>
<tr>
<td>Liquid crystal polymer</td>
<td>500 (260)</td>
</tr>
<tr>
<td>Nylon (Type 6)</td>
<td>500 (260)</td>
</tr>
<tr>
<td>Nylon (Type 6/6)</td>
<td>525 (274)</td>
</tr>
<tr>
<td>Polylolomer</td>
<td>485 (252)</td>
</tr>
<tr>
<td>Polymide-imide6</td>
<td>50 (343)</td>
</tr>
<tr>
<td>Polylarlyte</td>
<td>700 (371)</td>
</tr>
<tr>
<td>Polylbutylene</td>
<td>475 (246)</td>
</tr>
<tr>
<td>Polecarbonate</td>
<td>550 (288)</td>
</tr>
<tr>
<td>Polyetheretherketone (PEEK)</td>
<td>720 (382)</td>
</tr>
<tr>
<td>Polyetherimide</td>
<td>700 (371)</td>
</tr>
<tr>
<td>Polyethylene (low-density)</td>
<td>325 (163)</td>
</tr>
<tr>
<td>Polyethylene (high-density)</td>
<td>400 (204)</td>
</tr>
<tr>
<td>Polymethylpentene</td>
<td>275 (135)</td>
</tr>
<tr>
<td>Polyethylen oxide</td>
<td>385 (196)</td>
</tr>
<tr>
<td>Polyethylene sulfide</td>
<td>75 (302)</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>350 (177)</td>
</tr>
<tr>
<td>Polystyrene (general purpose)</td>
<td>350 (177)</td>
</tr>
<tr>
<td>Polystyrene (medium-impact)</td>
<td>380 (193)</td>
</tr>
<tr>
<td>Polystyrene (high-impact)</td>
<td>390 (199)</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>700 (371)</td>
</tr>
<tr>
<td>PVC (rigid)</td>
<td>350 (177)</td>
</tr>
<tr>
<td>PVC (flexible)</td>
<td>325 (163)</td>
</tr>
<tr>
<td>Styrene acrylonitrile (SAN)</td>
<td>225 (107)</td>
</tr>
<tr>
<td>Styrene butadiene</td>
<td>360 (182)</td>
</tr>
<tr>
<td>Tetrafluoroethylene</td>
<td>600 (316)</td>
</tr>
<tr>
<td>Polybutylene terephthalate (PBT)</td>
<td>425 (218)</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td>450 (232)</td>
</tr>
<tr>
<td>Urethane elastomer</td>
<td>425 (218)</td>
</tr>
</tbody>
</table>

This requirement demands that the mold contain some method of temperature regulation which, in turn, regulates the plastic cooling rate. To achieve this, the mold is connected to a temperature control unit, and flowing water is used as the medium for temperature control. Every combination of plastic and product has a specific temperature at which the mold is maintained to ensure quality molding, but Table 6-2 shows starting points for common plastics.

The object of the cooling process is to reduce the temperature of the plastic to the point at which it solidifies. At this point, the molded part is ejected from the mold with relative safety.

Postmold shrinkage control. Although molded thermoplastic products appear stable, they continue to cool and shrink for up to 30 days after molding. Most (90%) of the shrinkage occurs during the time the plastic is cooling in the mold. The remaining shrinkage takes place over the next 30 days, but most of it occurs within the first few hours after ejection from the mold. Thus, it is important to inspect molded parts after they have stabilized. Initial inspection can be performed as soon as the part cools to the touch.

TABLE 6-2
Suggested Sustaining Mold Temperatures for Various Plastics After Plastic is Melted

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature, °F (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetal (copolymer)</td>
<td>200 (93)</td>
</tr>
<tr>
<td>Acetal (homopolymer)</td>
<td>210 (99)</td>
</tr>
<tr>
<td>Acrylic</td>
<td>180 (82)</td>
</tr>
<tr>
<td>Acrylic (modified)</td>
<td>200 (93)</td>
</tr>
<tr>
<td>ABS (medium-impact)</td>
<td>180 (82)</td>
</tr>
<tr>
<td>ABS (high-impact and/or flame retardant)</td>
<td>185 (85)</td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>150 (66)</td>
</tr>
<tr>
<td>Cellulose acetate butyrate</td>
<td>120 (49)</td>
</tr>
<tr>
<td>Cellulose acetate propionate</td>
<td>120 (49)</td>
</tr>
<tr>
<td>Ethylene vinyl acetate</td>
<td>120 (49)</td>
</tr>
<tr>
<td>Liquid crystal polymer</td>
<td>250 (121)</td>
</tr>
<tr>
<td>Nylon (Type 6)</td>
<td>200 (93)</td>
</tr>
<tr>
<td>Nylon (Type 6/6)</td>
<td>175 (79)</td>
</tr>
<tr>
<td>Polylolomer</td>
<td>200 (93)</td>
</tr>
<tr>
<td>Polylarlyte</td>
<td>275 (135)</td>
</tr>
<tr>
<td>Polybutylene</td>
<td>200 (93)</td>
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<tr>
<td>Polecarbonate</td>
<td>220 (104)</td>
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<tr>
<td>Polyetheretherketone (PEEK)</td>
<td>380 (193)</td>
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<tr>
<td>Polyetherimide</td>
<td>225 (107)</td>
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<tr>
<td>Polyethylene (low-density)</td>
<td>80 (27)</td>
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<tr>
<td>Polyethylene (high-density)</td>
<td>110 (43)</td>
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<tr>
<td>Polymethylpentene</td>
<td>100 (38)</td>
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<tr>
<td>Polyphenylene oxide</td>
<td>140 (60)</td>
</tr>
<tr>
<td>Polyethylene sulfide</td>
<td>250 (121)</td>
</tr>
<tr>
<td>Polypolypropylene</td>
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</tr>
<tr>
<td>Polystyrene (general purpose)</td>
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<td>Polystyrene (medium-impact)</td>
<td>160 (71)</td>
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<tr>
<td>Polystyrene (high-impact)</td>
<td>180 (82)</td>
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<tr>
<td>Polysulfone</td>
<td>250 (121)</td>
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<tr>
<td>PVC (rigid)</td>
<td>140 (60)</td>
</tr>
<tr>
<td>PVC (flexible)</td>
<td>80 (27)</td>
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<tr>
<td>Styrene acrylonitrile (SAN)</td>
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</tr>
<tr>
<td>Styrene butadiene</td>
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<tr>
<td>Tetrafluoroethylene</td>
<td>180 (82)</td>
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<tr>
<td>Thermoplastic polyester (PBT)</td>
<td>180 (82)</td>
</tr>
<tr>
<td>Thermoplastic polyester (PET)</td>
<td>210 (99)</td>
</tr>
<tr>
<td>Urethane elastomer</td>
<td>120 (49)</td>
</tr>
</tbody>
</table>

Mold temperature control. The plastic material is then injected as in a normal cycle, but it is injected into air rather than the mold. The material falls onto a tray and is then quickly measured. A measured temperature within 10˚ F (5.5˚ C) of the desired temperature is acceptable.

Insulation blanket. An insulation blanket is used to better regulate and control the temperature of the injection barrel (cylinder). This nonflammable jacket fits around the outside of the heating cylinder, directly over the heater bands, and keeps heat from escaping to the atmosphere. Use of these blankets can reduce plastic-heating energy costs by 50% or more.

Mold temperature control. The plastic material is now ready to flow through the mold. It first travels through the machine nozzle, which is actually the last heating zone provided by the machine. As the material exits the nozzle and enters the mold, it immediately begins to cool. The mold material absorbs heat from the flowing plastic; the rate at which this heat is absorbed determines how far the plastic flows before it begins to solidify. Each product design and plastic material demands a specific cooling rate, and this rate is critical to producing quality products.
CHAPTER 6

TRADITIONAL INJECTION MOLDING

after ejection. More accurate inspection, however, is only performed after the part has cooled for two to three hours.

Hydraulic system temperature control. In addition to melt temperature and mold temperature, heat is generated by the hydraulic system of the press. The temperature of the hydraulic oil used in these systems is typically maintained at 80–140˚ F (27–60˚ C). If the oil is too cool, it becomes thick (viscous) and causes sluggish action of the hydraulic components. Excessively hot oil breaks down, causing sticking components or inoperable valves. Oil temperature is regulated by a heat exchanger mounted on the injection machine. This unit acts like a radiator and cools the oil by recirculating-water-filled tubes.

Ambient temperature control. Ambient temperature is also a concern. A particular job may be running well until a nearby loading dock door is opened, for example. This causes a temperature change of the air surrounding the machine, resulting in fluctuations in the various temperature control units. The injection process then becomes unstable.

Pressure

Two areas of the injection machine require pressure and pressure control: the injection unit and the clamp unit. The two are closely related in that the clamp unit must develop enough pressure to overcome the pressure developed by the injection unit during the molding process. Three types of pressure are developed by the injection unit: initial pressure, hold pressure, and back pressure.

Initial pressure. This is the first pressure that is applied to the molten plastic. It develops as a result of the main system hydraulic pressure pushing against the rear of the injection screw (or plunger). The main system develops a pressure of approximately 2000 psi (14 MPa). This is converted to a maximum of 20,000 psi (138 MPa) at the injection unit’s nozzle by way of the design and shape of the injection screw. Most products can be molded in the range of 5,000–15,000 psi (35–103 MPa). The pressure used depends on the type, viscosity, flow rate, and temperature of the plastic as well as the mold.

The ideal situation is to fill the mold initially with the highest practical pressure in the fastest practical time. Normally, the initial fill is accomplished in less than three seconds. Although higher molding pressures facilitate filling, excessively high values induce voids in the molded product. If less than 50 psi (345 kPa) back pressure is used, faulty readings and settings can occur. If more than 500 psi (3447 kPa) is applied, the screw may not return or may stay forward too long, and the plastic material degrades. In the case of reinforced plastics (such as glass-filled materials), the reinforcement material breaks down, resulting in poorer molded product strength.

Clamp Unit

Clamp pressure. The purpose of developing clamp pressure is to keep the mold closed against the forces developed from material injection. Therefore, the clamp force must at least equal the injection force.

Clamp pressure is applied to the mold either hydraulically or mechanically. There are advantages and disadvantages associated with each method.

Hydraulic clamp system. In this method, the clamping force is developed with a hydraulic cylinder. A piston from the cylinder is attached to the moving platen, on which the mold is mounted (see Fig. 6-13).

The advantage of this type of clamp system is that the clamp pressure can be regulated over a wide range. The disadvantage of the hydraulic clamp method is that, if press clamp tonnage is marginal for a given job, the injection pressure may overcome the hydraulic clamp pressure, forcing the mold open during material injection. This results in flash, short shots, and possible cycle interruption.

Mechanical clamp system. The mechanical clamp system features a "knuckle-and-scissors"–style mechanism to close the mold. This mechanism, shown in Figs. 6-14 and 6-15, is also attached to the moving platen. Figure 6-14 shows the machine in the open position. A small hydraulic cylinder is used to actuate the mechanical arms by pushing along their centerline. As the piston moves forward, it pulls the arms together, thereby closing the mold, as shown in Fig. 6-15. For the mold to close under full tonnage, the knuckles must “pass center” to lock.

The main advantage of the mechanical system is that, once the system is locked, it is virtually impossible to force the mold open, even with excessive injection pressures. There are, of course, lim-
its to this capability, and machine damage can occur if excessive injection pressures are present for extended periods of time.

There are two disadvantages to this system. First, there is considerable wear on the knuckle linkages, and bushings must be replaced regularly. Second, there is no clamp force adjustment. For example, if a machine is rated at 250 tons (2.2 MN) capacity, the only clamp tonnage available is 250 tons (2.2 MN). Therefore, small molds that are run in a large press can suffer crush damage.

Some machines combine both hydraulic and mechanical systems to achieve mold-clamping capability.

**Pressure Required**

As previously mentioned, the required total clamp force is determined by the projected area of the molded part. This area is then multiplied by a clamp force factor. As a general rule, a factor of 4–5 tons/in.² (55–69 MPa) is used for most products.

**Time**

During the injection molding process, many internal activities take place. Some occur while others are active (parallel), and some must wait until others are completed. The most important activity at this point is the overall cycle time. This is usually referred to as the "gate-to-gate" cycle time, because it is common to start timing the overall cycle when the machine operator closes the machine's safety gate. The timing continues until the operator closes that gate to start the next cycle. This number is then used to determine the cost of manufacturing the product; the value ultimately affects the product's selling price.

Using the gate-to-gate concept, typical steps in the injection molding cycle are shown in Table 6-3.

While the time totals 50 seconds, the actual total cycle time is 28 seconds, because some operations are performed in parallel.

Gate close time. This is the time it takes a machine operator to close the safety gate, which starts the cycle. The gate close time
against the plastic after it has been injected into the mold. This pres-

rate timers.

time is the first part of that time, and injection hold is the latter
time that the injection screw is pushing forward. The initial injec-
material injection into the mold.

volume of oil through the system. This can increase the speed of

time. When a booster phase is used, the injection machine's entire
is available, it is included in the first stage of the initial injection

injection time is controlled by a timer. If a "booster" injection time
normally does not exceed four or five seconds. The initial

may fluctuate slightly from operator to operator. Operators must
understand that any slight change in the gate close pace may affect
the overall machine cycle time. In fact, an increase of 2 seconds in
the average 30 second cycle time can cost approximately $20,000
annually, depending on the number of cavities, hourly wages, and
utility costs. Of course, similar savings can be achieved by a time
reduction in gate closing.

Mold close time. Mold close time is the time it takes the mov-
ing half of the mold to travel the distance required to meet the sta-
tionary half of the mold and lock with full clamping force. This
motion is usually initiated by a limit switch that is engaged when
the operator closes the safety gate to start the cycle.

There are two mold-closing phases. The first is the initial close,
which uses low pressure and quickly brings the two mold halves
together. This takes one or two seconds. This action stops when the
mold halves come to within 1 in. (25 mm) of fully closing. At that
point, high pressure is engaged, and the closing speed slows. This is a
safety feature that prevents fully closing the mold if an obstruc-
tion, such as a part, remains from a previous cycle. It also allows
slides or cams to operate slowly without danger of crushing. This
final closing normally takes two or three seconds.

Initial injection time. When the mold is fully closed, either a
limit switch or a pressure buildup (or both) signals the injection
screw to push forward and inject the molten plastic into the mold.
The screw does not turn at this point; it acts only as a plunger to
force the material into the mold. This initial injection is performed
using the highest practical pressure for the specific application (nor-
mally 10,000–15,000 psi [69–103 MPa]) in the fastest practical
time. In most cases, this is less than two seconds and rarely more
than three seconds.

Depending on the machine design, this action may be divided
into two or three smaller actions. In those cases, the total injection
time normally does not exceed four or five seconds. The initial
injection time is controlled by a timer. If a "booster" injection time is
available, it is included in the first stage of the initial injection
time. When a booster phase is used, the injection machine's entire
hydraulic system (injection and clamp) is combined to push a large
volume of oil through the system. This can increase the speed of
material injection into the mold.

Injection hold time. On most machines, the timer for initial
injection time (also called injection forward time) controls the total
time that the injection screw is pushing forward. The initial injec-
tion time is the first part of that time, and injection hold is the latter
part. On some machines, the hold time and initial time are on sepa-
rate timers.

The hold time is the time the injection screw maintains pressure
against the plastic after it has been injected into the mold. This pres-
sure is applied against the "cushion," or "pad," long enough for the
gate to freeze off (solidify). The molten plastic enters the mold
cavity through a gate, the first point that the plastic is exposed to the
cavity. Once all of the required material goes through the gate and
packs the cavity, the plastic is allowed to cool, under pressure, to the
point at which it all solidifies. However, because it is normally the
thinnest part of the cavity, the gate is the first portion to solidify.

Once it does, the hold pressure is not required. A 0.060 in. (1.5
mm)-thick gate would take approximately six seconds to solidify.

Cooling time. This is an important amount of time to consider
in the injection process. The cooling time is the total of (a) the
time required for the plastic to cool and solidify and (b) the time
necessary for the part to become rigid enough to withstand the
jection process.

Most material vendors supply cooling time requirements for
their materials at varying thicknesses. On average, a 0.060 in. (1.5
mm) thick part takes 9–12 seconds to solidify and permit ejection
from the mold without undue distortion.

Screw return time. After the screw pushes the plastic into the
mold and holds it there until the gate freezes, the screw starts turn-
ing to auger fresh material into the heating cylinder in preparation
for the next shot. Although there is no timer that adjusts the screw-
returning time, sufficient turning must occur before the cooling
timer (sometimes called the dwell timer) expires. If the screw has
not turned long enough, there will be insufficient material ready
for the next shot.

The time required for the screw to turn and return to the inject
position is determined by how much back pressure is applied
(higher back pressures increase the screw return time) and how
much material is prepared for the next shot. If the machine is the

correct size for the job and the back pressure is properly set, the
screw return time is a few seconds less than the total cooling timer
setting. In most cases, this amounts to approximately eight seconds.
The point at which the screw stops its return travel is determined by
a limit switch. This switch is set to ensure that there is enough mate-
rial ready for the next shot. As the screw turns (augers), it is pushed
back toward its starting point by the pressure built up in front of it
by the incoming material that augers forward.

The screw continues to turn until it has traveled back and
touches the preset limit switch. Other than for continuous purging,
this is the only time that the screw turns (bringing material forward).
It does not turn during injection except under rare circumstances
when the turning is used to force more material into the mold.

Mold open time. This is the time it takes the mold to open. It
is not determined by a timer (unless the machine is running fully
automatically), but rather by the distance and speed required for
the mold to fully open.

The mold usually opens in two stages. The first stage is very
slow and for a short distance. This allows minimization of the vac-
uum that is created during the molding process. When plastic is
injected into the mold, it displaces the air that is trapped in the
closed mold. When air is displaced, a vacuum occurs. This vac-
uum causes the two mold halves to tend to stick together, if it is
not released, when the machine opens. After opening approxi-
mately 0.25 in. (6.4 mm) to relieve the vacuum, the mold fully
opens. If the mold contains fragile cams, slides, or lifting devices,
the slow-speed opening distance is increased. The final opening
speed is much greater than the initial speed and is often as fast as
the machine allows.

Ejection time. When the cycle is complete and the mold has
fully opened, the ejection system comes forward and forces the
parts out of the mold. This action is normally started by a limit
switch that actuates at the full opening of the mold. The ejection

<table>
<thead>
<tr>
<th>Step</th>
<th>Time, second</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate close</td>
<td>1</td>
</tr>
<tr>
<td>Mold close</td>
<td>4</td>
</tr>
<tr>
<td>Initial injection</td>
<td>3</td>
</tr>
<tr>
<td>Injection hold</td>
<td>5</td>
</tr>
<tr>
<td>Cooling</td>
<td>20</td>
</tr>
<tr>
<td>Screw return</td>
<td>8</td>
</tr>
<tr>
<td>Mold open</td>
<td>4</td>
</tr>
<tr>
<td>Ejection</td>
<td>1</td>
</tr>
<tr>
<td>Part removal</td>
<td>2</td>
</tr>
<tr>
<td>Mold inspection, clean, and spray</td>
<td>2</td>
</tr>
</tbody>
</table>
stroke itself is normally controlled by another limit switch that actuates when sufficient ejection has taken place, but the speed at which the system comes forward is controlled; this speed determines the ejection time.

Some vacuum remains in the cavities, because the formed plastic has displaced air. To release this vacuum, the ejection system is pushed forward (usually by a small hydraulic cylinder) at a rate that is slow enough to overcome the vacuum but fast enough that it is practical. This would normally be one or two seconds, depending on the length of ejection.

The ejection system must then return before the next cycle can start. In some cases, it is not necessary to return the system because the mold closing performs that action. However, in most cases, this is a dangerous practice.

A double-ejection cycle may be required to release reluctant parts from ejector pins. This action effectively doubles the ejection time.

Part removal time. In cases where an operator demolds the parts, time is included in the cycle for that operation. This operation usually takes two or three seconds, depending on the degree of difficulty.

Mold inspection, clean and spray time. These procedures are often overlooked in estimating total cycle times. It is good practice to have the operator (when one is present) look over the mold before closing the gate to start the next cycle. This takes only a second but can save thousands of dollars in repairs if a part is stuck or if slides have been knocked out of adjustment. The operator may also clean the mold surfaces to eliminate flash, grease, outgassing, or other contaminants. Finally, the operator may periodically apply a mold release. All of these operations must be included in establishing the total cycle time.

**Distance**

Although distance is the last parameter discussed, control of distances is critical to producing high-quality products at a reasonable cost. Because distance is so closely related to time, the various functions involving distance are basically the same as those that concern time.

Mold close distance. There are two phases to the mold close distance. The first, the initial close, covers the major portion of the closing process. The second, or final close, covers the latter portion.

The initial mold closing should move the mold halves to within approximately 0.25 in. (6.4 mm) from touching each other. This closing distance is normally traveled under high speed to minimize overall cycle time.

The mold closing speed is then slowed to a crawl but placed under high pressure. This occurs for the final travel distance until the mold halves are closed tightly. This slow final closing minimizes closing damage. If a foreign object is caught in the mold during the initial closing phase, the closing action stops. The foreign object is crushed and mold damage may occur.

When the mold is closed and placed under full clamp tonnage, the injection phase may begin.

Initial injection distance. Approximately 95% of the intended material is injected in the initial injection distance. This distance varies based on machine size and the barrel capacity that is injected for each shot. The limit switch governing the shot size is set on a measurement scale. This scale is usually located on the injection barrel but is often part of the electronic control system.

Injection hold distance. After the initial injection phase, the machine switches to holding pressure. This finishes filling the mold and holds pressure against the material that was injected. The hold pressure engagement point is set near the end of the injection screw’s stroke. There is a pad of material, 0.125–0.25 in. (3–6 mm) thick, that remains in the barrel against which this hold pressure is applied (see Fig. 6-16). The cushion size is established by creating a total shot size that is slightly larger than that required to fill the mold.

The cushion thickness is critical. A minimum pad thickness of 0.12 in. (3 mm) is essential for accurate process control. If the cushion thickness approaches zero (the screw bottoming out), there will be no pressure against the material in the mold, and the molded part may warp, crack, or partly fill. In this case, the shrinkage may also vary, affecting part dimensions.

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**Fig. 6-16 Pad of material in barrel against which hold pressure is applied.** (Courtesy Texas Plastic Technologies)
If the cushion thickness is greater than 0.25 in. (6 mm), the plastic in the cushion may cool and begin to solidify, causing a blocked nozzle.

Screw return distance. The primary function of the screw return process is to prepare the charge for the next shot. After the injection phases are complete, the screw turns to bring fresh material forward into the heating cylinder. As the material is brought forward, it pushes the screw backward while it is turning. This continues until the screw has returned to its set point, at which time it stops turning. The rate of screw return is based on the speed of the screw drive motor. There is a speed range in which each material is best prepared for injection, and each screw design affects the screw rotation speed. The recommended screw speed range is 30–160 rpm.

Mold open distance. To break the vacuum that was created in the cavity during the injection process, the mold is opened slowly. After the mold has opened about 0.25 in. (6 mm), the vacuum on the stationary side is relieved, and the mold continues to open at a faster rate, which reduces the overall cycle time. If a mold contains slides or cams, the mold may open slowly for a longer distance. The mold should only open a distance that is twice the depth of the molded part (see Fig. 6-17). If an operator must remove the parts from the ejection system, the opening distance is usually longer to accommodate safe part removal. In most cases, this distance does not exceed 2.5 times the part depth.

Ejection distance. The ejection distance required is only that needed to push the part free of the mold. The only area of the part that is ejected is the portion that is held in the moving mold half. It is good practice to calculate the required ejection distance and add a safety factor of 0.12–0.25 in. (3–6 mm).

DETERMINING INJECTION MOLDING COSTS

Total manufacturing costs include many items such as packaging, advertising, and secondary operations. The following sections address only the tooling and operational costs for the injection molding process.

Tooling Costs

In some cases, the tooling costs are amortized over the total production run of a product. This method is often considered when the volume requirements are low (less than 5000 pieces) or when capital is not available for the tooling before production begins.

The practice of amortizing tooling is difficult to justify, because it is based on the assumption that product volumes do not fluctuate from original estimates. Those volumes invariably change. Tooling vendors are also discouraging the practice because it delays payment to them.

The more common payment method for injection molds is to submit one-third of the tool cost with the purchase order, one-third on delivery of the tool, and the final third on product acceptance. Detailed acceptance criteria are presented by the buyer and accepted by the toolmaker prior to the start of tool production. Both parties should expect some changes in areas of gate design or location, runner sizes, and water line construction. Periodic maintenance of the mold components may also be required, and the moldmaker may include those costs in his quotation.

Mold costs depend on many variables; these are discussed in the following sections.

Type of mold material. Molds can be machined or cast from many different materials. Low-volume molds are made of epoxy, aluminum, mild steel, urethane, or a combination of these materials. Higher-volume molds are usually made of prehardened steel, tool steel, hot-rolled steel, stainless steel, or a combination of these. High-grade aluminum has shown limited success for high-volume molds. Although the projected mold weight indicates material costs, the majority of the overall tool cost is the labor cost.

Labor rates. Labor rates vary with geographic location and with the expertise required to build a given mold. Furthermore, a highly skilled moldmaker is required to perform the final fitting of complicated subassemblies, while a semiskilled laborer may drill the water lines.

Design costs. The cost of designing a mold, normally about 10% of the final mold cost, is usually included in the overall mold cost. However, design costs may be identified separately.

Hours to build. The final mold cost depends on the number of hours required to design, fabricate, and assemble the mold. This can range from less than 100 hours for a small, simple, short-run mold to thousands of hours for large, complicated, high-production tools. When determining labor costs, the moldmaker usually uses a flat hourly figure that includes labor, overhead, and profit. On average, approximately 1200 hours are required to build a mold. This covers a standard, production-level mold made of a high-grade steel and includes some minor slide and cam actions.

Fig. 6-17 Mold opens only far enough to eject the finished part. (Courtesy Texas Plastic Technologies)
Geographic location. In the United States, the 1994 rate for moldmaking was $40–70/h. Therefore, a mold that required 1200 hours to build would cost from $48,000–$84,000, depending on where it was built.

In the past, some molds were built overseas because of lower hourly rates. Because the overall cost of overseas-built tools was higher than anticipated, this practice has diminished. Furthermore, overseas moldmakers are not able to match current increased quality requirements. Some overseas toolmakers have also increased their rates, further detracting from their previous price advantage.

Operational Costs

The total cost of molding products includes comprised material costs, labor charges, and machine rate costs.

Material costs. Material charges are determined by calculating the total volume of a molded plastic product and converting that value to a weight. For example, consider a molded product in the shape of a box with one open side, as shown in Fig. 6-18. To determine the total volume, the box is first broken down into its main geometric patterns. For an open box, this includes four rectangular sides and one rectangular back (the front is open), as shown in Fig. 6-19. These patterns are first analyzed to determine the number of square inches (millimeters) that each contains. This value is then multiplied by the wall thickness to determine the part volume in cubic inches (millimeters).

For the patterns shown in Fig. 6-19, the part volume is:

\[
\begin{align*}
118 \text{ in.}^2 \times 0.090 \text{ in.} & = 10.62 \text{ in.}^3 \quad (2) \\
76,129 \text{ mm}^2 \times 2.29 \text{ mm} & = 174,335 \text{ mm}^3 \quad (3)
\end{align*}
\]

The part volume is then multiplied by the material’s specific gravity, which is provided by the material supplier or found in other reference material. The box shown in Fig. 6-19 is made of polycarbonate, which has a specific gravity of 1.2. A final conversion factor (0.0361 for in.\(^3\) and 1 × 10\(^{-6}\) for mm\(^3\)), which is independent of the material, is also used to obtain the material weight.

For the sample box, the weight is calculated as follows:

\[
\begin{align*}
10.62 \text{ in.}^3 \times 1.2 \times 0.0361 & = 0.46 \text{ lb} \quad (4) \\
174,335 \text{ mm}^3 \times 1.2 \times 1 \times 10^{-6} & = 0.21 \text{ kg} \quad (5)
\end{align*}
\]

This weight is often registered for 1000 pieces. In this case, the calculation reveals 460 lb (209 kg) per 1000 parts.

Labor charges. Labor charges for a single operator are typically included in the machine hour rate for the molding process. However, if an operator is used and labor charges are not included, or if additional labor is required, the following information is used to determine the incurred costs.

First, the average payroll cost for machine operators is established, and specific overhead and burden rates are added. However, a general guideline of doubling the operator’s hourly wage is often used to approximate total hourly labor charges.

The labor piece cost is then calculated by dividing the hourly labor charge by the number of pieces produced in that hour. For example, for a production rate of 150 pieces/h and a labor charge of $15.00/h, the labor piece cost is $15.00/150 = $0.10.

Machine rate costs. The first item to consider in this category is the set-up charge. This is a one-time fee that is assessed each time a mold is installed in (and removed from) a press for a production or trial run. (The charge for a trial run is normally double that for a production run.) The fee is derived by establishing the set-up time and then multiplying it by the hourly rate of the machine. Thus, a two-hour set-up on a 300-ton (2.7-MN) machine costs approximately $90 (see Table 6-4). This can be assessed as a 24
24
15
15
+ 40
118 in. \(^2\) \text{ (total)}

Fig. 6-19 Example reduced to its main geometric patterns. (Courtesy Texas Plastic Technologies)

A scrap percentage is also often added to this total. Depending on a number of production factors, this percentage can range from 0.5–10%. For the box example, a 5% scrap rate is appropriate. Therefore, an additional 23 lb (10.5 kg) are added to the total material required for 1000 pieces, giving a grand total of 483 lb (219.5 kg).

This number is finally multiplied by the per-pound material cost to determine the overall material cost.

Machine operating costs. The most significant item in this category is the machine cost. This is the cost that is charged to each job and is based on the machine’s capacity, the number of hours it is used, and the rate at which it is charged. The rate is usually quoted in terms of dollars per hour and can vary widely depending on the type of machine and the manufacturer. For example, a 200-ton (1.8-MN) machine might have a rate of $30/h, while a 500-ton (4.5-MN) machine might have a rate of $50/h.

TABLE 6-4

<table>
<thead>
<tr>
<th>Machine Capacity, tons (MN)</th>
<th>Cost/hour, $</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–100 (0–0.9)</td>
<td>25–30</td>
</tr>
<tr>
<td>100–200 (0.9–1.8)</td>
<td>30–35</td>
</tr>
<tr>
<td>200–300 (1.8–2.7)</td>
<td>35–45</td>
</tr>
<tr>
<td>300–500 (2.7–4.5)</td>
<td>45–55</td>
</tr>
<tr>
<td>500–750 (4.5–6.7)</td>
<td>55–75</td>
</tr>
<tr>
<td>50–1000 (0.4–9.0)</td>
<td>75–90</td>
</tr>
</tbody>
</table>
one-time charge for each run or amortized over the number of pieces molded in each run.

The cost to operate a molding machine must include the costs for utilities and the overhead costs of the molding plant itself, including payroll, rent, repairs, travel, maintenance, and insurance. This rate, normally compiled by the financial department, is determined for each size range of machine. A 1994 listing of approximate national averages is shown in Table 6-4. The costs include the cost of one machine operator.

The machine rate is expressed as part of the piece price by dividing this rate by the number of pieces (acceptable and rejected) produced per hour. To estimate the hourly production, the gate-to-gate cycle is established or estimated. Table 6-5 shows estimated gate-to-gate cycle times based on common nominal wall thicknesses and assuming proper mold construction.

Once the gate-to-gate cycle is determined or estimated, the total number of pieces per hour is determined. This value is calculated by dividing the number of seconds per hour (3600) by the number of seconds in the cycle, and then multiplying this value by the number of mold cavities. For example, a 0.100 in. (2.5 mm) thick part yields 128.6 cycles/h (3600/28) on a single-cavity mold. A two-cavity mold produces twice that amount.

The final machine rate piece cost is calculated by dividing the machine rate by the number of pieces produced per hour. Thus, a two-cavity mold with a 0.100 in. (2.5 mm) nominal wall thickness (28 seconds to produce one part), running on a 300-ton (2.7-MN) machine ($45/h), yields a machine rate piece price of $0.175. That calculation is performed as follows:

\[ \text{Piece price} = \frac{45}{\left(\frac{3600}{28}\right) \times 2} = \$0.175 \]  

**Final Part Cost**

At this point, the three basic costs (material, labor, and machine rate) are totaled to obtain the final part cost for the injection molding operation. This is then the cost to manufacture the molded part. Packaging and secondary-operation costs are added to this figure. The selling price is determined by factoring this final number by a mark-up (which includes profit and a complexity value) that is determined by the molder.

**MELT FLOW AND PROCESSIBILITY**

To properly control the quality of a molded product, the molder must understand the flow characteristics of the plastic being molded. Each material demonstrates a specific ability to flow under given molding conditions. An inexpensive melt index indicator (extrusion plastometer) can test for this ability, using ASTM test method #D1238.

Melt index (melt flow or flow rate) is a measurement of a plastic’s ability to flow. It is the amount of plastic that extrudes in a specific time from a heated cylinder. The test consists of placing 0.07–0.3 oz. (2–8.5 g) of plastic into a preheated cylinder and applying a load to force the melted plastic through an orifice (see Fig. 6-20). The amount of material that extrudes is measured and factored.

Table 6-6 shows property changes with decreasing melt index.

<table>
<thead>
<tr>
<th>Property</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness</td>
<td>Increase</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>Increase</td>
</tr>
<tr>
<td>Yield strength</td>
<td>Increase</td>
</tr>
<tr>
<td>Hardness</td>
<td>Increase</td>
</tr>
<tr>
<td>Creep resistance</td>
<td>Increase</td>
</tr>
<tr>
<td>Toughness</td>
<td>Increase</td>
</tr>
<tr>
<td>Softening temperature</td>
<td>Increase</td>
</tr>
<tr>
<td>Stress-crack resistance</td>
<td>Increase</td>
</tr>
<tr>
<td>Chemical resistance</td>
<td>Increase</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>Increase</td>
</tr>
<tr>
<td>Permeability</td>
<td>Decrease</td>
</tr>
<tr>
<td>Gloss</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

The melt index is usually stated as grams per 10 minutes. A low melt index, for example, represents a high-viscosity material that is difficult to flow. Changes in melt index values produce the results shown in Table 6-6.

**MINIMIZING MOLDED-IN STRESS**

Other than contamination, the most significant reason for injection-molded product failure is molded-in stress. Stress is defined as a resistance to deformation from an applied force. If a force is applied to an object, the object resists having its shape changed. The amount of resistance that is present is identified as stress.

Plastic material is initially forced into the mold, causing the molecules to align. Following injection, the material cools and solidifies. As that happens, the molecules slow down until they stop moving. If they cool too quickly, or under excessive pressure, and are kept from relaxing to their original state, they solidify under stress.

Proper product design, mold design, material selection, and processing minimize molded-in part stresses.

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**FIG. 6-20** Melt index indicator. (Courtesy Texas Plastic Technologies)
Product Design

Three product design areas are identified as the main causes of part stresses. These are draft angles, sharp corners, and gate location.

Draft angles. The draft angle on a part is the amount of taper required for proper ejection from the mold. Figure 6-21 depicts a part’s draft angle.

An ideal draft angle is 2˚ per side of the part. However, as little as 0.25˚ may be used, although part ejection is often difficult at this value.

Cavities without draft angles. Figure 6-22 shows a design with no draft angle. A vacuum is created during the molding process, and the air that was trapped in the closed mold cavity is displaced by plastic during the injection phase. With a straight-wall (no-taper) design, the molded part must travel the entire depth of the cavity before the vacuum is released. This generally requires excessive ejection forces. By adding a minimum draft angle to the part, the ejection stresses are minimized (see Fig. 6-23.)

Uniform wall thickness. Nonuniform wall thicknesses also generate molded-in stresses. Figure 6-24 shows the cross-section of a molded part with uniform wall thicknesses. Both side walls have the same thickness as the base wall. Furthermore, the corners feature radii to keep the section uniform and promote flow.

Figure 6-25 shows parts with and without corner radii. In the left part, the molten plastic molecules are injected into the mold and flow through the wall freely as they fill the cavity. In the right part, the molecules enter the wall but are squeezed, compressed, expanded, and sheared as they are forced around the sharp corners, and stresses are much higher in the molded part.

A similar condition occurs when there is an abrupt wall thickness change, as shown in Fig. 6-26. Stresses are high with this design. If the wall thickness must change, it should feature a gentle, tapered transition, as shown in Fig. 6-27.

Mold Design

Gate location. To minimize stresses, a gate is best located so that the molten plastic enters the cavity at the part’s thickest cross-section. Figure 6-28 illustrates this concept.

Runner design. Proper runners feature a full-round design, because a circular cross-section creates equal pressure in all directions (see Fig. 6-29). Using the round runner design minimizes the molecular distortion created while the molten plastic is flowing through the runner.

Venting concepts. A large amount of air becomes trapped in a mold when it is closed in preparation for the injection phase. This air must be displaced so that incoming plastic material can fill every
available section of the cavity. Air that remains trapped in the cavity is generally pushed toward the corners and results in nonfills and other defects.

The most efficient method of releasing air from cavities is to machine vents into the parting line of the mold. A general rule is to allow 30% of the parting line perimeter for venting (see Fig. 6-30). It is also good practice to vent the runner, as shown in Fig. 6-31.

**Proper Material Use**

Stress can be induced by selecting the wrong material or grade of material. An appropriate material flows freely yet is stiff enough to maintain the required properties. Although stiffer materials have greater strength, they also generate higher molded-in stresses because they require higher injection pressures.

Because there are many variables involved, it is often difficult to purchase an acceptable off-the-shelf material. It may be more efficient and practical to purchase materials from a compounder, who uses a common base resin but customizes it for specific applications.

**Processing**

Molding is done using the highest pressure and fastest injection time available for a specific material. However, because high
pressures can cause stresses, each job is evaluated to ensure the correct pressure is used. If unacceptable stresses are present, compromises in molding pressures and temperatures or material grade and type are necessary.

**MATERIAL SELECTION**

**Amorphous Versus Crystalline**

There are approximately 18,000 plastic materials available today. Because of the associated wide range of properties and costs, proper material selection is imperative.

There are two major categories of thermoplastic materials: amorphous and crystalline. Amorphous materials feature a molecular structure that is random and becomes mobile over a wide temperature range. As a result, these materials do not melt but rather soften as heat is applied to them.

Crystalline materials have a molecular structure that is well ordered and becomes mobile only after heating to the melting temperature.

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**Fig. 6-28** Gate is placed so that molten plastic enters the part’s thickest cross section. (Courtesy Texas Plastic Technologies)

**Fig. 6-29** A full-round runner design is preferred over the trapezoidal shape. (Courtesy Texas Plastic Technologies)

**Fig. 6-30** Approximately 30% of the parting line perimeter is vented. (Courtesy Texas Plastic Technologies)
point. These materials have no softening stage. They remain rigid until heated to a specific temperature, at which they melt.

When plastic is injection molded, its molecules bond during polymerization and form chains. With amorphous materials, these chains have little structure. With crystalline materials, these chains are very structured. A physical property comparison of amorphous and crystalline materials is presented in Table 6-7.

Table 6-8 shows the classifications of common plastics.

Cost Versus Performance

With many materials to choose from, and considering that specialty compounders can create many additional variations, the molder indeed has many options. However, as performance increases, cost increases and processibility suffers (see Fig. 6-32). Because of this relationship, it is important to analyze the physical, chemical, mechanical, and thermal requirements of each product design and to select a material that meets those requirements with minimal cost. Compromises in design requirements often reduce overall product costs.

Fillers and Reinforcements

Although the terms filler and reinforcement are used interchangeably, there is a subtle difference between the two. Fillers are additives that are mixed with a base resin to change the properties of that resin. Reinforcements, while also additives, are included to increase only the strength of the base resin. Therefore, a reinforcement is considered a filler, but the converse is not necessarily true.

Adding fillers may reduce the cost of a compound. By adding talc or clay, resin cost is reduced because the filler is less expensive than the resin, and the filler adds bulk, which reduces the amount of resin required for a specific compound. However, adding fillers usually increases the cost of a plastic compound. Fillers are normally added to improve a property such as impact resistance, melt flow, flame retardancy, shrinkage rate, or flexibility. In other cases, they are used to make the plastic conductive, such as when adding nickel or steel fibers. Fillers are also used to add color.

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**TABLE 6-7**

<table>
<thead>
<tr>
<th>Physical Properties of Amorphous and Crystalline Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amorphous</strong></td>
</tr>
<tr>
<td>Clear</td>
</tr>
<tr>
<td>Low shrinkage</td>
</tr>
<tr>
<td>Softens (no melting)</td>
</tr>
<tr>
<td>High impact resistance</td>
</tr>
<tr>
<td>Poor chemical resistance</td>
</tr>
<tr>
<td>Poor lubricity</td>
</tr>
</tbody>
</table>

**TABLE 6-8**

<table>
<thead>
<tr>
<th>Plastic Classifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amorphous</strong></td>
</tr>
<tr>
<td>ABS</td>
</tr>
<tr>
<td>Acrylic</td>
</tr>
<tr>
<td>Cellulose propionate</td>
</tr>
<tr>
<td>Polyamide-imide</td>
</tr>
<tr>
<td>Polyarylate</td>
</tr>
<tr>
<td>Polycarbonate</td>
</tr>
<tr>
<td>Polyetherimide</td>
</tr>
<tr>
<td>Polyether sulfone</td>
</tr>
<tr>
<td>Polyphenylene oxide</td>
</tr>
<tr>
<td>Polystyrene</td>
</tr>
<tr>
<td>Polyurethane</td>
</tr>
</tbody>
</table>
Reinforcements, on the other hand, are additives, such as glass fibers, graphite, or mica, that are mixed in the plastic to impart strength. Tensile strength, compressive strength, flexural strength, and impact strength are increased by adding reinforcements. In most cases, reinforcements are added at a level of 10–40%, but loadings of up to 80% are feasible. A reinforcement usually lowers a plastic’s melt index.

A major concern when using reinforcements is wear on the mold. Most reinforcements, by nature, are extremely abrasive and can quickly wear gates, mold texture, runners, or other areas that cause a flow restriction. For this reason, carbide inserts are often used in gate locations. Chapter 2 of this handbook describes in greater detail considerations for material selection.

TROUBLESHOOTING THE MOLDING PROCESS

Troubleshooting relies on singular, rational steps to solve molding problems. Variables are changed one at a time, and the results are evaluated before proceeding further. Assistance from outside sources is often appropriate and may shorten the troubleshooting process.

One source of troubleshooting assistance is material suppliers. They often observe similar molding problems at various customers, and their problem-solving often provides the molder with a rational explanation or a solution that may not surface with in-house troubleshooting. An approach that relies on a combination of material suppliers, molding handbooks, and common sense is the most efficient.

The causes of common injection molding defects are process related and do not include those resulting from poor product design. Defects are usually traceable to problems with one or more of the following items: the molding machine, the mold, the plastic material, and the machine operator. Figure 6-33 shows the respective percentages relating to these four areas. Based on this information, troubleshooting should begin at the molding machine.

The following sections discuss common molding defects and their remedies. Discussions focus on the four areas shown in Fig. 6-33.

BLACK SPECKS OR STREAKS

- Excessive residence time in barrel—20–80% of the barrel capacity is injected in each cycle. If the plastic stays in the barrel longer than normal, it begins to degrade. This degradation results in carbonized plastic, which appears as small black clusters. These clusters are carried through the melt stream and appear as spots or streaks in the molded part, are visible on the surface of an opaque part, and appear throughout a transparent part. The solution is to place the mold in a properly sized machine.

- Sprue bushing cracked, nicked, or not seating properly—each of these conditions causes plastic to remain in the crack, nick, or offset seating. This material can overheat due to excessive residence time at that location, and this causes degradation and carbonizing. The retained resin eventually breaks loose and enters the melt stream and flow path. The remedy is to replace cracked or nicked bushings, and to use a blueing agent to check for central seating of the bushing against the nozzle tip. The nozzle tip opening must also have a diameter that is equal to or smaller than the sprue bushing to ensure a proper seal.

- Contaminated raw material—contamination is often the result of dirty regrind, mixed regrind, improperly cleaned hoppers or grinders, open or uncovered material containers, and poor-quality virgin material. The remedies include purchasing from high-quality suppliers, using good housekeeping practices, and providing proper training for material handling personnel.

- Inconsistent cycle—the operator may inadvertently cause delayed or inconsistent cycles. This results in either excessive material residence time in the heating cylinder or overcompensating heater bands. Both conditions result in degraded material, especially with heat-sensitive materials. One remedy is to place the machine in an automatic mode and use the operator only to stop the press if an emergency develops. Operator training, emphasizing the importance of consistent cycles, is also appropriate.

BLISTERS

- Low back pressure—as the material is heated and augered through the heating cylinder, air becomes trapped within the melt. Back pressure is used to force out this air before it is injected into the mold cavity. Back pressure is set at 50 psi (345 kPa) and increased in increments of 10 psi (69 kPa) until the ideal setting is reached.

- Low mold temperature—as material is injected into a mold, it starts to cool immediately and a skin forms on the surface of the part. If this skin forms too quickly, any air that is mixed into the material cannot escape as intended in the molding process. A mold that is too cool causes early skin formation.

- Use of regrind that is too coarse—this practice increases the amount of air that becomes trapped in the melt, because the coarse, uneven regrind particles create air pockets between themselves and the smaller, consistently sized base material.

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Fig. 6-33 Product defects are traceable to at least one of four areas. (Courtesy Texas Plastic Technologies)
CHAPTER 6
TROUBLESHOOTING THE MOLDING PROCESS

particles. One remedy is to use a finer-gage screen in the regrinder. Another is to limit the amount of regrind to 5%. A third solution is to increase the back pressure on the injection screw, assuming good heat sensitivity of the base material. The final solution is to use only virgin material.

• Early gate opening—blisters may form if the operator opens the gate too soon, thus preventing the part from properly cooling in the mold.

BLUSH

• Excessive injection speed—the speed and pressure of the melt as it enters the mold determine the melt’s density and consistency in packing the mold. Excessive fill speeds cause the material to “slip” over mold surfaces, especially at the gate area, and the material at the slipped surface skins over before the balance solidifies. The slipped material does not reproduce the mold surface as does the material in other part areas because it has not packed as tightly in the mold. Thus, the underpacked area has a dully finish. The injection fill speed is decreased until proper filling occurs; barrel and mold temperatures are often adjusted as well.

• Low mold temperature—if the mold is too cool, molten material flow is hindered, and the material solidifies before it fills and packs the mold. Blush, or dull finish, appears in the last area packed, which is usually at the gate. Increasing the mold temperature allows the material to flow farther and pack properly.

• Excessive moisture—excessive melt moisture may accumulate in the gate area, because injection pressure forces trapped moisture out of packed areas and into unpacked areas. Because the gate area is the last to pack, it is often the location where moisture collects. The blushing may be accompanied by splay, or silver streaking.

• Inconsistent cycling—inconsistent cycling of the molding process by the operator may cause the material to overheat. If this occurs, the injection fill rate may increase in random cycles. Operating the machine on automatic cycle mode ensures consistent cycles.

BOWING

• Clamp pressure is released too quickly—in an effort to increase the number of cycles per hour, molders may increase the clamp release speed. If the clamp pressure is released at the instant of the “mold open” portion of the cycle, the part can remain on the injection (stationary) half of the mold. As the mold continues to open, the part snaps back onto the clamp (moving) half of the mold, and the part may bow from this distortion. The solution is to ensure that the first 0.25 in. (6 mm) of mold opening is done at a slow speed.

• Low temperature—some materials, such as polyesters, require mold temperatures that are higher than the boiling point of water to achieve maximum material physical properties. Parts molded at a temperature that is too low can bend when the mold opens, and bowing may result. Material suppliers can supply the proper molding temperatures, which may require the use of mold heaters.

• Improper handling—the operator may improperly handle molded parts after ejection from the mold. If parts are packed for shipment too soon after molding, the residual heat may not dissipate, and bowing can occur. Also, relief operators may handle parts differently from the main operator. Proper operator instruction is required.

BRITTLENESS

• Improper screw design—a screw with a compression ratio that is too low for the molded material does not properly melt and mix the material. This results in weak molecular bonds in the material. Using an injection screw with a higher compression ratio can resolve this problem. The material supplier can indicate the proper screw design for specific materials.

• Condensation—although it does not occur with regularity, condensation in the mold is a possible source of moisture, which in turn causes brittleness in molded parts. Condensation is especially prevalent in molds that are operated in humid conditions. Mold cooling water may be the source of condensation. One remedy is to use insulation panels between the mold and the press, as well as on all of the mold’s outside surfaces. Another is to slightly increase the mold temperature. A small fan operating near the mold may provide benefit, but it must not move air directly at the molding surfaces.

• Excessive moisture—all materials need a small amount of moisture to properly process, but this is usually restricted to 0.01%. Some materials, such as nylon and ABS, are hygroscopic and readily absorb moisture from the atmosphere, even after initial drying. These are difficult materials to keep dry. Moisture causes brittleness because the water droplets turn to steam when heated in the injection unit. This steam explodes through the melt stream, causing voided areas, which are not properly bonded.

• Some materials (especially hygroscopics) may require conditioning after molding to return the moisture that was removed for molding. Nylons, for example, are normally conditioned after molding.

• Inconsistent cycles—an operator who is variably controlling the cycle may cause part brittleness, because the material degrades in the heating cylinder. Degraded material causes weak molecular bonding, which results in brittle parts.

BUBBLES (VOIDS)

• Excessive injection temperature—high injection temperatures can make the molten material too fluid. The material becomes so turbulent that air and gases are trapped in the melt stream. These trapped gases appear as voids in the molded part. Reducing the injection temperature allows the material to stiffen, permitting the trapped gases to escape from the melt stream. However, apparent voids may be unmelted particles. If this is the case, a temperature reduction only worsens the condition.

• Excessive section thickness—when a plastic part consists of varied wall thicknesses, the thicker walls cool last. A pressure loss occurs in those thick areas as they continue to cool after the thinner areas have solidified. The plastic is pulled toward the solid section and causes a void in the thick section. When the void is on the surface of a part, it appears as a sink mark. When it is below the surface, it appears as a bubble. The best solution is to use metal core-outs to thin the thicker wall. If possible, the wall thickness is changed so that the thick section is at most 25% thicker than the thin section.

• Excessive moisture—excessive moisture can get trapped in the resin as the molding process progresses, and appears as bubbles in the molded part. The moisture turns to steam during the heating process and cannot escape from the material; it then forms a gas pocket that appears as a void. The solution is to properly dry the material before molding.

• Inconsistent cycle—this may cause an overrun of the heating barrel temperature controllers, making the material too fluid. As
a result, the material is injected too quickly. This may cause trapped gases, and these gases then appear as voids. Automatic-mode operation is used when possible to ensure consistent cycles. Otherwise, the operators are trained in the consequences of running inconsistent cycles.

**BURN MARKS**

- Excessive injection speed or pressure—if the injection pressure is excessive, the resin is forced in so quickly that air trapped in the runner system or mold cavities is not forced out ahead of the resin flow. The trapped air then becomes compressed to the point that it ignites and burns. This causes the surrounding plastic resin to burn until the air is consumed or exhausted. Reducing the injection speed and pressure allows the gas or trapped air to escape through normal venting methods.
- Improper venting—mold venting systems are used to exhaust gases or trapped air. If the vents are too shallow or narrow, or if there are insufficient vents, the air is compressed before it is exhausted; it then ignites and burns. A minimum vent width of 0.12 in. (3 mm) is required. The vent land should not exceed 0.12 in. (3 mm) in length. Blind areas, such as the bottom of holes, should feature vents on the side of ejector pins that are placed there. A total venting length that is at least 30% of the parting line’s perimeter is required.
- Excessive regrind use—a limited amount of regrind is permitted when using heat-sensitive materials such as PVC. Regrind material absorbs heat in the injection barrel at a slower rate than the virgin material due to its irregular surfaces and larger particle size. This results in a longer heating cycle, which causes the virgin pellets to overheat and degrade. The degradation appears as burned particles that are transported through the melt stream into the cavity. A regrind limit of 10% minimizes burn marks. If the shot size is small (less than 20% of the barrel volume), it may be necessary to eliminate regrind. One solution is to start with 100% virgin material and slowly build up regrind use in 2% increments until burning occurs.
- Inconsistent cycles—erratic cycles cause the barrel heating system to heat unevenly, resulting in barrel hot spots. The material is overheated and degraded in these areas. The degradation again appears as burned particles that are transported through the melt stream and into the cavity. If possible, the press is run in automatic mode.

**CLEAR SPOTS**

- Low barrel temperature—low barrel temperatures result in improper molecule blending due to unmelted particles. These particles travel through the melt stream and enter the cavity. In transparent parts, they appear as clear spots (visible as an outline), and in opaque parts, they may also show if near the surface. Sectioning an opaque part reveals the spots as voids. Increasing the barrel temperature in 10˚F (5.5˚C) increments, and allowing the temperatures to stabilize for ten cycles before increasing again, minimizes clear spots.
- Water leaks—the mold may have developed cracks that allow water to seep into the cavity from the cooling lines. If this occurs, the water may appear as clear spots in transparent parts. A pressure check of closed water lines determines if cracks are present. If welding these cracked areas is not possible, tubing inserted in the lines may stop the leaking. It is essential to correct the crack-causing condition; the mold base is reinforced if it is considered usable.
- Excessive regrind—because regrind absorbs heat more slowly than virgin material (due to irregular particle sizes), the regrind may melt less evenly under normal heat settings. Increasing the barrel temperature slightly may accommodate the regrind if the molded material is not overly heat sensitive.
- Inconsistent cycles—erratic cycling of the machine can result in uneven barrel heating; this can cause hot and cold spots. Material from the cold spots may continue through the melt stream without proper heating and appear as clear spots in transparent parts.

**CLOUDY APPEARANCE**

- Low barrel temperature—a cloudy appearance, especially in transparent parts, is different than blush. True cloudy appearance is normally caused by a group of improperly melted particles. These particles are not blended with the main melt and isolate themselves in a group pattern. Increasing the barrel temperature reduces the likelihood of unmelted particles, but this increase must not degrade the virgin resin particles.
- Uneven cavity packing—uneven packing is normally traced to poor housekeeping practice or poor material handling practices. Mold release is used in small portions if at all. Improper regrind—regrind may contain a number of contaminants such as food containers, soft drink spills, dust and dirt particles, and other plastic materials. This is usually due to poor housekeeping practice or poor material handling proce-
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TROUBLESHOOTING THE MOLDING PROCESS

CRAZING
Because crazing is essentially a fine network of cracks, the causes of and remedies for cracking also apply.

DELAMINATION

- Low injection speed—if the injection rate is too slow, the material cools and solidifies before the mold is filled. Because the material fills the cavity in a tongue-on-tongue fashion, one layer may begin to solidify before the next layer bonds to it. This results in a separation after demolding and manifests itself as delamination. Injection speed is increased in 2% increments until delamination is eliminated. If flashing or burning occurs, injection speed cannot be further increased, and other defect sources are investigated.
- Low mold temperature—if the mold temperature is too low, the incoming layers of molten material cool too quickly and do not bond to each other. On ejection, these unbonded layers separate, causing delamination. Increasing the mold temperature in 10°F (5.5°C) increments can eliminate the delamination. Once delamination is stopped, a further 10°F (5.5°C) increase is added to compensate for mold thermal fluctuation.
- Foreign material or additives—if a pigment or color concentrate is used to color the resin, it may not be compatible with the base resin. Furthermore, accidental mixing of two incompatible resins results in lack of bonding. In all of these cases, nonbonding of the materials results in delamination of the finished product. Material suppliers can verify the compatibility of additives. Also, properly identifying materials ensures that incompatible materials are not mixed.
- Excessive mold release—it is important to limit the use of mold release. Excessive mold release causes a penetration of molded layers by the release itself. This prevents bonding and results in delamination. Operator training should reinforce the minimal use of mold release.

DISCOLORATION

- Excessive barrel residence time—the time that the plastic material remains in the heated barrel before it is injected into the mold is the residence time. If the shot size is less than 20% of the barrel capacity, degradation of the plastic eventually occurs. This degradation causes a darkening of light-colored materials and a graying effect on dark materials. The shot-to-barrel ratio is optimized by moving the mold to a press in which the shot size is closer to 50%.
- Incorrect mold temperature—a hot mold generally causes the material to stay molten longer and allows the molecules to pack tighter. This results in a very dense part that appears darker due to its density. On the other hand, a cold mold causes a loss in gloss, because the material cools before it is forced against the mold surface; this causes a less dense part, which appears lighter. The mold temperature is adjusted, within the limits of the particular plastic, to the point at which the material yields the proper shade and gloss properties. Note that the color changes slightly after the part has completely cooled.
- Contamination—material may appear discolored if it is contaminated with items such as the wrong regrind, fabric strands, thermally degraded material, or food particles. Also, the entire shot of material is darkened if exposed to excessive temperature. Proper housekeeping minimizes most of this discoloration, and close control of molding temperatures minimizes the rest.
- Inconsistent cycles—erratic cycling creates hot spots in the heating barrel, and the material in these areas may degrade due to overheating. This degraded material does not bond properly with surrounding material particles and can cause weak areas in the molded product; these areas may develop into cracks.

CRAZING
Because crazing is essentially a fine network of cracks, the causes of and remedies for cracking also apply.

Molded-in stresses—stresses are molded into a product by excessive filling rates. The plastic is injected and held against the restraining surfaces of the mold cavities. When the part is ejected, the cooling process continues, and the highly pressured plastic may begin to relieve. If the skin of the molded part is not solid enough, it cracks open. The solution is to reduce the injection pressure and speed to the lowest values that successfully mold the part.

Insufficient draft angle or polish—a minimum draft angle of 1° per side facilitates demolding the part. Ejector pressure can crack parts if lower angles are used. Rough cavity surfaces also cause a part to drag as it ejects. This may cause cracking if the ejection pressure is increased. Proper material drying prior to molding minimizes cracking due to moisture content.

Inconsistent cycles—erratic cycling causes hot spots in the heating barrel, and the material in these areas may degrade due to overheating. This degraded material does not bond properly with surrounding material particles and can cause weak areas in the molded product; these areas may develop into cracks.

Foreign material or additives—if a pigment or color concentrate is used to color the resin, it may not be compatible with the base resin. Furthermore, accidental mixing of two incompatible resins results in lack of bonding. In all of these cases, nonbonding of the materials results in delamination of the finished product. Material suppliers can verify the compatibility of additives. Also, proper identification of materials ensures that incompatible materials are not mixed.

Excessive mold release—it is important to limit the use of mold release. Excessive mold release causes a penetration of molded layers by the release itself. This prevents bonding and results in delamination. Operator training should reinforce the minimal use of mold release.

Inadequate mold supports—components called "support pillars" are used in mold construction to give extra support behind the cavity retainer plates on the ejector half of the mold. These pillars keep the mold from collapsing during injection. If there are too few pillars, or they are not properly designed or located, the mold can deflect when injection pressure is applied. The mold opens slightly, and flash occurs. The use of fewer large-diameter pillars instead of more small-diam-
FLOW LINES

- Low injection pressure—flow lines may result from improperly bonded material. If the injection pressure is too low, the tongues of material that enter the cavity are not packed sufficiently to form smooth layers against the molding surface, and wrinkling can occur. Increasing the injection pressure forces the layers together quickly while they are hot enough to bond tightly.
- Low mold temperature—a hotter mold generally allows the molten plastic to flow farther before cooling and solidifying. This results in a dense part, which has minimal flow lines. Increasing the mold temperature in 10°F (5.5°C) increments, allowing 10 shots for stabilization between adjustments, minimizes flow lines.
- Improper flow rate—a material that is too stiff (that is, with a low melt index) may not flow fast enough to pack the mold before it solidifies, and flow lines result. Following material supplier guidelines, a faster-flowing material will reduce flow lines.
- Inconsistent cycles—erratic cycles cause cold spots to form in the heating barrel. Some material may not reach the proper injection temperature, resulting in a slower flow rate. The slow rate then causes cavity underpacking, which can result in flow lines.

LOW GLOSS

- Low injection pressure—with insufficient injection pressure, the molten material can cool and solidify before it packs against the cavity surfaces. If this occurs, the material does not reproduce the polished mold surface. Increasing the injection pressure forces the material against the mold surface, minimizing flow lines, and duplicates the finish and gloss of the mold.
- Low mold temperature—a hotter mold generally produces a higher surface gloss, because the particles stay molten longer and form a denser product. Increasing the mold temperature improves material flow and better packs the mold, resulting in a higher gloss.
- Improper flow rate—stiffer materials are usually preferred because they impart improved physical properties. However, because these materials flow with more difficulty, they may cool and solidify too quickly, causing underpacking. If that occurs, the surface gloss level is reduced because the material is not packed against the cavity surface. Changing to a higher-flow grade allows the material to be forced against the mold surface, replicating the mold finish and resulting in higher gloss.
- Inconsistent cycles—erratic cycling can cause cold spots in the heating barrel. The material in these areas enters the melt stream and the cavity without proper heating. As a result, poor flow and cavity packing occur. This defect may appear in spots or over the entire product and may fluctuate from cycle to cycle.

JETTING

- Excessive injection speed—an injection speed that is too high causes the molten plastic to form jet streams, instead of the more desirable wide "tongue" of material, as it is forced through the gates. These snake-shaped streams cool independently from the surrounding material and are visible on the molded part surface. Reducing the injection speed allows the plastic flow front to stay together and resist forming the individual streams that cause jetting patterns.
- Improper gate location—if material is injected directly across a flat cavity surface, it slows quickly because of frictional drag and cools before the cavity is properly filled. When this occurs, flow streams can form, and the molded part surface shows a jetting appearance. Relocation or redesign of the gate may be required to stop jetting.
- Improper flow rate—a stiff material may not flow fast enough to enter the cavity at the proper speed. It can break up into streams, causing the jetting appearance. Using a higher-flow-rate material, in some cases with only two to three points additional melt index, can stop the jetting defect.
- Inconsistent cycles—erratic cycling can cause cold spots in the heating barrel; the material in these areas flows more slowly than the surrounding material. The slow areas may not flow fast enough to form the desired tongue shape as the material enters the cavity. Jetting can occur as a result.

KNIT LINES (WELD LINES)

- Low barrel temperature—knit lines are the result of a material flow front that is injected at an obstruction in the mold cavity. The flow front breaks up into two separate fronts and goes around the obstruction. When the two fronts meet on the opposite side of the obstruction, they try to weld together again (knit) and re-form a single front. If the barrel temperature is too low, the material does not retain its heat, and the two fronts cannot knit because the material has begun to solidify. Increasing the barrel temperature allows the melt fronts to stay molten longer and knit properly.
- Low mold temperature—for the reasons previously mentioned, a low mold temperature does not allow the flow fronts to knit again, because the material cools too quickly. Increasing the mold temperature in 10°F (5.5°C) increments can minimize knit lines.
- Improper flow rate—a stiff material cannot knit as well as a free-flowing material, because the stiff material moves more slowly and begins to solidify before the flow fronts are properly knit. Increasing the flow rate by two to three melt index points may provide a proper knit.
- Inconsistent cycles—erratic cycling creates cold spots in the heating barrel. The material from these areas enters the gates more slowly, and the two fronts may not knit because the colder material has begun to solidify.

NONFILL (SHORT SHOTS)

- Insufficient material feed—the most common cause of nonfill is insufficient injection of material into the mold. The amount of material fed to the mold is increased by adjusting the return stroke of the injection screw so that more material is transferred from the hopper system with each screw rotation. This setting is adjusted until there is an additional 0.12–0.25 in. (3–6 mm) of cushion at the front of the injection cylinder.
- Insufficient venting—venting is used to remove trapped air from the closed mold so that molten material can flow into...
every mold section. If the air is not removed, it acts as a bar-
rier to the incoming plastic and does not allow it to fill all
mold sections. To minimize nonfill, runners are vented, and
the parting line is vented to 30% of the cavity perimeter.
Another approach is to use a vacuum system to remove the
cavity air before injecting material.
• Improper flow rate—using a material with an excessively low
melt index may result in the material solidifying before the
cavity is filled. Increasing the flow rate by two to three melt
index points may eliminate nonfill.
• Inconsistent cycles—erratic cycling may cause cold spots in
the heating cylinder, and the material in these areas flows more
slowly than the surrounding material. When the slower mater-
ial enters the cavity, it solidifies more quickly and can result in
nonfill.

EXCESSIVE SHRINKAGE

• High barrel temperature—if the barrel temperature is too high,
the resin absorbs an excessive amount of heat. The heat causes
excessive expansion of the resin molecules and increases the
voided area between these molecules. After injection and upon
cooling, the skin of the molded product solidifies first, and the
remaining resin closes the molecular voids as it cools, pulling
the solidified skin with it. Decreasing the barrel temperature
allows the resin to stay molten without creating excessive void
areas, and normal shrinkage should return. Material suppliers
can supply the appropriate shrinkage data.
• High mold temperature—a hot mold generally causes the ma-
terial to stay molten longer, and the required skin may not form
properly before part ejection. When this occurs, the cooling
material continues to shrink because there is little restraining
skin to control the shrinkage. Decreasing the mold temperature
in 10˚ F (5.5˚ C) increments allows the material to flow and fill
the cavity properly.
• Improper flow rate—a stiff material may not get fully packed
into the cavity. If packing is insufficient, part density is low,
and excessive shrinkage occurs. Increasing the melt index
allows full cavity packing and minimizes excessive shrinkage.
• Early gate opening—if an operator opens the gate too soon,
the cooling plastic may not suffice before the cavity is fully packed. The individual plastic
molecules are then insufficiently packed and can move as the
part cools. While the outer skin of the product may be solid,
the internal sections continue cooling. The molecular move-
ment determines the degree of warpage. By increasing the
injection pressure or time, the cooling molecules are retained
more rigidly until they are solid enough to prevent movement.
• Insufficient injection pressure or time—if too little injection
pressure or time is used, the plastic material cools and solidi-
fies before the cavity is fully packed. The individual plastic
molecules are then insufficiently packed and can move as the
part cools. While the outer skin of the product may be solid,
the internal sections continue cooling. The molecular move-
ment determines the degree of warpage. By increasing the
injection pressure or time, the cooling molecules are retained
more rigidly until they are solid enough to prevent movement.
• Low mold temperature—a hot mold generally causes the ma-
terial to stay molten longer and allows the molecules to
pack more tightly. This results in a denser part, which resists
warpage. Increasing the mold temperature in 10˚ F (5.5˚ C)
increments permits proper flow and mold packing.
• Improper flow rate—stiff materials are favored because they
impart good material properties. However, an excessively stiff

SINK MARKS

• Insufficient injection pressure or time—the injection pressure
must be high enough to move the material into the mold and
force it to fill every part of the cavity until packed solidly.
When properly achieved, this packing ensures that all the resin
molecules are held closely together. In this case, the molecules
do not travel far upon cooling and sink marks are minimized.
If the pressure (or time the pressure is applied) is too low,
excessive voids occur between the molecules, especially in
areas where two walls meet. When the resin cools, these voids
collapse, bringing cooled material into them. Excessive shrink-
age and the resultant sink marks occur. Increasing the injection
pressure in 10% increments can minimize sink marks.
• Excessive rib thickness—ribs are normally designed into a
part to add strength. If the rib thickness is the same as the
adjoining wall thickness, an excessively thick area is created
at the rib/wall junction. This thicker area, which takes longer
to cool, pulls in the cooled and solidified area around it,
resulting in a sink mark. The rib wall should not exceed 60% of the adjoining part wall thickness.
• Excessive use of regrind—regrind is usually received in larger
pellets than virgin material due to the nature of the regrind-
ning process. These larger, inconsistent particles do not nest well
with the virgin particles, and gaps that trap air during the
melting process are formed. This trapped air impedes the
packing ability of the molten plastic. Sink marks may form
where trapped air bubbles exist. A regrind limit of 10–15% may
be necessary.
• Early gate opening—if an operator opens the gate too soon,
the cycle is shortened, and the molten material may not solidi-
fy enough to restrain shrinkage. This can cause sink marks,
especially at wall junctions and around bosses. By reviewing
defects caused by early gate openings, the operator under-
stands the importance of proper gate openings.

SPRAY (SILVER STREAKING)

• High barrel temperature—high barrel temperatures cause the
resin to decompose and carbonize. The charred particles rise
to the resin surface during injection. The result is charred
particles on the part surface fanned out from the gate loca-
tion. Decreasing the barrel temperature allows the plastic to
stay molten without degrading and charring.
• Small gates—gates that are too small cause friction in the plas-
tic flow, and this can cause degradation of the material at that
location. The degraded material enters the cavity and is forced
to the surface in a splay pattern. Removing burrs from gate
areas reduces splay. The gates may be enlarged until their
depth is 50% of the wall thickness that the gate is injecting.
Gate width can be increased until it is as much as ten times the
depth without affecting cycle times.
• Excessive moisture—if the material was not properly dried,
excessive moisture turns to steam as it travels through the heat-
ing barrel. This steam becomes trapped and is carried into the
mold cavity, where it is usually spread across the molding sur-
face. It appears as streaks of silvered char, which is splay.
Drying conditions are critical, and material suppliers have doc-
umented conditions for specific materials and grades.
• Inconsistent cycles—erratic cycling causes hot spots in the
heating barrel. Material becomes degraded in these areas and
may char. These charred particles enter the melt stream and
the cavity, where they are fanned out across the molding sur-
face and appear as splay.

WARPAGE

• Insufficient injection pressure or time—if too little injection
pressure or time is used, the plastic material cools and solidi-
fies before the cavity is fully packed. The individual plastic
molecules are then insufficiently packed and can move as the
part cools. While the outer skin of the product may be solid,
the internal sections continue cooling. The molecular move-
ment determines the degree of warpage. By increasing the
injection pressure or time, the cooling molecules are retained
more rigidly until they are solid enough to prevent movement.
• Insufficient injection pressure or time—if too little injection
pressure or time is used, the plastic material cools and solidi-
fies before the cavity is fully packed. The individual plastic
molecules are then insufficiently packed and can move as the
part cools. While the outer skin of the product may be solid,
the internal sections continue cooling. The molecular move-
ment determines the degree of warpage. By increasing the
injection pressure or time, the cooling molecules are retained
more rigidly until they are solid enough to prevent movement.
• Low mold temperature—a hot mold generally causes the ma-
terial to stay molten longer and allows the molecules to
pack more tightly. This results in a denser part, which resists
warpage. Increasing the mold temperature in 10˚ F (5.5˚ C)
increments permits proper flow and mold packing.
• Improper flow rate—stiff materials are favored because they
impart good material properties. However, an excessively stiff
material may not flow fast enough to pack the mold before it cools and solidifies. Stresses build as the material stretches in an effort to fill the mold. This stretching results in warpage when the part is demolded and the stresses are relieved. A faster-flowing material may be required to eliminated warpage.

- Improper part handling—when the finished parts are demolded, they are warm enough to distort if forces are applied to them. Parts should cool in ambient conditions for at least six cycles before they are packed.

TROUBLESHOOTING TIPS

In the previous sections, note that troubleshooting often focuses on one or two major areas. In the “machine” category, excessive pressure and insufficient pressure cause the majority of the defects. In the “mold” category, mold temperature and gate design are responsible for the majority of defects. In the “material” category, moisture and improper flow rate cause most of the defects. Finally, in the “operator” category, inconsistent cycle is mentioned most frequently.

Successful troubleshooting usually requires making changes to an existing process. These changes may have an immediate effect, but in all cases, the changes also have long-term consequences. This is because the molding process requires time to stabilize after any change is made. There are two general rules to follow when making adjustments to molding parameters:

- Change only one variable at a time.
- Allow a machine to stabilize for 10–20 cycles after any process change is made.

This demonstrates that troubleshooting can be a time-consuming process. The troubleshooter must be objective in analysis, selective in solution, and most of all, patient in activity.

Rules of Thumb

Several rules of thumb are appropriate. Some are the result of scientific research while others evolved through trial and error.

- Back pressure. The initial setting, 50 psi (345 kPa), is increased in 10-psi (69-kPa) increments. A maximum of 500 psi (3447 kPa) is recommended.
- Barrel temperature. The rear zone is the coldest and the front zone is the hottest, in 10˚ F (5.5˚ C) increments.
- Booster time. Booster pressure time is adjusted in 0.1-sec increments. Machine stabilization for two to three cycles between adjustments is required.
- Clamp tonnage. Clamp tonnage requirements are calculated by determining the projected area of the molded part and multiplying that area by approximately 4 tons/in.² (55 MPa). An additional 10% is added for each inch (25 mm) of molded depth, and a 10% safety factor is added.
- Cold slug well. The diameter and depth of a cold slug well are the same dimensions as the largest inside diameter of the sprue bushing.
- Cushion. The most effective cushion depth is 0.12 in. (3 mm). A maximum of 0.25 in. (6 mm) is recommended.

REACTION INJECTION MOLDING

Reaction injection molding (RIM) is a form of injection molding that brings temperature- and ratio-controlled, liquid-reactant streams together under high-pressure impingement mixing to form a polymer directly in the mold. Two liquid reactants (monomers) are mixed as they enter the mold. A chemical reaction produces the plastic as it forms the part.
CHAPTER 6

REACTION INJECTION MOLDING

When compared to other molding systems, RIM offers more design flexibility, lower energy requirements, lower pressures, lower tooling costs, and lower capital investment. Significant advantages in design and production are gained from the RIM-fabricating capability for incorporating a load-bearing, structural skin and a lightweight, rigid, cellular core into a part in one processing operation.

While initial RIM applications were primarily automotive, nonautomotive uses are increasing in industrial, business, and consumer-product applications. Recent production applications include business machine cabinets and vacuum cleaner housing. Thermosetting polyurethanes are the most common RIM materials. Recently, however, successful development and testing programs on other plastics, such as nylon and epoxies, has led to RIM production usage of these materials. Table 6-9 compares the properties of various RIM materials systems.

RIM ADVANTAGES

Where RIM polymer physical properties are suited for an application, a comparison of RIM to conventional injection molding and sheet molding compound (SMC), discussed later in this chapter, reveals advantages to using RIM.

Design Freedom

With RIM, the designer has exceptional freedom. Parts can be complex and large, and produced without molded-in stresses. Inserts are easily incorporated. Properly designed RIM parts can include ribs, bosses, cutouts, and attaching ears as well as a variety of cross-sectional thicknesses without sink marks. For flexible RIM with 25–50 ksi (172–345 MPa) flexural modulus, undercuts are attainable on visible surfaces.

Low Pressures

Pressures within the RIM mold are 50–100 psi (345–689 kPa) and require correspondingly low clamp capacities—about 100 lb (45 kg) for each square inch of projected part area (114 kg for each square centimeter), or about 3–5% of the clamp force required for injection molding or SMC.

Low Energy Requirements

For RIM, the connected horsepower is about 25% of the power required for injection molding, and the percentage of time the maximum horsepower is required during an average cycle is about 25% of that for injection molding.

Lower Capital Investment

Reaction injection molding equipment requires lower capital investment for mixers, clamps, presses, and molds compared to other systems. The cost of RIM machinery is about one-third to one-half that of injection molding machinery for a given part size and is considerably lower than that of SMC machinery.

Lower Tooling Costs

Low molding pressures allow the use of less expensive tooling, because lightweight, easily machined materials are used. However, the mold must produce the required finish, since the RIM process precisely duplicates the mold surface. Reaction injection molding allows prototyping and low-volume applications with low-cost molds.

RIM LIMITATIONS

Reaction injection molding applications are limited by the availability and properties of materials suitable for the process. Originally, RIM materials were primarily polyurethanes. However, recent commercial availability of suitable epoxy and nylon formulations is broadening the potential for RIM applications. Relatively long cycle time, low production rates, and limited applicability are the other principal drawbacks of the RIM method. Progress is occurring rapidly, however, and developments in methods, materials, and equipment may eliminate the need for postcuring and mold spraying in the RIM process, thereby making it faster and more versatile.

RIM MATERIALS AND APPLICATIONS

Urethanes currently dominate commercial RIM production and can be formulated to produce a wide range of densities, flexible or rigid, from low-density foam to rigid structural foam and from low- to high-modulus elastomers.

Reaction injection molding urethane elastomers provide design freedom combining damage resistance, corrosion resistance, and parts consolidation with large and complex shapes. Current automotive applications include front and rear fascias, bumpers, fenders, and spoilers. Other transportation uses of urethane RIM products include bus bumpers, truck fender extensions, and interior trim panels.

Nonautomotive urethane RIM applications are increasing and include electronic equipment enclosures; recreation items; shoes; and products for the construction, furniture, agriculture, and appliance fields. Specific product applications include hay rollers, tractor grilles and cab roofs, water-bed frames, tennis backboards, window

<table>
<thead>
<tr>
<th>Property</th>
<th>Urethane Rigid Structural Foam 0.5 in. (13 mm) Thick</th>
<th>Urethane* Low-Modulus Elastomer</th>
<th>Urethane* High-Modulus Elastomer</th>
<th>Nylon 6* High-Modulus</th>
<th>Epoxy* High-Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, lb/ft³ (kg/m³)</td>
<td>37 (593)</td>
<td>62 (993)</td>
<td>62 (993)</td>
<td>71 (1137)</td>
<td>69 (1105)</td>
</tr>
<tr>
<td>Tensile strength, psi (MPa)</td>
<td>3400 (23.4)</td>
<td>3200 (22.1)</td>
<td>4650 (32.1)</td>
<td>6000 (41.4)</td>
<td>10,000 (69.0)</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>&lt;5</td>
<td>235</td>
<td>105</td>
<td>250</td>
<td>6</td>
</tr>
<tr>
<td>Flexural modulus, ksi (MPa)</td>
<td>160 (1103)</td>
<td>34 (234)</td>
<td>120 (827)</td>
<td>115 (793)</td>
<td>398 (2744)</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, 10⁻⁶ in./in./°F</td>
<td>—</td>
<td>—</td>
<td>60</td>
<td>70</td>
<td>31</td>
</tr>
<tr>
<td>(10⁻⁶ mm/mm/°C)</td>
<td>—</td>
<td>—</td>
<td>(108)</td>
<td>(126)</td>
<td>(56)</td>
</tr>
</tbody>
</table>

0.12 in. (3 mm) thick
frames, office furniture, work surfaces, and lawn and garden equipment housings.

**Urethane Development**

Commercially available RIM machinery that processes materials at a higher temperature increases urethane versatility. Material suppliers are seeking superior urethane properties, such as formulations that can withstand 325˚ F (163˚ C) automotive paint ovens, while retaining damage resistance. Such formulations could involve solid components such as pure diphenylmethane diisocyanate (MDI), which is solid at room temperature and melts at 100˚ F (38˚ C), and solid chain extenders such as hydroquinone di (beta-hydroxyethyl) ether (HQEE). Higher processing temperatures can also reduce urethane viscosities to shoot onto wet fibrous mat inserts.

**Nylon RIM**

Nylon (caprolactam polymerization) for RIM is commercially available and has potential for automotive applications and agricultural, appliance, electronic enclosure, and other nonautomotive applications. (Reaction injection molding machinery to process nylon is commercially available.)

**Epoxies**

Epoxies are available for RIM production applications. Potential applications are high-performance, large-size structural parts, including sheet metal replacement in the automotive and appliance industries. Epoxies for RIM can achieve high structural and impact strength by shooting over a continuous fiber mat in a closed mold. (Reaction injection molding machinery to process epoxies is commercially available.)

**Polyesters**

Polyester plastics, with the improved material properties needed to compete with alternative RIM materials, are being developed.

**Reinforced RIM**

Reinforcement and filler additions make stiffer, more heat-resistant parts that are less sensitive to temperature changes and have significantly reduced coefficients of thermal expansion. Table 6-10 compares properties of reinforced reaction injection molding (RRIM) systems.

The greatest interest has been in applications using 0.06 in. (1.6 mm) milled glass fibers, a fiber length that provides the best reinforcing properties consistent with reliable production. Since fiber orientation can be a problem, attention has turned to flake glass because of its isotropic properties. When added to the reactant monomers, the flake glass increases viscosity and imposes a high abrasive load on machine parts through which the filled components flow. Flake glass is significantly more abrasive than milled glass fibers.

**RIM PROCESS**

To produce quality plastics parts, the reaction injection molding machine and the RIM system must accurately control material conditioning, temperature, metering rates, mix ratio, and injection pressures. The basic components of a RIM processing system are shown in Fig. 6-34. Typical RIM processing parameters for various materials are listed in Table 6-11.

**Elements of the Process**

Elements of the RIM process include the material supply, injection, and mixing.

Material supply. The material supply system includes monomer conditioning (feed) tanks, with agitators and heat exchangers for temperature control, and low-pressure recirculation pumps for constant flow from the tanks to the mixhead supply lines.

Injection. The injection system delivers the preconditioned reactant monomers to the mixheads at controlled pressures and ratios using lance displacement of the liquid in a high-pressure cylinder. An alternate approach uses high-pressure, variable-displacement pumps.

Mixing. The mixhead is mounted directly to the mold and contains the small, cylindrical mixing chamber in which the reactive streams undergo thorough blending through high-pressure impingement mixing. The streams enter the mixing chamber from precise orifices while the shot is being made. A piston cleans the mixing chamber after the shot is completed. This method eliminates the solvent flush required with mechanical mixing devices.

**Mold Considerations**

The type of mold material, mold filling, and mold carriers affect RIM molding.

Mold material. The mold can be made from steel, aluminum, epoxy-reinforced nickel, Kirksite, or epoxy (in descending order of durability). Reinforced epoxy and sprayed metal molds offer a low-

<table>
<thead>
<tr>
<th>Property</th>
<th>Urethane High-modulus Elastomer</th>
<th>Nylon 6</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass content, %</td>
<td>23*</td>
<td>25*</td>
<td>45–52**</td>
</tr>
<tr>
<td>Tensile strength, psi</td>
<td>6490 (44.7)</td>
<td>7580 (52.3)</td>
<td>28,000–44,000 (193–303)</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>37</td>
<td>13</td>
<td>2.4</td>
</tr>
<tr>
<td>Flexural modulus, ksi</td>
<td>380 (2620)</td>
<td>275 (1896)</td>
<td>2600–3700 (17,926–25,510)</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, *** 10^-6 in./in./˚ F</td>
<td>25 (10^-6 mm/mm/˚ C) 29</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

* 0.06 in. (1.6 mm) milled glass
** Continuous glass
*** Parallel to fibers
cost option for prototyping and low-volume RIM applications. The importance of mold surface temperature control varies with the RIM material and the mold material. These parameters directly affect part shrinkage.

Mold filling. Mold filling occurs as the mixture flows from the mixing chamber at greatly reduced pressure. The mold is equipped with a simple static aftermixer (to ensure thorough mixing of reactants), a runner, and a gate. The cross-sectional area of the runner and gate is designed to ensure laminar flow into the mold at a rate of approximately 3–9 ft/sec (0.9–2.7 m/sec). Turbulent flow causes undesirable air bubble entrainment in the molded part. Controlled venting of the mold is essential to avoid trapped air. A range of mold release sprays is available for the urethane RIM process for easier part removal. Development programs for internal mold release technology, that focus on significantly reducing mold spraying and cycle time by as much as 50%, are in process.

Mold carrier. The mold carrier units (clamp, press, etc.) provide mold clamping and opening functions, including positioning movements in some cases to present the mold to the operator. Mold carriers can also be the vertical-pillar press type, or they can be self-contained molds.

**Areas of Progress**

In addition to the increase in varieties of plastics materials that are suitable for reaction injection molding, other major developments are fostering rapid growth for the RIM process. Advancements in internal mold release agents are leading to significant reductions in cycle time. Fast-cycling RIM is no longer limited to amine extended systems. Greatly improved conventional glycol-extended systems are now competitive with the amines. Light-stable RIM materials now simplify the coloring of RIM parts and eliminate the need for painting and finishing. Furthermore, the new nylon RIM resins with improved dimensional stability broaden the applications for RIM.²

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**TABLE 6-11**

**Typical RIM Processing Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Urethane</th>
<th>Nylon 6</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing temperature</td>
<td>90–120°F</td>
<td>160–265°F</td>
<td>100–160°F</td>
</tr>
<tr>
<td>(°C)</td>
<td>(32–49)</td>
<td>(71–129)</td>
<td>(38–71)</td>
</tr>
<tr>
<td>Mold temperature</td>
<td>150–200°F</td>
<td>265–280°F</td>
<td>200–300°F</td>
</tr>
<tr>
<td>(°C)</td>
<td>(66–93)</td>
<td>(129–138)</td>
<td>(93–149)</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>1500–3000 psi</td>
<td>200–800 psi</td>
<td>500–1500 psi</td>
</tr>
<tr>
<td>(MPa)</td>
<td>(10.3–20.7)</td>
<td>(1.4–5.5)</td>
<td>(3.5–10.3)</td>
</tr>
</tbody>
</table>

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Fig. 6-34 Basic elements of the reaction injection molding process. (Courtesy Modern Plastics Encyclopedia)
The structural foam (SF) molding process is an offshoot of conventional injection molding for solid-wall parts; however, SF parts are rigid and foamed, having a cellular core and an integral solid skin. Some advantages of SF molding are as follows:

- The SF process is used to mold very large, heavy parts that are not feasible or cannot be economically produced by other processes.
- Molded parts are free from stresses as well as the warp and sink marks typical of solid, heavy-walled parts made with the standard injection molding process. This is the result of a low in-mold pressure.
- The rigidity of SF molded parts is three to four times that of equal-weight parts made with standard injection molding.
- Molded parts have a strength-to-weight ratio that is two to five times better than that of metal parts.
- Molds are cheaper. Because a low-pressure system is used, the molds are usually made of aluminum.

The major disadvantage of SF molding is that the part surface has a swirled, mother-of-pearl pattern caused by the blowing agent used to create the cellular core. This pattern is about 90% visual and 10% physical—extremely fine irregular grooves exist. These characteristics are tolerated on products such as material handling devices, leisure items, outdoor consumer products, and some automotive and building products. However, this swirl pattern is not desirable on products such as highly visible in-house consumer products, business machine housings, and some automotive and building parts. This appearance factor has restricted the acceptance of SF molding in some markets.

**MATERIALS**

In theory, any thermoplastic can be molded into a structural foam part. However, there are practical limits. The most common SF machines are two-stage designs. Because of their design, the hot-melt flow path is about 10 ft (3 m) rather than the 10 in. (254 mm) used in converted conventional machines. Because of this length, the melt is conveyed through the machine at about a 40–50°F (22–28°C) higher temperature; this in turn limits the types of resins that are molded.

The three commodity resins—polyethylene (PE), polypropylene (PP), and polystyrene (PS)—account for about 75% by weight of all moldings used in SF machines. Historically, SF parts were designed with 0.25 in. (6 mm) thick walls. Although this remains the most common thickness, some parts are also molded at 0.19 in. (4.8 mm) thickness.

**MACHINES**

Virtually any standard injection molding machine can be retrofitted for SF molding; it can then mold both conventional and SF parts. This is accomplished by using a shutoff nozzle, which interrupts or minimizes the foaming action in the extruder. The limitations of this approach are that only relatively small parts can be molded and only one nozzle is available.

The most common SF machines are two-stage designs. The output of the extruder is delivered to an accumulator set to accept a precise shot. At the injection stage, a ram behind the accumulator forces the shot through a manifold that services a number of nozzles, which in turn directs the shot into the tooling. The system is known as multiple-nozzle, low-pressure SF molding. Low pressure is categorized as an injection pressure that is about 10% of conventional injection molding with a resultant mold pressure of about 400 psi (2.8 MPa). The most common machines feature 50–1,000 ton (0.45–9.0 MN) clamp force, and the most common sizes range from 300–400 ton (2.7–3.6 MN).

Because SF molding is a low-pressure process, very large parts can be produced. For example, a typical 1,000-ton (9-MN) machine has a platen that is 150 × 100 in. (3.8 × 2.5 m), with a shot capability of 175 lb (79 kg).

One benefit of a multinozzle, low-pressure SF machine is the capability of filling more than one cavity or mold at a time. Grouping molds on a single platen increases molding productivity by producing multiple and dissimilar parts per cycle on the same machine.

Balancing the shot size between the cavities is accomplished by individual throttling valves at each nozzle, and material is distributed between mold cavities of different shot size requirements. It is common to run four to six molds in one multinozzle platen and service these molds with one shot via the injection accumulator. The shot size variation between these molds can range from a few ounces to many pounds. On the other hand, a single giant part, where the tooling virtually covers the platen and several nozzles are necessary, can be molded.

**MINIMIZING SWIRL PATTERNS**

Vapor polishing was developed to minimize swirl patterns. It involves passing the part through a vapor cloud that exists over a tank holding a heated solvent. The solvent is a type that normally attacks the resin. Exposure time of only a few seconds is needed. Complete immersion is also effective.

Masking or hiding the swirl pattern is done by the secondary operation of painting. Two to three coats are often needed to cover the swirl pattern for items such as SF molded furniture parts and business machine housings. A deterrent to this approach is the need to allow several days after molding for the gas to bleed out of the part to avoid paint blisters. More recently, however, chemical blowing agents have eliminated this aging requirement.

In recent years, several technical approaches were developed to minimize or eliminate swirls by revising the molds and molding equipment. The major ones are as follows:

**Rapid Injection**

The mold shot is made in 0.1–0.3 seconds. The technique is possible only with single-nozzle, conventional-type, high-pressure machines. Molded parts still need one or more coats of paint.

**Heated Molds**

This technique calls for circulating warm to hot water through the mold cooling channels to provide a warm surface to the cavity. The resultant molded part has an improved swirl pattern; however, it still needs painting. In addition, the overall machine cycle is considerably longer, because more time is required before the part is cool enough to demold.

**Expanding Molds**

This is applicable only to high-pressure, fast-injecting machines. A steel mold, featuring a third component plate, is required. Injection occurs when the mold is "collapsed" and the clamping pres-
sure is relaxed to allow this third plate to "appear" and create the full cavity configuration. This relieves the pressure on the blowing agent, and it can expand to generate the cellular core. A solid, smooth skin results, and no painting is required unless so specified. The process is limited to relatively smaller and simpler designs, and it is not practical to convert existing molds. New molds cost 20–40% more than low-pressure aluminum molds.

Coinjection
In coinjection, the machine has two extruders. One plasticizes the skin material and the other contains the core material with the blowing agent. The materials are injected simultaneously and stay separate in the mold. No painting is necessary. However, the process works best for shallow, simple designs; a multitude of flow directions causes turbulence and the core material may break through the skin material, causing surface blemishes.

Mold Counterpressure
With mold counterpressure, all mold components must have O-rings or gaskets to make them airtight. A positive pressure buildup in the cavity prior to injection is necessary. This presents a flow resistance to the injecting material, preventing the blowing agent from expanding. The positive pressure is programmed to gradually reduce as injection is completed. When the shot is completely in the cavity and the pressure cycle is completed, an expansion of the blowing agent occurs, resulting in a solid smooth surface. One coat of paint may be required, and the mold cost is 10–20% higher. The part weight is 10–20% greater because a thicker skin is usually generated. The process is suitable for most small- and medium-sized parts but not practical for large, intricate parts.

RUNNERLESS MOLDING

Runnerless molding is not new; however, there is some confusion regarding runnerless versus sprueless molding. This description of the available systems can help determine the correct system for specific applications.

CATEGORIES OF RUNNERLESS MOLDING
Runnerless molding systems (RMS) generally fall into four main categories: externally heated, valve gate, internally heated, and insulated runner. While there are some systems that combine features from each type, knowing the advantages and disadvantages of each is important. Furthermore, there are subcategories within each type. Runnerless and sprueless systems are designed to eliminate much or all of the runners and sprues that create regrind, cause excessive mold opening distances to clear the sprue, reduce the injection pressure/velocity available to mold parts and, in most cases, extend the overall molding cycle because the runner and sprue often have the thickest cross section.

Most RMS are designed to run automatically, thereby eliminating secondary operations such as clipping sprues and runners; regrinding, storing, or discarding the regrind; grinder maintenance; and extra personnel. The processor can also inventory less material since runners and sprues account for a significant portion of the shot weight. This reduces the cost per part and makes this molding method an attractive alternative to cold runner systems, particularly in long production runs where the increased initial tooling investment is readily amortized.

Externally Heated Systems
Externally heated systems, commonly referred to as hot manifold systems, are systems in which the heat source surrounds the entire melt flow (see Fig. 6-35). They are popular with designers,
tooling shops, and processors. Some advantages of the externally heated system are as follows:

- Eliminates zero-velocity or "hang up" areas, where material can reside, degrade, and cross-link.
- Provides direct flow to the mold cavities, which is important when dealing with highly viscous, shear-sensitive materials.
- Reduces molded-in stress and material orientation because of the reduced resistance to material flow. This is especially true in modern systems where generous radii are provided in the melt flow path.
- Systems are purchased from many reputable manufacturers with many engineering and support services available.
- Easy to change colors, change materials of similar melt temperatures, and clean out degraded material.
- Excellent compatibility with shear-sensitive and filled materials.

Large orifice openings are available to properly fill the part and reduce the heat rise, which can cause gate blush and melt degradation.

Disadvantages of externally heated systems are as follows:

- Sizable energy losses because of heat dissipation to the atmosphere from the heated manifold block.
- Difficulties in sizing to the mold base because of thermal expansion. This can lead to material leakage, galling, and wear of internal mold components.
- Difficult to change materials of dissimilar melt temperatures due to thermal expansion and, therefore, the matching of the manifold to the mold base.
- Specialized application engineering required.
- Slow start-up period because it is necessary to bring the entire heated manifold and "drops" up to the required melt temperature. Much of this energy is lost to the atmosphere.
- Difficult to mold cosmetic gates without resorting to pin or valve gates that are expensive and may have other associated problems.

Valve Gate Systems

Valve-gated systems are essentially externally heated systems. They have, in addition to the manifold and nozzles, either pneumatic or hydraulic cylinders over each nozzle (see Fig. 6-36). These cylinders operate valve "pins" that extend through a seal on the top of the manifold and through the nozzle, and shut off at the nozzle tip. Most valve gate systems are designed for all the valves to operate simultaneously, which, if the all cavities are identical, demands a "balanced flow" manifold system. Some valve gate systems are designed for independent valve operation, thereby allowing change of the fill pattern. This permits moving knit lines to more favorable locations.

The following advantages apply to valve gate systems:

- Fast fill due to large gate size.
- Low shear due to large gate size.
- Less blush on gate areas due to less frozen material in the gate area.
- Fast cycling because no holding time is required as gate shutoff is positive. Thus, screw recovery can begin earlier. Because of the large gate size, injection time may be reduced.

The following disadvantages apply to valve gate systems:

- Higher initial cost.
- Higher wear because of moving parts and mechanical seals.
- Higher maintenance cost than static systems.

Internally Heated Systems

The internally heated system, also known as the distributor tube system, is one in which the melt flows around the heat source (see Fig. 6-37). The internally heated system relies on an insulating layer of material in the inside diameter of a bore that is located in the mold plate. Centered in this bore is a distributor tube, held in place at both ends, with an internal cartridge heater. The probe drops follow the same design as the large distributor tubes. This insulating layer keeps the heat in the melt flow and the surrounding coolness from the mold base out. It is this residing insulating layer of material, and its potential for degradation, that causes concern when choosing the internal system for engineering materials that are sensitive to prolonged residence times. This is a mature type of system, and it has gained widespread use, especially in the commodity resin molding community. Advantages are as follows:

- A very energy-efficient system, because only a small percentage of the material is heated and only that portion of the material flows. The remainder of the material acts as an insulator.
- Very fast start-up period.
- Simplified tool design and construction, because the mold base remains cool, typically about 100°F (38°C). There is little thermal expansion to contend with.
- Can be purchased from many reputable sources with engineering and support services available.
- Lends itself to commodity materials and cosmetic gate applications.

Disadvantages of internally heated systems are:

- Color changes are extremely difficult and, in some cases, impossible without dismantling and cleaning the system; this can lead to damaged components.
- Contains zero-velocity or "hang up" areas, where some materials may degrade or cross-link due to extended residence time.
at elevated temperatures. Such reactions may cause material to back up into the system and clog the flow paths. This material may also break off and contaminate the part (causing black specks).

- Materials are forced to orient and undergo high shear because of narrowed flow paths. This is an important factor when molding shear-sensitive materials, and one that may lead to high molded-in product stresses.
- Small orifice openings and splitting the melt flow around the probes cause melt shearing and heat rise that can damage some materials.
- Difficult to mold filled material due to the impinging of the material on internal components; this leads to their premature failure. Also, in some cases, the filler material can separate from the matrix and "pool" in the flow paths, causing difficult start-ups.
- Very high plastic injection forces can bend the distributor tubes, causing premature system failure.

**Insulated Runner System**

There are two styles of insulated runner systems, the cold block and the heated block. The heated block design is a hybrid of the internally heated system, with the heaters, in some cases, only used during start-up or freeze-up. This discussion focuses on the cold block. The oldest of the runnerless systems, it relies on an oversized bore in the mold plate that is filled with plastic material. The insulating quality of the plastic material forms a skin on the outer diameter of the bore and keeps the core material molten for a short time. This molten core is replenished by each succeeding shot (see Fig. 6-38). This system is still used for commodity materials. It has many associated drawbacks, which the other newer systems attempt to rectify. Following are some of the advantages of the insulated runner system:

- Lowest energy consumption of all the systems.
- A basic system that is understood by most molding shops.
- Easy to make color and material changes. Also, degraded material is easily removed.
- Due to the lack of auxiliary heat in the manifold, mold design and building are simplified.

Disadvantages of the insulated runner system are as follows:

- Any extended pause in the molding cycle causes the molten core to solidify. The solid runner must then be removed by partially disassembling the tool and removing the cull. This large mass of material is then discarded.
- Difficult system to start up and keep running.
- Has most of the disadvantages of the internally heated molding systems.
- Is not recommended for most engineering-grade materials. It is also not recommended for filled materials.

**SPRUELESS MOLDING**

Sprueless molding, which means eliminating all or part of the sprue, follows the same advantages and disadvantages of the runnerless systems. Most heated bushings resemble a section of pipe with heater bands wrapped around it (see Fig. 6-39). The melt flows through the center, but it is difficult to achieve a cosmetic gate with this type. Others have "torpedoes" in the center of the pipe that force the material to separate and rejoin before going through the smaller gate orifice. They are generally used where
good gate cosmetics are required. An extended nozzle, while not a heated sprue bushing, also aids in reducing the cold sprue length.

**NONTRADITIONAL TECHNOLOGIES**

**GAS-ASSIST INJECTION MOLDING WITH NITROGEN**

**Process Basics**

Gas-assist injection molding is a process enhancement to conventional injection molding that involves injecting high-pressure nitrogen gas into the melt stream immediately after injection of the resin. The intent is not to cause mixture of the nitrogen and resin but for the nitrogen to displace resin in thicker sections of the molded product.

The process is a low-pressure injection method, enabled by "short shooting" the tool and completing fill by using pressurized nitrogen at much lower pressures than conventional molding. The primary considerations for successfully applying the technology are control of the nitrogen injection time and pressure, and sequence and shot control of the molding machine.

**Reasons to Use Gas-assist**

The prime reasons to use gas-assist injection molding are to improve productivity, produce higher-quality parts, and expand design options not previously available for injection molded products.

Reduced cycle times. Reduced cycle times are a process benefit for several reasons. The most significant are the elimination of high-pressure injection in the tool and the elimination of thick molded part sections that retain heat. Low-pressure injection is realized because, in virtually all applications, the tool is only partially filled. After the partial filling, the injection barrel is isolated (to prevent nitrogen from entering the barrel and contaminating the resin), and nitrogen is injected into the part, displacing the hotter resin in flow channels and thicker part sections. The displaced resin completes the filling under pressures not exceeding 1000 psi (6.9 MPa), far lower than "pack-out" pressures experienced in conventional molding.

Because high injection pressures are unnecessary and thicker sections are now hollow, cycle times are reduced by shorter cooling times and no need to pack the part with injection pressures. Any pressure hold is maintained with the gas pressure, allowing the injection screw to return for the next shot.

Reduced part weight. Part weight reduction is accomplished by two methods. The most frequent way to reduce weight is through mass reduction in heavy sections and bosses, and at the intersection of ribs. This is further facilitated by actually making bosses and ribs heavier than those in conventional molding to enhance strength, and removing the resin in those areas to form hollow sections while improving the part’s structural integrity. In structural foam applications, the nominal wall thickness is reduced, and with the addition of gas channels, parts have a rigidity similar to their structural foam predecessors.

Expanded design options. Molded products are no longer restricted to the confining parameters of boss and rib size relative to wall thickness. Conventional injection molding techniques have many restrictions that frequently inhibit or disallow design options. With gas-assist injection molding, many of those concerns are eliminated or modified. Heavy ribs and bosses are not only acceptable, but are often necessary to facilitate the process.

Gas channels are used first as flow channels and become, after gas injection, gas channels. These channels, designed into the part to facilitate the process, ultimately improve product strength as well as the process. The flow channels also frequently eliminate the need for hot runners because they allow increased flow lengths. Tubular heating sources of information, however, are the system manufacturers.

**CONCLUSIONS**

Runnerless/sprueless systems are expensive, but cost is only one factor that is considered. A typical system adds 15–20% to the cost of the tool, depending on whether controllers are needed and the type of controller that is required. Because of the many advantages that have been discussed, a typical processor could realize savings in the range of 30–60%. Since profit is the primary motivator in the molding industry, a good system, if the added cost is readily amortized, is an attractive option. Also, many processors are using them for competitiveness in both cost per part and technology. Another consideration, especially when molding engineering materials, is the elimination of long flow paths, which can deplete the pressure/velocity needed to properly mold a part.

The technology of runnerless/sprueless molding is rapidly changing, especially with the advent of solid-state controllers. The best sources of information, however, are the system manufacturers.
sections are often designed into the product and consequently eliminate tool undercuts and lifters. This is another added feature, because tooling costs are lowered by reducing tool complexity. Clamp tonnage is seldom a consideration, because the criteria for machine size is not clamp pressure, but mold and shot size. Tools may run in molding machines smaller than those used for conventional molding, and with less tool action, tools for larger parts often fit in smaller molding machines.

Enhanced part strength. As previously noted, tubular and hollow part sections create a geometry that gives greater structural strength to the product.

Higher-quality parts. Part size repeatability and scrap reduction are other benefits of the gas-assist process. With shot size control, molded products are more uniform in size, because molded-in stresses due to pack-out pressures are eliminated. When stresses are present, the molded product tries to return to a condition other than the molded configuration after cooling. Due to the low-pressure nature of gas-assist molding and minimal pack-out pressures with only the nitrogen gas, stress is eliminated, and shot-to-shot sizes are maintained. Postmolding warpage is therefore eliminated.

Molding Machine Requirements

Gas-assist injection molding requires no special adaptation or modifications to a molding machine. The only requirement is control of shot size, because the volume of the gas channels and hollow product areas is controlled by the short shot, not by the gas pressure or volume.

Tooling Considerations

New tooling. New tooling considerations involve several items that are not part of conventional tooling design. Input is necessary to determine the gas channel location and shape and for design advice regarding ribs, bosses, and heavy part sections. Most often, tool design is simpler than that for conventional injection molding, as the part design constraints are fewer.

When injecting through the nozzle, gating size and location are important, and simplicity is the key. A single gate is preferred in most parts. Flow/gas channel feed to ribs, bosses, and heavy sections requires input from experienced gas-assist engineers or molders. Note that a hot runner is not used when injecting nitrogen through the sprue. This does, however, allow reduced tooling costs. Furthermore, no mechanical additions to an injection mold are required to facilitate gas injection, unless injecting through pins in the tool.

Converting existing tooling. Existing tooling is easily converted to gas-assist injection, provided the basic part design is conducive to the process. As previously mentioned, nitrogen cannot be injected through a hot runner. A tool with a hot runner has two options: (a) inject gas through pins in the tool or (b) modify the tool to eliminate the hot runner and revise the gating method. Gas channels may be required to facilitate the flow of gas channels and to flow gas to the required areas. The channels would lead to areas of intersecting ribs, under heavy bosses, and to any additional areas that would benefit from a gas channel.

Spillovers

Spillovers are pockets cut into an injection mold, outside the cavity area, that are used to receive “spilled over” resin from the cavity during gas injection. The spilolver is used for the following:

- A spilolver can be used to create a complete, circular gas channel, with the channels meeting, joining, and extending into the spilolver. This is the method used to join two channels in a molded part.
- A spilolver is used to eliminate hesitation lines or undesirable surface appearances in a product by displacing the resin that includes those characteristics into the spilolver, rather than having it remain in the molded product.

Product Applications

Part strength and rigidity. Structural integrity and part stiffness are major considerations for conversion to gas-assist. Relatively flat, thin-wall parts are made rigid by adding a gas channel around the periphery. The only change to the part is the channel, with a single gate feeding the channel. The part is made with a short shot, and the flow/gas channel fills with resin as well as 80–90% of the remainder of the cavity. Note that the cavity, in this example, is never completely filled with resin. Resin in the channel is displaced to fill the unfilled sections under low pressure. The peripheral channel is a tubular section, which significantly increases part rigidity, while low pressures facilitate a stress-free part and reduce cycle time.

Long flow lengths. Long flow lengths are accomplished in gas injection in the following manner. A common example is a front fascia molding that is approximately 6 ft (1.8 m) long and 3 ft (0.9 m) wide, with a 0.100 in. (2.5 mm) nominal wall thickness. The example part is molded with one gate in the center of the part, using a gate diameter of approximately 0.150 in. (3.8 mm). This may appear nearly impossible to fill, and if accomplished, it would result in a stressed and warped molded part. However, at the front edge of the molding, there is a flow/gas channel approximately 0.180 in. (4.6 mm) in diameter. At the time of short shot injection, the melt fills approximately 80% of the cavity, including the flow/gas channel. At the point of gas injection, the gas displaces the resin in the channel, completing the filling of the thin-wall molding section. The flow length, under any pressure, is effectively 3 in. (76 mm), not 36 in. (914 mm), as the final filling of the thin-wall section is from the flow channel, not from an adjacent thin-wall cavity area. Consequently, the part is molded under minimal pressures, stress and warp are eliminated, and close-dimensional tolerances are held.

Heavy and problem ribs and bosses. The natural tendency of the pressurized gas is to flow to the path of least resistance. This area is where the resin is the thickest, and consequently the most fluid, as heat is retained in the heavier sections. Correspondingly, gas channels are directed to locations under bosses and intersecting ribs. Because nitrogen evacuates the resin in the thicker areas, sink marks are eliminated, and a thick section of the resin no longer exists to shrink. Furthermore, the nitrogen pressure is held on all internal hollow sections, thereby retaining pressure at the cavity walls. This further facilitates shorter cooling cycles.

Structural foam products. Structural foam products frequently have the highest-available per-part cost reductions, because wall thickness can be significantly reduced with minor tooling modifications on existing products. This is accomplished by strategically locating gas channels to increase part strength in thin-wall parts. Cycle times are reduced from 180 sec–6 min to 70–80 sec, depending on part size. Existing tools, without wall thickness modification, can often use gas-assist by eliminating all but one central sprue and by proper guidance of gas channels. A uniform,
flat, thick-wall part is not conducive to this process, but a part with a differential in wall thickness to flow/gas channels and intersecting ribs is often a candidate.

Disadvantages. There are no disadvantages to processing with gas-assist, although it is not recommended in a few circumstances. Resins with very high melt flow indexes should not be used, because they displace too easily in the tool to allow the gas to seek the thicker cavity sections. Gas could permeate the thinner sections, resulting in weakened parts. This is easily overcome if the base resin is available with a lower melt index.

As previously mentioned, the gas cannot be injected through a hot runner.

Gas injection is also not recommended where there is a relatively thin, uniform wall without gas channels. In a part without the differential of nominal wall thickness to flow/gas channel thickness, it is impossible to properly direct the gas flow.

**Product Considerations**

Resin selection. Problems have only occurred in base resins with high melt flow indexes. Reinforced materials are not detrimental to the process but rather facilitate the injected gas flow through the channels and heavy sections.

Melt flow indexes. High-melt-flow indexes are avoided or changed, as previously noted. These high-index materials are generally selected when cavity filling is a problem; however, with gas injection and proper channel design, the cavity fills well, and resins are switched to those with lower melt flow indexes.

Reinforced materials. Gas-assist injection molding is successfully applied to parts molded with up to 50% reinforcement by weight. Reinforcement materials are fiberglass, calcium, talc, and combinations of these.

Part design. Part design is not encumbered by the gas-assist process. Many of the rules for rib, boss, and heavy-part sections are relaxed. The keys to successful gas-assist molding are short-shot uniformity, gas injection pressure and time control, and careful design and location of the thickness differentials for proper gas flow. Gas channels leading from the gate in two different directions are generally acceptable, as long as they phase out distant from each other. The distance depends on the nominal wall thickness and gas channel size. Thick tubular sections can be molded. Parts with the geometry of shovel handles and baseball bats are successfully molded with gas-assist.

Gating methods. Gating is kept simple. Frequently, tools with five to ten drops, such as in many television cabinets, are reduced to one or two drops, each leading to a gas channel. Multiple gating locations can lead to opposing gas channels, and this practice is not recommended.

Gas channel design. The ideal gas channel is spherical, although this is usually impractical. Most channels, when designed properly, become hemispherical. The channel is two to three times the nominal wall thickness. Smaller channels do not allow the resin to reach the flow channel or provide the necessary reservoir for eventual evacuation. Significantly larger flow/gas channels are not recommended. Larger channels result in retaining more resin, causing unbalanced filling of the channels and nominal wall sections, increased part weight, and extended cooling times.

**LIQUID GAS-ASSIST INJECTION MOLDING**

Most current gas-assist technologies feature high-pressure nitrogen that is exposed to the melt at as much as 10,000 psi (69 MPa). Polymers can be damaged, and the part can explode if the gas is not properly evacuated before demolding.

One process that takes a different approach to gas-assist molding is liquid gas-assist. In this process, a proprietary liquid is gently injected into the melt stream with a special injection system and nozzle. The heat of the melt converts the liquid to a gas, which travels in a compressed state within the melt stream into the mold. Once in the cavity, the gas expands, pushing the melt against the cavity walls. This results in an excellent surface finish—often a problem with high-pressure gas-assist technologies.

Unlike nitrogen, the proprietary gas does not require venting from the part. Therefore, even after demolding—when 90% of shrinkage occurs—the gas maintains pressure in the part interior, preventing sink mark formation. When the part reaches normal temperature, the gas becomes dormant.

This process for low-pressure molding offers several advantages when compared with conventional gas-assist molding. With the low-pressure approach, larger free spaces can be formed. Hollow cores of up to 10 in. (254 mm) in diameter are possible, and channel lengths of up to 100 in. (2.5 m) are possible. Therefore, larger, more complex parts can be molded. Low pressure allows molding virtually any thermoplastic, including crystallines, copolymers, and fire-retardant materials, without risking blow-through. Furthermore, diverse components, such as film, textiles, and reinforcing metal mesh, can be simultaneously molded in.

The control package can precisely meter gas flow according to the geometry of the part. This makes it possible to vary hollow core size and wall thickness and create several hollow areas within the same part.

Cost savings are also attainable with this process. Because it requires only one-quarter to one-third as much clamp tonnage when molding most parts, aluminum molds are used in place of steel tools. Lower clamp tonnage promotes less tool breakage and energy requirements are significantly reduced.³

**LAMELLAR INJECTION MOLDING**

Lamellar injection molding technology (LIM) is a process that allows fabricators to create a multilayer structure with specific performance and cost advantages compared to copolymers and blends in injection molding applications.

LIM technology can offer improved barrier performance, chemical and temperature resistance, dimensional stability, and optical clarity in molded products. The process also provides repeatability and consistency in injection molded parts. LIM simultaneously injects material to produce continuous, thin multilayers called lamellae.

Commercial multibarrel injection molding machines can be adapted to LIM. Fabricators can use LIM with conventional molds and standard process controls.

**Cost-performance Benefits**

Using LIM technology with certain types of polymer combinations can yield cost-performance benefits. Figure 6-40 shows the performance advantages that LIM technology can offer compared to conventional injection molding techniques. This figure details the cost-performance economics of a LIM-produced structure that combines polypropylene with 10% ethylene-vinyl-alcohol-copolymer (EVOH) and a third component adhesive layer, relative to monolayer injection molded containers.

Depending on the choice of polymers, LIM allows fabricators to improve the barrier performance of the molded container while reducing production costs.
LIM can also offer improved performance in certain engineering thermoplastic structures. Table 6-12 illustrates a composite property profile for polycarbonate/polybutylene terephthalate structures. The lamellar injection molding process as practiced in scale-up using a 700-ton (6.3-MN) dual-barrel injection molding press is shown schematically in Fig. 6-41. Injection of the two polymers occurs simultaneously at predetermined rates that fabricators control (1). Individual melt streams are then combined in a feedblock to arrange a three-layer structure (2).

The combined stream passes through a series of multipliers that repeatedly subdivides and stacks to increase layer number and reduce layer thickness (3). The melt stream then passes through a standard injection nozzle before mold filling (4).

Structures of two or three polymer components are successfully achieved in layer multiplication of up to several thousand layers. Additionally, multicavity molding of complex parts is possible.

The morphology controls possible with LIM provide the capability to design structures that position polymers and adhesives in the exact places and proportions necessary to approach maximum performance. Superior barrier performance. LIM technology enables the introduction and maintenance of low levels (2–20%) of barrier polymer as cocontinuous lamellae in molded articles.

Figure 6-42 shows the oxygen permeability versus volume percent EVOH for polyolefin-based structures made by LIM. A 300-fold reduction in oxygen permeability is achieved compared to conventional blends with minor amounts of barrier polymer (10%).

Table 6-12: Performance Potential for Polycarbonate/Polyester Structures Made by LIM

<table>
<thead>
<tr>
<th>Property</th>
<th>LIM (138)</th>
<th>Conventional Blend (107)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature resistance, °F (°C) (annealed, 264 psi [1.8 MPa])</td>
<td>280</td>
<td>225</td>
</tr>
<tr>
<td>Heat sag, in. (mm) (1 h @ 250°F [121°C])</td>
<td>0.26 (6.6)</td>
<td>1.6 (41)</td>
</tr>
<tr>
<td>Toughness, ft·lb (m·kg) (5 mph [8 kph] @ 73°F [23°C])</td>
<td>38 (5.2)</td>
<td>41 (5.7)</td>
</tr>
<tr>
<td>Solvent resistance, %</td>
<td>95</td>
<td>36</td>
</tr>
</tbody>
</table>

Depending on the polymer used with LIM, improvements of 10–100 times the oxygen permeability of monolayer polyethylene terephthalate (PET) are achieved. Table 6-13 shows the performance characteristics of several blends using a barrier polymer.

Enhanced optical clarity. Fabricating parts with LIM technology improves optical clarity due to reduced light dispersion. Haze is often reduced by 60% absolute, and contact clarity is maintained even with significant differences in refractive indexes between polymer components.

Figure 6-43 shows the difference in optical clarity for two-component blends incorporating a polycarbonate resin and styrene-acrylonitrile resin fabricated by LIM and conventional injection molding.
Fig. 6-41 LIM process schematic using dual-barrel reciprocating screw injection molding. (Courtesy Dow Plastics)

Fig. 6-42 Improvements in oxygen barrier performance realized with LIM. (Courtesy Dow Plastics)
Improved solvent resistance. LIM technology improves the chemical resistance and environmental stress crack resistance of molded products. Tests show that, with nylon (polycaprolactam) loadings of only 5%, HDPE-nylon-6 articles fabricated with LIM exhibit a reduction in hydrocarbon permeability of more than 200-fold compared with HDPE (see Fig. 6-44).

Molded articles produced with LIM technology can exhibit nearly double the critical crazing strain and are more resistant to catastrophic failure when exposed to aggressive chemicals. For example, up to a 14-fold increase in time to fail under load can be achieved through LIM with PC-PBT blends.

Figure 6-45 illustrates the potential of using LIM to capture a preferred balance of optical and barrier properties not otherwise obtainable by traditional injection molding. This figure shows that barrier structures made by LIM, based on polystyrene copolymers and aromatic nylon, can offer clarity comparable to PS or PET, with a 5–1000-fold improvement in oxygen barrier.

Higher heat distortion temperature. Compared with conventional blends, LIM technology can provide an increased heat distortion temperature. In PC-PBT structures, the heat distortion temperature is increased by over 50˚ F (28˚ C) (see Table 6-12).

LIM is repeatable. LIM technology results in consistently molded parts. Repeatability was evaluated during a 50-cycle run

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**TABLE 6-13**

<table>
<thead>
<tr>
<th>Host Polymer</th>
<th>Compatible</th>
<th>Barrier Polymer</th>
<th>OTR</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>PE-g-maleic anhydride</td>
<td>EVOH&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.6</td>
<td>x</td>
</tr>
<tr>
<td>PP</td>
<td>PE-g-maleic anhydride</td>
<td>EVOH</td>
<td>0.6</td>
<td>x</td>
</tr>
<tr>
<td>PET</td>
<td>EVA&lt;sup&gt;3&lt;/sup&gt;</td>
<td>EVOH</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>PS</td>
<td>SMA&lt;sup&gt;4&lt;/sup&gt;</td>
<td>MXD6&lt;sup&gt;5&lt;/sup&gt;</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>SAN</td>
<td>SMA&lt;sup&gt;6&lt;/sup&gt;</td>
<td>MXD6</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>TIPS&lt;sup&gt;7&lt;/sup&gt;</td>
<td>None required</td>
<td>MXD6</td>
<td>1.0</td>
<td>x</td>
</tr>
<tr>
<td>TPU&lt;sup&gt;8&lt;/sup&gt;</td>
<td>None required</td>
<td>MXD6</td>
<td>0.4</td>
<td>x</td>
</tr>
</tbody>
</table>

<sup>1</sup>Oxygen transmission rate: Typical values using 10 wt.

<sup>2</sup>% barrier polymer, units of cm<sup>3</sup>-mil-(100 in.<sup>-2</sup>-day-atm O<sub>2</sub>).

<sup>3</sup>Pol(ethylene-co-vinyl alcohol).

<sup>4</sup>Pol(ethylene-co-vinyl acetate).

<sup>5</sup>Pol(styrene-co-maleic anhydride).

<sup>6</sup>Aromatic nylon.

<sup>7</sup>Nondetectable, <0.0001 cm<sup>3</sup>-[package-day-atm air].

<sup>8</sup>Transparent impact polystyrene.

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Fig. 6-43 Optical clarity advantage of LIM (shading indicates opacity). (Courtesy Dow Plastics)

Fig. 6-44 Solvent resistance to hydrocarbons. (Courtesy Dow Plastics)
of pigmented HIPS using a complex tool. Specimens were cross-sectioned at identical locations from moldings near the end of the flow path.

**Conclusion**

LIM technology offers opportunities to produce injection molded articles with significant property improvements and economic benefits. A variety of market segments and applications are candidates for the LIM technology.

Many different material combinations and lamellar structures are required for the range of applications. The following applications show potential for LIM technology use.

- **Food packaging.** LIM is used to fabricate rigid packages with improved oxygen barrier performance, increased optical clarity, hot-fill temperature acceptance, and toughness. Molded bottles and other containers are potential applications as well.
- **Chemically resistant packaging.** LIM has potential uses in rigid chemical packaging with improved chemical barrier properties, toughness, and increased chemical resistance. Other applications include hydrocarbon-resistant containers, receptacles, reservoirs, and fittings; ethanol- and hydrocarbon-resistant molded products; and oxygenated gasoline-resistant containers and products.
- **Automotive applications.** Increased chemical and oil resistance, dimensional stability and clarity, and increased temperature performance suggest LIM for fuel line parts, windshield washer parts, under-hood parts, exterior parts, brake system parts and fittings, and receptacles and reservoirs.
- **Health care products.** Packages, containers, valves, and fittings for the health care market segment can benefit from the improved oxygen resistance, environmental stress crack resistance, dimensional stability, and clarity offered by LIM.

Other applications. Other applications for LIM technology include a broad range of injection-molded articles for other market segments:

- Electronics.
- Appliances.
- Building and construction.
- Computers and business equipment.
- Custom injection-molded parts.
- Recreational products.

**Other Considerations**

Other characteristics of LIM technology for polymer blends include the following:

- Cycle times in LIM are equivalent to those for standard injection molding for similar conventional blends. For specific structures, cycle time may be reduced because of improvements in heat distortion temperature.
- For food applications, the material used must meet FDA guidelines for direct food contact because all components within the structure appear on the part surface.
- Complex parts are produced.
- LIM technology is amenable to multicavity molding.
- Compounding cost may be eliminated when using LIM.
- When compatibilizers are used, greater levels may be needed with LIM technology relative to conventional blends.
- Recycle and disposal procedures with parts produced by LIM are expected to be identical to those used for similar blends fabricated by conventional techniques.

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Fig. 6-45 Clarity versus barrier performance for LIM. (Courtesy Dow Plastics)
CHAPTER 6
AUXILIARY EQUIPMENT

CAVITY PRESSURE SENSORS

Cavity pressure sensing is a useful tool in monitoring and controlling the injection molding process. By monitoring cavity pressure, much effort is saved through reducing other process monitoring requirements. Molded part variation is a result of a variation in numerous input parameters. Some of the more important parameters are material variations (filler, colorant, and regrind) and equipment variations (barrel temperature, mold temperature, hydraulic pressure and flow variations, and check ring condition). Cavity pressure is successfully used to capture most of these variations. Cavity pressure is an output parameter, the result of many input parameters.

Peak cavity pressure is highly related to the amount of plastic that is injected into the cavity. This, in turn, is a gage of final part size. The rate of pressure increase and decrease through the injection cycle is correlated to the injection velocity or the time required to fill the part. This provides a gage for the molecular orientation and shear degradation. The entire pressure curve is important in duplicating the process through closed-loop cavity pressure control. The curve is also important when implementing in-mold quality control or assurance. Unfortunately, most machines lack the ability to control injection velocity through cavity pressure feedback. Therefore, many molders are restricted to using only peak cavity pressure variables.

Studies of the injection molding process indicate that the process is broken into four key variables: peak cavity pressure, fill time (or injection velocity), plastic temperature, and mold temperature. Variations in any of the latter three usually cause a variation in peak cavity pressure, further underscoring the importance of cavity pressure. Modern process control equipment provides accurate control of both melt and mold temperatures. This leaves fill time and cavity pressure as the remaining variables. However, fill time or injection velocity is also accurately controlled by many newer machines or older machines retrofitted with load-compensating hydraulics.

Implementing Closed-loop Cavity Pressure Control

Implementing control requires the installation of equipment to (a) sense cavity pressure, (b) process the pressure signal and provide feedback control, and (c) modify existing means of controlling the process. A number of companies offer equipment and technical support to cover these areas.

Pressure Sensor Selection

There are two major designs of pressure sensors: piezoresistive, or strain gage-based sensors, and piezoelectric sensors. Of the two designs, piezoresistive sensors are the most common in the U.S. injection molding industry. They are less expensive to manufacture and are easier to debug. Simple resistance continuity checks are used to test a sensor's electrical integrity. The piezoelectric sensor design is more popular in Europe and parts of Asia. Some direct-measuring devices have an upper temperature limit that prevents their use with some materials. Indirect measuring devices do not have this limitation because they can be isolated from high-temperature materials. There are two standard styles of indirect measurement sensors available in the industry: the button (also called miniature), as shown in Fig. 6-47, and the slide (also called the tongue), as shown in Fig. 6-48.

The slide style is easily installed and removed from the injection mold. This allows a single sensor to be readily used with multiple tools. The button-style sensor is permanently installed in the mold. Therefore, when using the button style, a sensor is generally required for every active tool. In practice, the button sensor's permanent installation helps prevent damage to the sensor leads, and in the long term, use of button sensors assures the viability of a pressure-sensing program.

The major cause of sensor damage is damage to the leads. The slide-style sensor has an integral cable that is not easily repaired or replaced. By comparison, the button sensor has a cable that attaches to the side of the mold. Should the cable from the mold to the monitoring or control equipment become damaged, it is quickly replaced. The damaged extension cable is also easily repaired and returned to service. Slide sensors that have had their leads torn from the sensing element are often not repairable.

Indirect pressure measurement requires an ejector pin. Existing ejector pin locations are often used for pressure measurement, although a new pin position may be required. It is usually not necessary to modify the tool near the expensive cavity area to install the sensor. The mold must only modify the ejector plates and possibly the housing.

The criteria for selecting a pin location is simple. First, the pin must strike on ejection. The use of static, nonstroking pins is not recommended unless frequent maintenance intervals are possible. Plastic material can flash between the pin and bushing (or mold) and cause resistance to motion. Even when plastic does not flash into this interface, the ejector pin provides a vent for material volatiles, and the pin becomes bound by the venting of gases from the cavity. If the pin strokes on ejection, it tends to self-clean. This cleaning action is enhanced by adding a small amount of rifling to the pin's midsection. This causes the pin to rotate upon ejection and return.

The selected pin is located at a proper position in the material flow. This position depends on whether the application is for process control or process monitoring (and quality control). For process control, the general rule is to place the pin one-half to three-quarters the distance between the gate and the end of flow. Placing the pin at the end of flow causes pressure sensing to occur too late in the injection process to provide timely control of the machine's functions, that is, booster pump cutout (also referred to as a high-volume-to-low-volume transfer). By contrast, using a pin at the end of flow is the best location for quality control purposes, because the last area of the mold that fills is the most difficult to fill. If this last area is made consistent, the entire shot is usually consistent as well.

Opinions vary as to whether a pin near the gate is necessary. Use of sprue puller or sucker pins is not recommended. Pins used across from gates experience loading from material jetting well before the part begins to fill. This may make it difficult to determine when the filling phase ends and the packing phase begins.
Use of pins in locations that may freeze off before filling is also not recommended. It is not possible to sense the complete injection phase. This also suggests not using pins that are located under bosses.

Large parts may require multiple transducers to determine part quality. The non-Newtonian flow characteristics of plastic flow coupled with large and multiple-melt flow fronts make it necessary to treat large parts like several smaller ones. Where process control is concerned, only one sensor is needed, because there is only one set of controls on the machine, regardless of part size or number of cavities. However, multiple sensors may be installed to assist in tool development.

Placing sensors in runners is acceptable as long as the aforementioned rules are followed. The pins must stroke on ejection, suggesting that pins are not interfaced into hot runner systems. Sensors are also not placed in cold-slug wells at the end of runners, because these freeze off prematurely. Supporters of runner-based sensing propose that sensing runner pressure gives the user an average of what is occurring in each cavity. They also propose that sensing the runner of a multicavity system is safer than sensing a cavity that may freeze off before filling. Should the sensed cavity freeze off, the remaining plastic is forced into the remaining cavities, causing overpacking and possibly flash. Even worse, since the instrumented cavity experienced no pressure rise, it is not aware that there was a problem with overpacking in the other cavities. Furthermore, if the sensor is used for control of booster cutout, the cavity freeze-off probably extended the boost period, thus compounding the flash problem in the other cavities. Had
runner sensing been used, the problem would be avoided. The frozen cavity would cause an extreme pressure rise in the runner, thus triggering early cutout of the booster pump and eliminating the flash in the remaining cavities.

Runner sensing does not account for flow losses through the gates and part. It is therefore not the first choice for part quality. It may not be the optimum choice for process control, either. Also, if small gates are used, a pressure spike may occur as the runner fills against frozen gates and then forces the gates open. This pressure spike can cause false triggering of booster cutout in process control applications, thereby causing shorted parts. To avoid this problem, some applications use a timer to delay arming of the process control equipment until the gates are open and flowing plastic.

**Control Equipment Selection**

There are a wide variety of products available to the user. Most late-model molding machines have closed-loop cavity pressure control available as an option. Some machine manufacturers can also link their molding machines to a central host system, in which quality control information is gathered and tracked. Even if the machine manufacturer does not have the monitoring option available within his equipment, he may offer third-party monitoring systems that are often referred to as plant-wide data acquisition systems.

Unfortunately, many of the molding machines that offer closed-loop cavity pressure control (booster cutout) currently do not scan the pressure signal fast enough to allow repeatable and accurate cavity pressure control. A typical scan rate for some molding machines is 100 samples/second, which is too slow for many parts. A minimum scan rate of 1200 samples/second is recommended to fit the majority of applications. A sample rate of 100 samples/second may be adequate for large, slow-filling parts. It is not adequate for small, fast-filling parts.

Also, many machine manufacturers do not offer a direct interface for pressure transducers. An amplifier may be required to boost the sensor's millivolt signal to a higher voltage acceptable by the machine. This is a common strategy in which the machine is configured for use with a large variety of manufacturer's offerings—including piezoelectric sensors.

Few, if any, molding machines are immediately able to use cavity pressure sensing and control. Furthermore, many older machines do not have cavity pressure sensing available as an option. For these reasons, cavity pressure control is often implemented by retrofitting a new controller to the molding machine. Depending on the features requested, prices can range from $1000–$20,000.

The simplest pressure controllers merely override the existing methods of controlling booster cutout. In most cases, a timer or screw position limit switch is used by the machine to trigger the transition from high-volume (high-speed) fill to low-volume (low-speed) pack-out of the part. With the new controller applied, the existing boost timer is reset to a longer period to allow the pressure controller to control booster cutout. Similarly, an existing screw position limit switch on the machine is moved forward toward the screw bottom, so the pressure controller is the trigger mechanism for booster cutout. This strategy does not require significant machine modification. The new controller mimics relay contact or switch closures provided by existing controls. This allows quick removal and relocation of the control equipment to another more demanding application.

The pressure controller does not change or modulate the machine's pressure settings; it determines the amount of time the high-volume pump is applied to reach a desired cavity pressure. For this reason, some control engineers argue that this is not true closed-loop control. A typical cavity pressure curve is shown in Fig. 6-49. Note that the pressure set point is different from the
Because of the momentum of the injecting screw, it is impossible to brake the injection process at an exact point; the screw continues forward slightly. This phenomenon causes overshoot of the set point. It is therefore necessary to place the set point slightly below the desired peak pressure.

A more capable control is offered by several vendors. Expanding on the above controller, an improved controller adds a third stage of injection pressure. Adding the third stage is relatively easy. A new pilot valve is added to the main or second-stage relief valve pilot head. The addition of the third stage allows a more logical breakdown of the injection process into separate fill, pack, and hold phases. During fill, the machine runs on high-volume injection until 90–95% of the cavity is filled. During pack, the machine runs on low-volume pump to complete cavity filling and provide accurate cavity packing to a desired peak pressure. The machine is then transferred to the new low-volume, low-pressure hold stage. This stage provides sufficient pressure to keep plastic from discharging from the cavity until the gate seals off. The three-stage method provides more accurate control of peak cavity pressure and can provide electrical energy savings by reducing the horsepower requirements of the machine. Three-stage injection is often used to circumvent the addition of more costly velocity-profiling packages. A typical three-stage pressure curve is shown in Fig. 6-50.

Some control suppliers prefer the use of hydraulic injection pressure as a cut off means instead of cavity pressure. Years of studies and field use have proven that cavity pressure provides more accurate part size control. Hydraulic pressure is an input variable that does not provide feedback for variations in the process downstream from the screw. Hydraulic pressure is easier to implement and does not require sensor changes or recalibration when changing a mold. Unfortunately, this approach does not work well.

There are some low-cost pressure monitors and controls available from general purpose equipment suppliers. Unfortunately, most of these controls suffer the same drawbacks as molding machine controls: they are too slow to provide accurate control. Also, they are difficult to calibrate, because they do not include a provision for adjusting calibration for ejector pin size. This is a significant drawback.

A three-stage pressure controller is shown in Fig. 6-51. A preferred controller for use with indirect pressure sensing must
include a pin size selector switch. It should also provide a means to calibrate the sensor directly from the front panel. Other desirable features include a means to hold the peak cavity pressure reading, a high-level output for attachment to other process-recording equipment, and clocks to measure the duration of the injection phases. User-adjustable alarms can provide some in-mold quality screening.

**Interfacing Control Equipment to the Molding Machine**

As previously mentioned, interface of a booster cutoff controller is relatively easy. Most machines use either a timer or a limit switch to trigger the transfer. If both a timer and a limit switch are available, the first one to trigger controls the process. The added pressure controller parallels the existing functions of the machine. If booster cutout is caused by closing a switch, the pressure controller’s normally open relay is placed electrically in parallel with the existing trigger means, and this means is temporarily defeated. This is done by adding time to the boost timer or by moving the limit switch farther toward the screw bottom. The timer and limit switch are both still capable of triggering the transfer. For example, if the boost timer times out before the pressure controller triggers, the timer still controls the process. With this configuration, minimum modification is made to the machine, and the existing machine transfers remain in place as backup to the pressure controller.

The pressure controller interface can be set so that the controller is quickly disconnected and moved to another more demanding process. This portability allows the user to try a pressure controller on a greater number of processes with minimum investment. It also permits the user to quickly restore the machine to its original design should damage to the pressure controller or pressure sensor occur. A typical two-stage controller is interfaced to a molding machine in less than an hour, minimizing downtime. Three-stage controllers require more time because of the added hydraulics stage.
Monitoring Equipment Selection

There is a wide variety of monitoring equipment available. Portable process recorders that resemble electrocardiogram (EKG) machines were once the primary means of acquiring data from the process (see Fig. 6-52). These remain available today. For the most part, computerized data acquisition equipment has replaced the old pen-on-paper recorders. Personal computers are outfitted with data acquisition systems capable of monitoring pressures, positions, and temperatures. Plant-wide data acquisition systems are available from several vendors that specialize in the plastics industry. Injection molding machines are now often capable of providing graphic displays of machine parameters, including cavity pressure. However, some offerings may be too slow in acquiring meaningful data.

BARREL TEMPERATURE CONTROLLERS AND THEIR REPLACEMENT

Over the last several decades, significant improvements were made in controller technology. These improvements have allowed tighter process control, including the control of injection molding barrel temperatures. The owners of older machines are often unaware of the improvements available for their processes. These owners are usually content with temperature oscillations that sometimes exceed ±10°F (5.5°C) of the desired set points until these oscillations become the cause of inadequate repeatability in production. Older controls are also more prone to drift, and therefore error, in readout. This causes the user to initially set incorrect processing temperatures.

New Materials

Over the same time frame, many new polymer materials and applications have surfaced. Some of the new, difficult-to-process engineering resins have narrower processing windows than commodity resins. This suggests a need for tighter control of the process, including temperature control. Today's applications are also more difficult than those of the past; modern molded part designs are more demanding. This also suggests a need for tighter control.

The typical temperature controller on older machines is at best a simple on/off design. As a result, this style uses a control deadband or hysteresis that makes it difficult to hold temperature vari-
Improving Barrel Temperature Control

Machine rebuilding can be less expensive than total machine replacement. In most cases, the entire electrical system of the machine is removed and replaced with a programmable logic controller (PLC). In this case, the panel-mounted temperature controllers are usually replaced by a PLC. Temperature set points are often displayed and set on a CRT or other display device.

For those who cannot afford or do not need a complete machine rebuild, replacement controllers are readily available from many suppliers. These replacements are relatively low cost and can reduce temperature oscillation, possibly to within one degree of set point. This is a dramatic improvement over older controls. In some cases, this degree of control is better than that available from modern PLCs.

The newer controllers are usually much smaller than older units. This requires covering the gaping holes in the machine panel with blank or conversion panels in which the new controls are mounted. Most new controls have dimensions that follow the Deutsches Institut für Normung (DIN) standard. This standard is followed by all modern controls manufacturers and guarantees compatibility in the faceplate mounting dimensions if future replacements are justified.

Fuzzy logic. The newer controllers use proportional-integral-derivative (PID) control action. This allows them to provide tighter control. Unfortunately, this also requires someone to program the P, I, and D terms into the controller. Incorrect programming can have disastrous results, causing oscillations in temperature even greater than that of the controllers that were replaced. To avoid this problem, many of the newer controllers offer autotuning or fuzzy logic. These are features that are automatic or can be invoked, and force the controller to determine its own PID values, thus taking the guesswork out of PID programming.

Replacing heater contactors. In modernizing barrel temperature controls, the molder may consider replacing the heater contactors in the machine panel. However, the panel-mounted controls do not usually connect directly to the barrel heater. The panel-mounted controller provides a trigger that turns on a contactor (relay) in the machine panel, which in turn applies electrical power to the heater. In most cases, contactors that are still operating do not need replacement.

In summary, modernizing barrel temperature controls is a relatively inexpensive and easy task. The benefits of upgrading barrel temperature controls is immediately apparent once they are installed. Increased complexity in molded part design and in material processing requirements is sufficient justification.

INSULATOR SHEETS

Increased energy costs, as well as the need to provide even heat distribution within the mold, have resulted in a dramatic rise in the use of insulator sheets. Approximately 30 years ago, molders began looking for ways to reduce energy loss due to heat escaping from tooling and press platens. This search accelerated in the early 1970s as energy costs skyrocketed. The increasingly competitive nature of the injection molding business has required a significant improvement in part quality. Insulator sheets provide uniform heat distribution in the mold to give the molder greater control over part quality. In addition, insulator sheets can reduce mold start-up times, increase heater life, and reduce plant air circulation requirements due to heat loss.

Selecting Insulator Sheets

In selecting insulator sheet materials, the tooling engineer should consider the following material attributes:

- Low thermal conductivity.
- Long-term material stability.
- High compression strength.
- High flexural and impact strength.
- Resistance to attack from molding process chemicals.
- Cost.
- Machinability.

Uniform Thickness

An insulator sheet must have a uniform thickness. Parallelism between the platen, insulator sheet, and the mold is critical. A nonuniform insulator sheet creates uneven heat distribution, resulting in lower-quality parts. In addition, mold set-up times are increased as a result of shimming requirements.

Cost Effectiveness

To determine the cost effectiveness of using insulator sheets, the following equation is used. This calculation allows the determination of theoretical energy requirements.

\[
\Delta q = A(K_p/r_p - K_i/r_i) \Delta T
\]

where:

- \(\Delta q\) = energy required
- \(A\) = platen area, \(\text{ft}^2\) (\(\text{m}^2\))
- \(K_p\) = thermal conductivity of the platen
- \(r_p\) = platen thickness, in. (mm)
- \(K_i\) = thermal conductivity of the insulation
- \(r_i\) = thickness of the insulation, in. (mm)
- \(\Delta T\) = temperature difference between the platen and the air, °F (°C)

Insulator sheets are considered a way to control energy costs and improve process control, which results in higher-quality part production. The net result is a more competitive molder in the world market.

RUNNERLESS TEMPERATURE CONTROL SYSTEMS

Runnerless systems require electrical heaters to keep plastic in a molten state. These systems require independent control of numerous heat zones. Like barrel temperature control, modern runnerless systems require tight temperature regulation to maintain consistent flow characteristics during the injection process. Unlike barrel temperature controls, most runnerless temperature controls are not part of the molding machine and are portable so they can be moved among presses and molds as needed. This is a key difference in applying and understanding runnerless temperature controls.

Like barrel temperature control systems, runnerless control technology has advanced significantly over the last few decades to provide operation to match the performance requirements of runnerless molding systems. However, older controls are still found in the industry. The earliest control was typically a variable transformer. These devices have become expensive to replace because of the cost of copper wire. They are also heavy and require a significant amount of mounting space.

Power Controllers

The wire-wound variable transformers were later replaced with electronic power controls. The electronic version often operates in
the same way as a light dimmer switch found in many homes. The electronic versions are less expensive, much smaller, and weigh considerably less than the wire-wound versions. They also provide better portability. Heavy transformers make portability difficult.

Both the wire-wound and electronic versions are open-loop devices. They do not use thermocouples to control temperature. The control mechanism may have a pyrometer (temperature meter) available, but it is intended for reference purposes only. The operator or set-up personnel can occasionally obtain a temperature reading out of the system. The operator then makes a manual adjustment to the power output of the heater, if necessary. An excessive adjustment is often made, causing oscillation between low- and high-temperature situations.

**Variety of Unique Currents**

Some versions of electronic power controllers use a current meter (or ammeter) to monitor the power that is delivered to the load. If plant voltage drops, the current delivered to the load drops, and this shows up in the current reading. The molder can readjust the power output to match the previous current reading. Unfortunately, a variety of wattage heaters are used in runnerless molding systems, and each requires a unique current to maintain a desired temperature. For an effective means of temperature control, each unique current reading is recorded for future reference.

While some electronic power controls correct for fluctuations in line voltage, most do not. As line voltage varies, heat output varies as a result. Worse yet, the resultant change in heat output is not linear. For example, a 5% drop from nominal line voltage (240 VAC, for example) causes about a 10% drop in heater output. Similarly, a 10% drop in line voltage results in a 19% heat output drop.

Line voltage varies for a number of reasons, both internal and external to the plant. During peak demand hours, line voltage that is available to all users typically drops. At the plant level, voltage decreases as the number of machines being used is increased. Conversely, line voltage increases as machines are shut down. Air conditioning cycling, for example, can have a dramatic effect on available voltage.

Open-loop varics (power controls) do not provide a consistent temperature. If a runnerless system is too cold, the mold may be unable to inject plastic. Even if injection is possible, excessive shear may degrade material, and system leakage may occur, thus requiring tear-down and clean-up of the system. If the system runs too hot, material degradation and cross-linking could occur. If temperatures fluctuate wildly, the mold may alternate between periods of short shots and flashed parts.

**Controlling Temperature**

Temperature control is greatly improved with closed-loop controls. Usually electronic, these controls use a temperature-measuring device, usually a thermocouple, to automatically correct for variations in line voltage, ambient temperature, material temperature, and mold temperature. The electrical power delivered to the heater is automatically increased during periods of low temperature and decreased in periods of high temperature.

Thermocouples account for variation. Unlike controlling by current readings, controlling based on temperature readings allows for significant uniformity in set-up. That is, despite the variations in heater wattage within a runnerless system's manifold and nozzle drops, all heat zones run at a nearly identical temperature. (Small differences in set point temperatures are expected to balance flow). Also, the thermocouple accounts for variations in heat transfer from zone to zone. For example, nozzle drops often use coil or band heaters. The tightness of the heaters affects the amount of heat transferred from the heater to the nozzle. If heater tightness varies, different current readings (set points) are used to achieve an identical temperature in different nozzles. In comparison, different nozzles would probably still use the same temperature set point, assuming that the thermocouple is mounted in the nozzle drop itself and not in the heater. Thermocouples also correct for variations in heat caused by variations in mold cooling.

Time-proportioning controls. Because of the small mass of most runnerless system nozzles, a faster-acting control mechanism is used compared to that classically used for barrel heaters. The earliest of closed-loop controls, and even some modern home-grown systems, use time-proportioning controls. This is the control style used on almost all barrel heaters. A typical barrel heater cycle time is 10 seconds. This means that every 10 seconds power is applied to the heater. The controller determines what percentage of the time requires power output. For example, if the controller determines that 50% power is required, the controller turns on for 5 seconds and off for 5 seconds. This technique works well for thermal systems with a large mass such as injection barrels and runnerless molding systems (RMS) manifolds. The technique is far too slow for many RMS nozzle drops. When applied to RMS nozzles, this technique causes large temperature oscillations. Studies of various control methods have proven that a cycle time of one second or less is required to provide tight control of nozzle temperatures.

Distributed power patterning. In practice, most of the RMS temperature control systems use cycle times much less than one second. Cycle times of 0.1 second are not unusual. To further reduce temperature oscillation, distributed power patterning (or high-speed power distribution) applies a rapid succession of narrow power pulses. This virtually eliminates oscillation. It also extends heater life by reducing thermal shock of the heater windings. Slower time proportioning causes dramatic heat-up and cool-down of heater windings. This causes thermal expansion and contraction of the windings. This stresses the windings, causing earlier failure than that experienced with distributed power patterning. For this reason, distributed power patterning also benefits heaters in the slower-acting large thermal masses (manifolds and barrels). RMS temperature control suppliers often use trade names when referring to high-speed power distribution.

To use distributed power patterning, solid-state relays are incorporated as power output devices. Mercury contactors and other styles of electromechanical relays are not capable of the switching speeds of solid-state devices. Fast switching of mechanical relays shortens their life. Mechanical power relays are not recommended for cycle times less than five seconds.

High-speed power distribution does not help reduce oscillation if the controller cannot tune to or determine the characteristics of the thermal system. Most modern controls use PID (proportional-integral-derivative), PIDD (proportional-integral-derivative-derivative), fuzzy logic, or a combination of fuzzy logic and PID/PIDD to determine and control the thermal system characteristics.

PID control. This is a control method that offers significant control accuracy when compared to older on-off or proportional controls. The proportional action of the controller increases the amount of time that power is applied to the heater to increase temperature. It decreases the amount of time power is applied to lower the temperature. The integral action is also referred to as auto-reset. The integral action corrects for offset errors caused by inadequacies of the proportional term. That is, if proportional activity calls for 25% and process temperature is still 5°F (3°C) too low (under set point), the integral term forces the controller to increase power output to correct the error. The D (derivative) term corrects for time-lag related errors not addressed by the P and I terms. The D term helps
eliminate overshoot of set point on start-up, and over- and under-shoot of the set point when making set point changes. The second D term in PIDD (derivative) is argued to have even better control of the process temperature.

Fuzzy logic. Despite the fact that fuzzy logic was invented in the early 1960s, it has only begun receiving wider use. Fuzzy logic is a different method of learning the process characteristics and enforcing control. Some implementations of fuzzy logic offer improved control over PID control methods. For example, fuzzy logic is more capable of controlling the temperature of a process that has varying thermal system characteristics. Injection molding is such a process. During injection, plastic temperatures often rise as a result of shear. This can cause some PID controls to overreact by shutting off power during injection to counteract the heat rise due to shear. The result is a drop in temperature below the set point after injection is complete. A fuzzy logic controller can learn this special case and develop a special control algorithm to handle it.

Fuzzy logic has some drawbacks, however. Some implementations of fuzzy logic insert a periodic disturbance into the process. That is, the controller may increase or decrease power output briefly to verify the temperature result. This causes occasional minor oscillations about the set point. Some control suppliers offer hybrids or combinations of PID and fuzzy logic controllers. Normal PID control is used when the process is static or consistent (that is, between shots). During injection or when changing set points, fuzzy action is invoked to handle the special case(s).

Automatic tuning. Regardless of whether PID or fuzzy logic is used, the control system should feature autotuning or self-tuning. This negates the need for the user to program PID settings into the controller. As previously noted, incorrect PID settings can have disastrous results. For example, if a controller that is set up for a nozzle drop is used on a manifold, the user can expect to see a huge set point overshoot on start-up. This overshoot can cause material degradation within the manifold and possibly cross-linking. If cross-linking occurs, it is necessary to disassemble the tool to clean the manifold.

Some controls have autotuning but require the user to place the controller in autotuning mode when a new RMS is put in place. Should the user forget to autotune the controls, poor control results, including possible damage to the system. To be as fail-safe as possible, the controller should autotune automatically every time the control system is powered. Furthermore, for even more fail-safe operation, the control system should not allow the inexperienced user to easily change PID settings. The safest approach is to have a control mechanism that can intelligently choose its own settings. Autotuning (or self-tuning) is a must for safe, foolproof RMS operation.

Other temperature control features. There are a variety of other features available in RMS temperature controls; some are unique to RMS controls.

Heater bake-out. This feature is often referred to by various names. The purpose of these implementations is to provide drying of the electric heaters that are used in the RMS. As a result of shortcomings in heater manufacturing, moisture is often absorbed into the heater, especially during RMS cooling, when condensation occurs. Countless tools have been abandoned to soil because of such moisture absorption. Some methods were reasonably successful but are extremely expensive. Nevertheless, most cartridge and coil heaters in the industry are prone to moisture absorption, and a heater-drying method is necessary.

When a heater contains moisture, low voltages or very-short-duration pulses of power are used to drive out the moisture. If normal full power is applied to the heater when it is damp, arcing could occur inside the heater, causing premature destruction. This is typically not a problem with low-voltage RMS. A system that runs on 24 volts is not likely to arc inside the heater. Arcing problems are more prevalent on 120- and 240-VAC systems. Unfortunately, 24-volt applications are usually limited to small-size RMS. The manifold systems are often run on 240 VAC because it is impossible to create enough heat with 24-volt heaters.

Moisture can also affect the thermocouple readings of some control systems. Multiplexed temperature controls (also referred to as multiloop control systems) use a single set of electronics to monitor and control multiple heat zones. This can cause interaction between thermocouples. The symptoms are often enhanced by the presence of moisture. The symptoms are erratic thermocouple readings, or readings that are pegged either high or low and do not change. Along with requiring a sturdy ground connection between the RMS and the control system, it may be necessary to dry the heaters before accurate temperature readings are obtained.

There are two different techniques commonly used in industry to dry heaters. The first and more successful method is to lower the voltage to the heaters during the dry-out period. While some implementations of this use a transformer to step down the voltage, most use phase-firing techniques. Phase firing is used in incandescent light dimmer circuits found in homes. Similar to the light dimmer operation, the temperature controller can start with a very low voltage (that is, a very dim light) to initiate the dry-out without risking arcing. Once the drying period is underway, the controller may begin ramping or stepping up the voltage to accelerate dry-out. After a period of time, the dry-out function usually ceases, and normal controller operation commences to bring the heater to the desired temperature.

The second method used to dry heaters is power ramping. While this is not as successful in drying heaters without arc-over occurring, it is a less expensive method. This method works by applying full voltage to the heater for a very short period of time. Some implementations apply power for one-half an AC line cycle (0.008 seconds in the continental United States and 0.01 seconds in most other parts of the world). The theory is that by applying a short burst of voltage and then shutting off power, arc-over is less likely to occur because voltage is not established for a long enough period of time to create an arc. As the dry-out period extends, the power application time is increased, and the duration between power applications is decreased. After a period of time, the dry-out function usually ceases, and normal controller operation commences to bring the heater to the desired temperature.

Whether power ramping or low voltage is used to dry heaters, the performance is enhanced by integrating ground fault current measurement to detect moisture presence. This is patented technology that uses ground fault current measurement to close the loop on heater dry-out. The controller applies low power or voltage and then checks to determine if there is electrical current flowing from the heater leads to ground. If no leakage is detected, dry-out is terminated, and normal operation commences. If ground fault currents are detected, the controller maintains dry-out until such currents are nonexistent. This technology has proven successful in preventing damage to heaters.
required to maintain temperature while the controller is in automatic mode. Upon failure, the controller can automatically transfer from automatic to manual operation, using the previously learned percentage of power as a set point. Different controls suppliers use different means to learn the percentage of power. This has a dramatic influence on the controller’s ability to accurately learn the desired percentage of power.

Standby or idle heat. This is a second set point that is used to maintain the RMS at a lower heat level when it is not in production. Typical uses are for maintenance intervals and shut-down periods. Standby heat is used to keep heat on the system to prevent moisture impregnation in heaters. It also allows faster start-ups.

Boost or gate break. This is another set point that is typically used to increase the temperature of nozzle drops to initiate plastic flow. This is often necessary immediately after system start-up. Only the nozzle drops usually need boosting. It is not usually necessary to boost manifold temperatures.

Thermocouple isolation. A larger problem than most molders are aware of, thermocouple isolation is paramount for accurate monitoring and therefore temperature control. Most modular controllers have independent power supplies in each module. The clue is the presence of a power transformer in each module. If one module has a transformer, thermocouples are properly isolated. If one is not present, the power supply is probably built into the mainframe and isolation is not present. Each thermocouple must be isolated from the others. If thermocouples are not isolated, erroneous readings occur. The errors can manifest themselves as noisy, erratic readings or “crosstalk.” Thermocouple crosstalk is the interaction in readings between temperature zones. To test for this, all zones are placed in manual mode at 0% power. A nozzle zone is set in automatic with an elevated set point (for example, 400˚ F [204˚ C]). If other zones show a heat rise, crosstalk is present and is corrupting readings. The nozzle’s heat should not affect the readings of other nozzle zones. It may have a minimal effect on the manifold area that the nozzle is in contact with.

Properly isolated thermocouples also help prevent cascading of failures through the control system. If heater power (that is, 240 VAC) accidentally contacts thermocouple circuits, isolation prevents other zones not in contact with the 240 VAC from being affected. Damage, if any, is isolated to the zone that came in contact with the 240 VAC. In nonisolated systems, the 240 VAC short can cascade from module to module via the common DC power supply, thus causing failure of more than the immediately affected module. This is also an inherent problem of multiplexed (or multiloop) systems if other safeguards are not in place to prevent high voltage from reaching the sensitive areas of the controller’s circuitry.

References

Bibliography
Bryce, Douglas M., Thermoplastic Troubleshooting for Injection Molders (Brookfield, CT: Society of Plastics Engineers, Inc.).
Weir, Clifford L., Introduction to Injection Molding (Brookfield, CT: Society of Plastics Engineers, Inc.).
BLOW MOLDING

INTRODUCTION

Although packaging such as bottles and barrels represents the single largest market for blow-molded products, the industrial and consumer products market—which includes toys, automotive parts, structural panels, and cases—is now the fastest growing segment. Blow molding produces hollow, thin-walled thermoplastic parts. However, blow-molded parts can also have heavy walls formed by compressing two thicknesses of material together, with hollow ribbed areas. These parts are generally flat and can be used as reinforcing panels. Applications include seating reinforcement and furniture components, carrying cases, boxes, and structural wall panels for office equipment and appliances. This chapter will discuss the industrial blow-molding process and provide insight into the practical applications of other blow molding processes. Industrial blow molding usually refers to large blow molding machines with accumulators used to produce big parts such as barrels. In this case, accumulators store extra resin because the barrel screws cannot provide enough to make the part.

The blow-molding process competes with injection molding, thermoforming, and rotocasting. Table 7-1 compares the advantages and disadvantages of these processes. While there is no hard-and-fast rule as to when each process should be used, tooling cost, type of material, quantity, dimensional control, and surface quality are factors that must be addressed in selecting the appropriate process. Because blow molding is a low-pressure process when compared to injection molding, the tooling costs are less. Light-duty cast tools can be used for prototyping or limited production. A growing advantage of blow molding is the ability to consolidate a number of parts into one larger component to further reduce tooling and assembly costs. Blow molding is limited, however, by the poor internal dimensional control and the quality of the surface finish that can be obtained.

BLOW MOLDING TERMS

accumulator. A cylinder that contains a plunger and stores plastic melt. The plunger pushes the melt from the accumulator through the die to form the parison. It is a type of intermittent blow molder.

blow pin. A tube through which air is injected into the parison to form a part. Often located at the top of a part, it is fed with air through the head of the blow molder. It can be located at the bottom of the mold and used with a separate assembly. Also referred to as a blow needle when mounted in the mold and pushed into the parison with an air cylinder.

blow ratio. The amount a parison is blown or stretched to form a part. For a round part, it is the diameter of the part divided by the diameter of the parison. For nonround parts it is the width of the cavity divided by the depth of the cavity.

Blow ratios should be greater than one.

convergent head. Type of tool head that directs the flow inward because the parison diameter is smaller than the flow diameter of the head.

die. The removable bottom part of the head which controls the outside diameter of the parison. Also called the chase.

divergent head. Head tool type that directs the flow outward since the diameter of the parison is larger than the internal flow diameter of the head.

flash. Any extra plastic attached to the molded part which must be trimmed off. Blow-molded parts are often designed to have flash as a result of the part geometry.

head. The section of the blow molding machine that forms the plastic into a tubular shape to form the parison. It holds the mandrel.

lay-flat area. The recessed area of the mold which accommodates the flash of excess plastic attached to the part.

mandrel. The center post in the head, around which the plastic melt flows (also called the pin). This part moves up and down on most programmed machines.

parison. The plastic tube that is extruded through the head to form the molded part. In injection blow molding it is called a preform.

parison swell. The ratio of the diameter of the parison to the diameter of the die opening. It varies with different materials and operating conditions.

parting line. The point at which the flow separates. It should divide the part approximately in half to minimize the stretching of material and facilitate part ejection.

pinch bars. Used on the blow molder to close the parison during the blowing process.

The Contributors of this chapter are: R.J. Abramo, President, R.J. Abramo Associates, Inc.; Al Dickerson, Engineering Manager, Carlisle Geauga Company; Gerald R. Hobson, President, Hobson Brothers Aluminum Foundry & Mould Works, Inc.; Alan Low, Market Manager, Husky Injection Molding Systems.

The Reviewers of this chapter are: Samuel Belcher, Owner, Sabel Plastechs, Inc.; Mike Brown, Manufacturing Engineer, DeRoyal Plastics Group.
CHAPTER 7

BLOW MOLDING TERMS

TABLE 7-1
Competitive Process Comparison*

<table>
<thead>
<tr>
<th>Process</th>
<th>Tooling Cost</th>
<th>Cycle Time</th>
<th>Part Price</th>
<th>Finish Cost</th>
<th>Tolerance Control</th>
<th>Physical Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blow Molding</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Injection Molding</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Thermoforming</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>(Twin Sheet)</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

1 indicates the best or least costly method
4 indicates the worst or highest cost method

*Assumes that a part can be produced by any of these four methods.

pinch-off. The raised edge around the cavity in the mold. It defines the edge of the part and separates the excess material as the mold is closed. The pinch edge needs to be sharp enough to facilitate trimming but not cut the parison.

programmed parison. A parison whose wall thickness changes as a result of the mandrel movement. This change is needed to offset gravitational effects and to provide additional material in sections with lower blow ratios or heavier wall thickness requirements.

sag. A thinning of the upper portion of the parison due to the weight of the parison as it hangs from the die head.

shrinkage. The amount a part contracts after it is ejected from the blow mold. This varies with materials and operating conditions. It is compensated for by making the mold larger than the final part dimensions.

vents. Small air passages cut into the surface of a mold to allow the air to escape as the parison is being blown.

HISTORY

The development of the blow-molding industry has grown because it often proves to be the most economical way to produce a part, once a suitable material becomes available. In fact, the development of new thermoplastic polymers that are blow-moldable has always preceded the conquering of a new market by the blow-molding process.

Glass blowing by early civilizations was the forerunner of the blow-molding process. However, it was not until the 1880s that a patent was granted for a machine to blow-mold celluloid into items such as handles, jewelry, and toys. The process involved heating sheets of material and blowing them into closed molds with air pressure. The first modern equipment that extruded a tube of melted material into a closed mold and injected air into it was developed in the mid-1930s. Cellulose acetate replaced celluloid during this period. Following World War II, the availability of low-density polyethylene (LDPE) led to the mass sale of squeeze bottles for a variety of household products. The development of high-density polyethylene (HDPE) in the late 1950s led to the 1-gal (3.8 L) milk bottle and many other types of containers. The 1970s were characterized by the availability of thermoplastic polyester (PET) and the development of the injection stretch blow molding process to produce PET bottles. With the development of blow-moldable grades of polypropylene (PP), polyvinyl chloride (PVC), and various engineered resins, the industrial market for blow molding was started.

TYPES OF BLOW-MOLDING PROCESSES

There are two basic blow-molding processes: injection blow molding and extrusion blow molding. The injection blow-molding process is similar to injection molding and is limited to smaller sizes of parts than extrusion blow molding. The injection blow-molding process produces parts to tight dimensional or weight tolerances that might not be achievable with the extrusion blow molding process. These tight tolerances may be required for some automatic filling applications. Injection blow molding is also used to mold parts out of materials such as PET or polystyrene (PS) which are difficult to mold by the extrusion blow molding process. Injection blow-molded parts can be produced without flash or trimming. Some materials produce clearer bottles when injection blow molded. Although tooling is more expensive for injection blow molding, the cycle times are faster than for extrusion blow molding. Table 7-2 compares the two processes.

INJECTION BLOW MOLDING

Figure 7-1 shows the setup for a typical injection blow molder. The plastic is melted in an injection-molder-style extruder and is injected into a steel mold under high pressure to create a preform. A core rod forms the interior dimensions of the preform, while the steel mold forms the outside dimensions. When the preform has cooled sufficiently, the mold opens vertically and the preform on the core rod is lifted and rotated to the blow mold. The blow mold, which is usually aluminum, closes on the core rod and preform, air is blown through the core rod, and the final shape of the part is formed. Thus, injection-molded details can be obtained on a hollow part which could not otherwise be injection molded. Sometimes a fourth station is used on an injection blow molder for printing or orientation. A variation of injection blow molding involves biaxial orientation of the preform. This is done to pro-
duce PET bottles and is referred to as injection stretch blow molding. This process can be done in one machine or it can be done in two separate processes in which the preforms are first molded on conventional injection molding equipment and then reheated and blown. This type of biaxial orientation improves the heat distortion, clarity, and impact characteristics of the PET bottle.

**Process Characteristics of Injection Blow Molding**

During the initial stage of this process, the injection stage, the melt is injected into a split parison cavity and around a predetermined core rod (see parison station in Fig. 7-2). Once the melt is conditioned, the molds open and then rotate 120° to transfer the parison into a split blow-mold cavity (blow-mold station). Compressed air enters through the core rod, blowing the conditioned parison melt against the blow-mold cavity wall. After the material has cooled in the blow-mold cavity, the molds open and the finished container is then rotated 120° for transfer to the pick-off (eject) station for removal from the core rod.

In the pick-off station, bottles are automatically removed from the core rods and fall directly into a shipping carton or are placed in an upright position on a conveyor belt for posthandling.

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**TABLE 7-2**  
Molding Process Comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>Extrusion Blow</th>
<th>Injection Blow</th>
</tr>
</thead>
<tbody>
<tr>
<td>L/D ratio</td>
<td>25:1 or more</td>
<td>12:1 need development</td>
</tr>
<tr>
<td>Elliptical ratio</td>
<td>12:1 or more</td>
<td>3:1</td>
</tr>
<tr>
<td>Blow-up ratio</td>
<td>20:1 or more</td>
<td>3:1</td>
</tr>
<tr>
<td>Handleware</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Offset neck</td>
<td>Yes</td>
<td>No (development)</td>
</tr>
<tr>
<td>Tooling cost</td>
<td>Low</td>
<td>2.5–3 times cost of extrusion blow</td>
</tr>
<tr>
<td>Number of parts/year</td>
<td>Low</td>
<td>7,000,000 or more</td>
</tr>
<tr>
<td>Neck finish and tolerance</td>
<td>Limited</td>
<td>Superior</td>
</tr>
<tr>
<td>Bottle size–high volume advantage</td>
<td>Over 16 oz (0.473 L) small neck</td>
<td>16 oz and under</td>
</tr>
<tr>
<td></td>
<td>Over 32 oz (0.946 L) medium neck</td>
<td>32 oz and under</td>
</tr>
<tr>
<td></td>
<td>Over 1 gal (3.8 L) wide neck</td>
<td>1 gal and under</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Styrene</td>
<td>Very poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>PVC - small</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>PVC - large</td>
<td>Excellent</td>
<td>(To be developed)</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>HDPE</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Barex</td>
<td>Good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

---

Fig. 7-1 Injection blow molding.
In addition to the predominantly used three-station machines, four-station machines are available (see Fig. 7-3). With four stations, the machine indexes in 90° increments instead of the 120° movements of the three-station machine. The fourth station can be used for additional core rod conditioning, necessary when processing engineering thermoplastic materials such as PET. The pick-off (eject) station functions the same as on the three-station machine.

Types of Injection Blow-molding Machines

Two major manufacturers supply the injection blow-molding industry with integrated injection blow-molding systems.

One company equips all its molding machines with a horizontal reciprocating screw plastifier. It employs a tie bar clamp design in the molding area like injection molding machines. All clamp hydraulics in this area are underneath the stationary machine platen. The other manufacturer equips its molding machines with a vertical nonreciprocating screw plastifier or, on request, with a horizontal reciprocating screw plastifier. It employs a C-clamp design in the molding area. The clamp hydraulics in this area are above the movable machine platen.

The vertical screw plastifier is adaptable to most materials that require low shear (see Fig. 7-4). For high-torque materials, the horizontal reciprocating screw plastifier is preferred.

Applications

Injection blow molding offers many advantages for producing plastic containers and has become the standard for quality packages. The ability to produce closely tolerated, completely finished containers without secondary trimming operations, and to consistently repeat dimensions bottle-to-bottle, make injection blow molding an economical process for the packaging industry.

Advantages. Some of the advantages of injection blow-molded containers are:

- Precise neck finishes (see Fig. 7-5).
- No trimming or reaming of excess flash.
- High cavitation.
- Repeatability.
- Excellent surface appearance.
- Greater range of rigid materials, such as polystyrene, styrene-acrylonitrile (SAN), and acrylonitrile-butadiene-styrene (ABS).
- Produces hollow parts.
- Large part capability.
- Opportunity for parts consolidation.
- Multimaterial capability.
- Lower cost mold versus injection molding.

These advantages make injection blow molding suitable for producing containers to the cosmetic, pharmaceutical, and food
CHAPTER 7
TYPES OF BLOW-MOLDING PROCESSES

Fig. 7-3 Four-station injection blow molding.
Fig. 7-6: Vertical plastifier.
industries. In the past, the process was used to produce only small containers. Today, it is often used to produce 32 oz (1 L) bottles and jars.

Disadvantages. Injection blow molding cannot yet fabricate:

- Containers with handles.
- Containers having elliptical ratios (bottle width to thickness) greater than 3:1.
- Containers with overall length-to-diameter ratios greater than 12:1.
- Containers with blow-up ratios (neck finish diameter to bottle diameter) greater than 3:1.
- Requires materials with melt strength.
- Material or color changeover can take longer versus injection molding.
- Knit lines.
- Draw ratio.

Industrial applications. With new technology in materials, screw design, larger tonnage machines, tool design, and feedback process control, the injection blow-molding process is becoming well suited to packaging for other than cosmetic, pharmaceutical, and food applications. Industrial products such as the automotive bellows and seal for the universal joint on front-wheel-drive axles—and consumer products such as toys, decorative curtain rod ends, vases and pots, and utility household items such as vacuum cleaner parts—are now being injection blow molded. Previously, these products were processed by extrusion blow molding and injection molding.

**EXTRUSION BLOW MOLDING**

The basic extrusion blow-molding cycle is as follows (see Fig. 7-6):

1. The thermoplastic resin is melted in the extruder and is extruded or rammed out of the die head between two mold halves. The tube of melted plastic is called a parison.
2. The mold halves come together when the parison has reached the correct length. Pinch bars at the bottom of the mold close off the tube and maintain some air in the parison to prevent the walls of the parison from sticking together prematurely.
3. The molds are closed completely, sealing the parison and creating flash on the edges of the mold.
4. Air is blown through the blow pin mounted in the head of the machine, forcing the soft plastic of the parison out against the walls of the mold. The part is cooled in the mold, under pressure, until it can maintain its shape and required dimensions. Before the mold is opened, the blowing air is stopped and the air is vented to prevent part distortion.
5. The mold is opened and the part is stripped from the blow pin by either mechanical devices or by blowing it off. The blow pin may also be retracted into the head.

The extrusion blow-molding process is primarily used for smaller, high-quality bottles, such as those required by the cosmetics industry, or whenever a good neck finish is important. It is also used successfully for open containers such as plastic drinking cups, which could be molded in conventional injection molds, except that blow molding yields walls that are substantially thinner and lighter than those...
Fig. 7-6 Steps in the basic extrusion blow molding process.
made by injection molding, without sacrificing any significant properties.

The extrusion blow-molding process is either intermittent or continuous. In a continuous operation, the plastic is melted in an extruder very similar to the kind used in any extrusion process. The melted material enters the die head, where it is formed into a parison. If the flow of the parison out of the die head is constant, it is referred to as a continuous process. If the flow of the parison stops and starts, it is referred to as intermittent, even though the extruder may run continuously. Continuous machines are generally used for bottle or container applications in sizes up to 5 gal (19 L), but they are finding increasing industrial applications when the part size, cost, and quantity justify the extra investment.

Machine Types

The three types of continuous machines are stationary, shuttle, and wheel. The shuttle machines shown in Fig. 7-7 operate with the molds and press platens moving up to grab the parison and pull it from the die head. While the first parison is being blown in the first set of molds, a second parison is being extruded. When the parison is complete, the second mold moves up to grab it. By the time a third parison has been extruded from the same die head, the first part has been ejected from the first mold, which is free to grab the third parison.

A variation of this type of continuous machine grabs the parison and moves it into the mold where it is blown. In this case, the press section is stationary. The parison can also be stretched in this process, which is called extrusion stretch blow molding. The wheel machine rotates a mold into a continuously extruded parison. The mold closes and the parison is blown. The wheel continues to rotate and another mold is brought into position to close onto the parison. When the parison is cool, it is ejected from the mold. The part may be separate or attached to the previous part by the continuous parison. Wheel machines may be vertical or horizontal and are used in very high-volume situations where more expensive tooling and equipment can be justified. Figure 7-8 illustrates both vertical and horizontal continuous blow-molding machines.

Intermittent blow-molding machines are available in either accumulator head or reciprocating screw versions. In the accumulator head machine, the melted material accumulates in the die head. The head is designed so that hydraulic cylinders (plungers) on the top of the head ram the accumulated material. In reciprocating screw machines, the melted material accumulates in the barrel of the extruder. As the material accumulates, the screw backs up like an injection molding machine. When the screw rams, moving forward as in the injection cycle of an injection molding machine, it pushes the plastic out of the barrel and through the die head to form the parison. The intermittent processes are shown in Fig. 7-9.

EXTRUSION STRETCH BLOW MOLDING

In molding radially symmetrical shapes (cups, bottles, etc.), the core is rotated during injection in relation to the cavity before the plastic is fully rigid. This creates an effect similar to the biaxial stretching of a sheet. While such product conventionally molded would be fairly strong longitudinally, it would have little resistance to crushing forces applied sideways or to internal pressures. When molded with rotation, the product can be equally strong in both directions.

In stretch blow molding, a similar principle is applied to the hot parison, before and during blowing. The hot and relatively thick-walled parison is shorter than the finished product, and much smaller in diameter. Stretching takes place in two directions (to a lesser degree in the direction of the product length and much more in the transverse direction.)

Single-stage Process

There are several different systems used for single-stage stretch blow molding. They all have the following production sequence in common, although their mechanics may be quite different.

- Parisons are molded in an injection mold.
- Parisons are then transferred to a heat conditioning setup, to lower the temperature suitable for blowing.
- Parisons are introduced into the blow mold.
- Parisons are stretched and blown.
- Finished products are ejected.

The advantage of the single stage process is that it is an in-line process, without intervening storage of unfinished products. It is
Fig. 7-8 Wheel machines for continuous extrusion blow molding: (a) horizontal; (b) vertical.
Fig. 7-9 Machines for intermittent extrusion blow molding: (a) accumulator head; (b) reciprocating screw.
also more energy-efficient since the heat required for the injection molding of the parisons is not completely removed from the products, but is partly utilized for the blow cycle.

Another advantage is the immediate feedback of possible quality problems. Also, since every injection cavity corresponds to a specific blow cavity, the source of deviation from specification can be readily identified.

The process is similar to injection blow molding, apart from the heat conditioning and the stretching. There are also some injection blow molds that utilize stretching features without the conditioning step.

The disadvantage of some single stage systems is their relatively low output. The blow cycle could usually be four to five times faster than the injection cycle, but must be deliberately held to the same speed as the injection cycle. However, other systems now use injection molds in which the number of cavities is a multiple of the number of blow cavities, at a ratio equal to the ratio between injection time and blow time. (For example, with 24 second injection time and 4 second blow time, the cavity ratio would be 6:1 between injection and blow mold.)

**Two-stage Process**

In this method, the parisons are produced in conventional injection-molding machines. After molding, the products are cooled completely and removed to storage, or conveyed directly to specialized “reheat and blow” machines. There are several versions of these machines but the principle is basically the same:

- Cold parisons are arranged (automatically) on carriers.
- Parisons are transferred to a heating station, where they are heated to blowing temperature.
- Parisons are transferred to the blow mold.
- Parisons are stretched and blown.
- Finished products are ejected.

The advantages of the two-stage system are:

- The parisons can be produced by the most efficient methods by specialized, experienced molders (molding of preforms from PET is considerably more difficult than conventional plastic molding).
- Parisons can be stored to take up slack in production and permit extensive maintenance or retooling, without interruption of production, and without taking up much space.
- Shipping may be simplified. Parisons, rather than bulky bottles, can be shipped to a user such as a bottling plant. The blowing setup is relatively simple and can easily be an in-house process at the bottler.

The main disadvantage of the two-stage system is that the parisons may appear to be satisfactory when molded but may turn out to be unsuitable for blowing, or produce finished products with characteristics below the expected standards. For example, it may take weeks to find that a certain lot shipped had too high an acetaldehyde level, and that the finished bottles had to be scrapped. Another disadvantage is the additional energy requirement, because the parisons must be reheated for blowing.

**MATERIALS**

Most thermoplastic materials can be blow-molded. The type of material will have a great influence on the choice of the particular blow-molding process. The grade of material used for extrusion blow-molding processes generally has a fractional melt index, high molecular weight, and good melt strength since it needs to be able to support its weight while it is hanging as a parison. The injection blow-molding process can tolerate a much broader range of melt flows. Increasingly, glass- and mineral-filled materials are being blow-molded to produce parts which are more rigid and can be used at higher temperatures. Thermoset materials are not blow-molded.

The largest group of blow-molded thermoplastics is polyolefins, which includes LDPE, linear low-density polyethylene (LLDPE), and polypropylene (PP). Polyolefins offer a number of advantages, including excellent melt strength and a wide temperature processing window. Good blow characteristics allow the materials to stretch without tearing. Polyolefins do not require drying and can be reprocessed many times without degrading. Polyolefins are soft, enabling easy removal of flash, and are very resistant to most chemicals. All of these factors account for the use of polyolefins in a number of bottle and container applications, ranging from food products to motor oil, chemicals, and hazardous waste. Polyolefins are used in a number of industrial blow-molding applications and can be blow molded by any of the various processes mentioned. Higher-molecular-weight grades of polyolefins have expanded the uses for industrial blow-molded products.

The next largest volume resins used in blow molding are PET and PVC. Most of these resins go into bottles. Both materials have good clarity and impact strength characteristics. The disadvantages of PET and PVC include lower chemical resistance, higher cost, and increased difficulty of processing. PET requires an orientation process to develop its properties. It also is very moisture-sensitive and requires drying. Likewise, PVC needs to be oriented but can be extrusion blow molded by a continuous extrusion stretch molding process. It is temperature-sensitive and will degrade if overheated.

Engineered resins are increasingly used in blow-molding applications. These resins include polycarbonate (PC), nylon, thermoplastic elastomers (TPE), polyurethane (PU), and various alloys or blends including polyphenylene oxide/poly styrene (PPO/PS), PPO/nylon, and PC/acylonitrile-butadiene-styrene (ABS). The engineered resins are used for increased impact strength, higher heat deflection temperature, reduced flammability, and better fatigue properties. Talc, mica, and fiberglass can be compounded into both engineered and non-engineered resins to improve stiffness and heat deflection characteristics. Figure 7-10 shows a blow-molded seat back made from 25% mica-filled HDPE. This part provides the basic structural strength for the rear seat back in an automobile. Materials that are filled do not blow as well as unfilled materials, since the filler does not stretch like the thermoplastic material. Table 7-3 lists some of the common blow-molded materials and compares various characteristics. Table 7-4 lists materials used for injection blow molding.

Because of the amount of flash and trim scrap generated in the blow-molding process, it is critical to the economics of the process that this excess material be reused. Reground material should be extrudable and moldable to match the amount of flash generated by a particular part configuration. This can be done with most thermoplastic materials. Physical properties are usually not reduced by several generations of regrind, since the blow-molding process is a rela-
tively low shear process and does not degrade most thermoplastic materials. However, viscosity and melt strength are the first properties subject to change. Reduction of the amount of regrind material will offset any loss of processing properties. Care should be taken in the design of a part and mold to guarantee that the amount of regrind generated from trim scrap will be able to be reused in the part. Regrind use of heat-sensitive materials such as PVC, or any material that is subjected to excessive heat during the molding process, may be limited.

### TABLE 7-3

<table>
<thead>
<tr>
<th>Material</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>The easiest material to blow-mold, due to wide processing temperature window, good melt strength, and blow ratio. Material is relatively inexpensive and has good chemical resistance, does not require drying, and does not degrade easily when recycled.</td>
</tr>
<tr>
<td>PP</td>
<td>Relatively easy to blow-mold. It has a fairly wide processing window and good melt strength with fractional melt materials. Material has slightly higher heat distortion and melting temperature than HDPE. Material cost is slightly higher than HDPE. It does not require drying. The regrind degrades more readily than HDPE. Slightly better dimensional control than HDPE.</td>
</tr>
<tr>
<td>PC</td>
<td>More difficult to blow mold due to a narrow processing temperature window relative to melt strength. The material requires drying and, because of its toughness, is also difficult to grind. The material has a higher glass transition temperature than HDPE, so cycle times can be faster, but processing temperatures are higher. Usually requires elevated mold temperatures.</td>
</tr>
<tr>
<td>PPO/PS</td>
<td>Easier to process than PC because of a larger processing window, but more difficult than HDPE. This material requires drying and is not as difficult to grind as PC. Regrind is fairly stable and can be used without much difficulty. Usually requires elevated mold temperatures. Parts have good dimensional control.</td>
</tr>
<tr>
<td>TPE</td>
<td>These flexible materials are more difficult to mold than HDPE, but have generally good blow ratios and processing windows. More problems occur when regrind is reused on these materials. Most TPEs require drying and the cost of the materials varies from moderate to very expensive.</td>
</tr>
</tbody>
</table>

### TABLE 7-4

<table>
<thead>
<tr>
<th>Material Used for Injection Blow Molding</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE</td>
</tr>
<tr>
<td>HDPE</td>
</tr>
<tr>
<td>PP</td>
</tr>
<tr>
<td>PS</td>
</tr>
<tr>
<td>PC</td>
</tr>
<tr>
<td>SAN</td>
</tr>
</tbody>
</table>
This section will discuss the following:

- Tooling.
- Parison neck ring.
- Parison (preform) cavity.
- Blow-mold neck ring.
- Blow-mold cavity.
- Bottom plug.
- Core rod assembly.
- Injection manifold systems.
- Parison (preform) design.

**TOOLING**

Tool components for injection blow molding must be machined to precise tolerances because of their critical combined function in the overall molding cycle. The parison molds are more critical than the blow molds, since they are subjected to direct hydraulic clamp pressures and material injection pressures. The core rods are subjected to the same conditions as the parison molds and must be concentric to initiate good blowability. The blow molds are subjected to only a third of the clamping force of the parison cavity. Due to the precise machining and interrelations of the component parts necessary to make up a complete injection blow-molding tool, excessive dimensional variations between tool components cannot be tolerated.

**Parison Neck Ring**

The parison neck ring forms the finished shape of the threaded or neck section of the container (see Fig. 7-11). It also centers and securely retains the core rod inside the parison to alleviate core rod deflection during the injection part of the cycle. The neck ring is a separate component which must be precisely fitted into the parison cavity to obtain a flash-free part. The parison neck ring has its own independent thermal control channels for conditioning the molded neck finish.

The parison neck ring is mostly made from nondeforming air-hardened tool steel.

**Parison (preform) cavity.** The parison mold consists of stationary and movable halves, with cavity dimensions determined by the weight, wall thickness, and type of resin of the final part to be injection blow molded. The width of the parison mold is governed by the number of mold cavities that will fit into the specific machine, limited by length of the machine trigger bar, machine clamp tonnage, and plastifier melt capacity.
Temperature control (material conditioning) is an essential part of the cavity design. Temperature zones are created by channels drilled into the mold body for the circulation of a liquid conditioning medium. These channels are connected to form individually controlled temperature zones. The number and location of the zones within the parison cavity are critical considerations in the design as they directly affect the blowability efficiency of the parison shape. Each temperature control channel is positioned along the parison cavity profile to serve a specific predetermined purpose so that the temperature can be varied along the parison profile to ensure uniform blowing of the parison wall.

Depending on the type of plastic material being molded, parison cavities are made from air hardened tool steel or prehardened steel.

Blow-mold neck ring. Unlike the parison neck rings that actually form the desired neck finish shape, the blow-mold neck contains and secures the already formed neck finish during the blow sequence of the process (see Fig. 7-12).

The neck finish diameter of the blow-mold neck ring is slightly larger than the parison neck ring so that it can accept the already formed parison neck finish without distorting it during transfer and seating into the blow-mold neck ring.
Independent cooling is incorporated in the blow-mold neck ring for thermal control.

Depending on the plastic material being molded, the blow-mold neck ring is generally made from air hardened tool steel or prehardened steel.

Blow-mold cavity. The blow-mold cavity consists of stationary and movable halves similar to the parison mold cavity. Depending on the type of plastic material to be molded, these cavities are made from air-hardened tool steel, prehardened steel, aluminum, or beryllium copper.

Blow molds are used to shape the final form of the container and are not exposed to the severe clamp and injection pressures of the parison mold. The blow mold is subjected to the minimal blow clamp pressure needed to withstand the 150 psi (1034 kPa) air pressure necessary to blow the parison shape.

The most important consideration in the blow-mold cavity design is to ensure adequate cooling. Here again, as in the parison mold cavity, peripheral channels should be provided for maximum cooling to help reduce overall cycle time.

Bottom plug. The bottom plug is an independent part of the blow mold cavity and forms the bottom configuration of the container. It is usually made in halves, may be fixed in position or retractable, and can be water-cooled. For most polyolefin containers, push-up heights can be stripped over the fixed bottom plug when the mold is opened. With polystyrenes, polycarbonates, and other rigid materials, a retractable bottom mechanism is necessary.

When a retractable bottom mechanism is used, the upward movement of the top half of the mold allows the bottle to evacuate the blow mold cavity without stripping or distortion. The retractable mechanism can be operated by a cam or, in difficult cases, by air or hydraulic cylinders (see Fig. 7-13).

Core rod assembly. The core rod forms the inside diameter of the neck finish and the inside shape of the parison (see Fig. 7-14). The core rod incorporates the air channel and valves used to blow the plastic melt into the final shape of the bottle. Core rods are usually made of oil-hardened tool steel. A hex nut, spring, and star nut assembly at the back end section of the core rod opens the core rod valve for blowing and closes the valve prior to injection.

Non-temperature-controlled core rods are heated by the melt to provide blowability; however, they do not maintain a consistent temperature profile along the molding surface as do core rods with temperature control. With the advent of heat-sensitive and engineering thermoplastic resins, temperature-controlled core rods provide a more accurate and consistent temperature profile along the core rod molding surface.

Injection manifold systems. The manifold assembly is fastened to the stationary parison die set. The manifold assembly itself is made up of the manifold, a manifold base, nozzle clamps, and nozzles. The injection nozzles are held by the nozzle clamps with retaining screws accessible from the rear of the manifold (see Fig. 7-15).

The hot melt is injected from the machine nozzle into a manifold which performs the same function as a hot-runner manifold in regular injection molding. The manifold design used for injection blow molding, however, is far less sophisticated than the type used in hot-runner or insulated-runner injection molds. The simple manifold design has been adequate because most resins used for injection blow molding are easily processed. But with the advent of higher-cavitation, heat-sensitive, and engineering thermoplastic materials, more sophisticated special manifold designs are required (see Fig. 7-16).

The injection nozzles allow passage of the melt from manifold to parison cavities. Nozzle orifices generally vary in diameter from cavity to cavity in a given mold set to provide a balanced fill of...
Fig. 7-14 Core rods, standard and temperature-controlled.
Fig. 7-15 Manifold assembly.
cavity to cavity in a given mold set to provide a balanced fill of all cavities.  

Parison (preform) design. A crucial element of injection blow molding is the configuration of the core rod and parison. Each container shape has its own unique core rod and parison design. If the initial design of the parison and core rod is not suited for the particular bottle to be molded, a production processing problem will continue until the design is corrected.

The designer should always keep in mind maximum processibility or blowability when selecting the parison and core rod shapes. Do not, under any circumstances, sacrifice processibility for maximum cavitation. Consider injection clamp tonnage relative to the projected area of the parison shape, the physical limitations of the machine platen area, the machine trigger bar length, and the total shot capacity of the machine plastifier. Always insist on building a single- or unit-cavity tool first, before going into production tools. Much can be learned about the molding characteristics of a particular core rod and parison design through single-cavity sampling. If the design is difficult to process during the single-cavity stage, you can be sure the process window will be narrow in production, and this is not a desirable goal. Design changes are normally made during the single-cavity stage to produce parts in specification with as broad a process window as possible. Normally, the unit cavity tool can become part of production tooling.

**EXTRUSION BLOW-MOLDING EQUIPMENT**

This section will discuss the following:
- Screw design.
- Parison forming section.
- Machine types.
- Head tooling size.
- The blowing section.
- Trimming section.
- Auxiliary equipment.
- Process control.
- Mold design and construction.
- Maintenance.

Extrusion blow-molding equipment generally consists of an extruder or melting section, a parison forming or preform section, a blowing section, and a trimming station. The thermoplastic material used in blow molding is melted in an extruder similar to a conventional extruder. It should have barrel cooling in order to maintain the melt temperature at the desired level. It is best to extrude at the lowest possible temperature to minimize the amount of heat that must be removed from the material in the cooling cycle, and to maintain the maximum melt strength of the material. As the material extrudes or rams out of the die head, gravitational effects tend to cause the parison to stretch. The wall of the parison is thicker at the bottom of the parison than at its top (see Fig. 7-17a). The hotter the material when it exits the die head, the lower the viscosity or melt strength of the material and the more it stretches.

**SCREW DESIGN**

The design of the screw used in the extruder will also determine the melt temperature of the exiting material. The material is melted...
by the shear created between the screw and barrel of the extruder on
the plastic pellets. The lower the RPM a screw can run for a given
output, the lower the melt temperature. This is a function of screw
geometry and size. Larger-diameter screws and deeper metering
sections increase output.

The screw also serves to mix the melted material. Since ther-
moplastic materials have laminar flow characteristics, mixing is
not always easy to achieve while attempting to keep the melt tem-
perature as low as possible. A variety of screw mixing and melting
devices and designs are available. Equipment and resin suppliers
should be consulted for the preferred design.

Extrusion screws are classified by diameter, L/D ratio (the
flighted length of the screw divided by the diameter), and the
compression ratio (depth of the feed section divided by the depth
of the metering section).

The output of a screw is given by the following formula:

\[
\text{Output} = 2.3 \, D^2 \, M \, g \, R \, \text{lb/h}
\]

where:

- \( R \) = screw RPM
- \( M \) = depth of the metering section
- \( g \) = specific gravity of the resin being extruded
- \( D \) = diameter of the screw

Many other factors determine actual output. These include
the bulk density of the resin pellets, screw clearance with the
barrel, processing temperatures, and back pressure on the screw.
A variety of mixing and melting designs can be incorporated
into screw designs to improve dispersion of colorants and additives
and improve melt uniformity. The most common of these is the
Maddock mixer, which is used extensively on polyolefins and poly-
olefin blended materials. A variety of barrier-type screws have been
developed to improve melt efficiency by separating the melted and
unmelted material as it passes down the screw channel in the barrel.
Equipment and resin suppliers can provide specific designs.

PARISON-FORMING SECTION

The parison-forming section of an extrusion blow molder is
called the head, and its design and operation are unique to extrusion
blow molding. The head must split the melted polymer into two flow
streams and distribute it around a mandrel, then join the two streams
back together without forming a weld line. The lower mandrel sleeve
restricts the flow, creating back pressure which helps to uniformly
distribute the material. Blowing air is channeled into the head and
donw through the center of the mandrel. Heater bands on the outside
of the head maintain a uniform preset temperature.

As the polymer moves down the inside of the head, it flows
toward the die and mandrel (chase and pin) at the exit. The die is
clamped to the bottom of the head and the pin screws into the bot-
tom of the mandrel core rod. The diameter of the die controls the
diameter of the parison as it exits the mandrel. The mandrel core
rod moves up and down, closing off or opening up against the die
(in some cases the chase moves and the pin is stationary). This
opening and closing controls the thickness of the parison. Most
blow molders have parison programming which adjusts the thick-
ness of the parison as it is rammed. The mandrel core rod has a
programming cylinder attached at the top of the head. The role of
parison programming is shown in Fig. 7-17b.
MACHINE TYPES
In accumulator head machines, the melt accumulates in the head and pushes up a ram cylinder as it is filling the head. When sufficient material has accumulated in the head to form the parison, the cylinder rams down, forcing the melted plastic between the die and pin. A variety of head designs are used to obtain a uniform wall thickness in the parison; Figure 7-18 shows a typical design. If the wall thickness is not uniform, the parison will bend or hook to one side or the other. The die can be adjusted from side to side as shown in Fig. 7-19 to compensate for this action. Accumulator heads allow a slight amount of leakage out of the top of the head to provide a thin layer of polymer as a lubricant for the ram parts.

Reciprocating screw machines do not have a ram cylinder, since the melt accumulates in the barrel of the extruder and the extruder screw does the ramming. Continuous extrusion machines do not have ram cylinders, since the flow is continuous through the head and pressure to exit the head is provided by the extruder.

Accumulator head machines are classified by the shot size of the head when filled with HDPE material. Thus, a 5-lb (2.3-kg) machine can extrude 5-lb (2.3-kg) of HDPE (including flash) in one cycle or shot. Reciprocating screw machines are classified by the shot size of the machine in terms of the volume available in the barrel and head for melt accumulation. Continuous machines are classified by the size of the extruder, the number of heads, and the size of the press.

HEAD TOOLING SIZE
Critical to the success of the blow molding process is the choice of the head tooling size in relation to the part to be blow molded.

Head tool sizing can be done by analyzing the results of previous head tool diameters for similar materials, equipment, and operating conditions.

- Determine if the part will be flashed or if the parison will be captured (the parison diameter is smaller than the smallest section of the part and is blown entirely within the cavity of the part).
- If the part is flashed, determine the peripheral dimension of the part to be molded at the largest point on the part perpendicular to the parison (normally the longest section of the part is parallel to the parison). Divide the peripheral dimension by 3.14 to obtain an effective diameter. If there were no other influences, the available head tool with the closest match to this diameter would be the head tool diameter to use. The effective diameter needs to be either increased or decreased according to the swell factors indicated in Table 7-5 to yield a final diameter.
- If the part is not flashed, the head tool will need to produce a parison diameter small enough to fit within the smallest non-flashed section of the part cavity. From this effective diameter and the swell factors, the head tool diameter can be determined.

Fig. 7-18 Internal design of parison head: (a) cross-section; (b) cutaway view.
If the choice of head tooling is too small, the part will have too thin a wall or will not be completely formed. Although parison programming allows the wall thickness to be varied, this will not compensate sufficiently for an incorrect head tool diameter. If the head tooling is too large, the part will have excessive flash and it may not be possible to completely close the molds.

Polymers generally swell as they exit the die, thus giving a parison of larger diameter than the die. Table 7-5 gives some information on die swell and processing parameters which will affect the diameter of a parison. Since the head diameter is fixed and the diameter of the desired parison changes, the diameter of the head tool may be larger or smaller than the internal flow diameter of the head tool (mandrel). When the die tooling is larger than the internal head flow diameter, the tooling is referred to as divergent, and when it is smaller it is referred to as convergent. This is shown in Fig. 7-20. Table 7-6 shows the size and capacity range for the various types of blow molds.

**THE BLOWING SECTION**

Once the parison is formed, the mold must be closed around it and held together while the part is blown. Each equipment manufacturer has its own press design. Continuous machines have smaller size platens working at lower tonnage and higher speeds. With shuttle machines, the press must move as it grabs the parison. These presses tend to be operated by toggle action with hydraulics. Intermittent machines are usually larger and slower, so straight hydraulic clamping is used. Platens should be large enough so that molds do not need to be overhung and rigid enough to withstand the maximum clamp tonnage without deflection. The press should be designed to allow easy part removal and mold change. Parts usually drop onto a conveyor or are removed by a mechanical picker that attaches to the top flash of the part prior to mold opening. Most molding operations are automatic (closed gate) so that the parts are automatically ejected or removed.

Blow air is forced into the part, either through top or bottom blow pins that extend inside the parison or through smaller blow needles which penetrate the parison from inside the mold while the part is blown. Blow air pressures range from about 60 up to 300 psi (414–2068 kPa). The usual pressure is about 100 psi (689 kPa). Liquid nitrogen or carbon dioxide can also be used to blow parts and provide additional cooling to the inside. It is important to have a sufficient volume of flow to blow a part quickly. It is also important not to restrict the flow of air during the part venting cycle prior to opening the mold. Cycle times can be reduced by using multiple needles and circulating air inside the part during the cooling cycle. Needle or pin diameter is determined according to equipment or design restrictions.

**TABLE 7-5**

<table>
<thead>
<tr>
<th>Material</th>
<th>Swell (%)</th>
</tr>
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<tbody>
<tr>
<td>HDPE (varies with polymer</td>
<td>15–60</td>
</tr>
<tr>
<td>manufacturing process)</td>
<td></td>
</tr>
<tr>
<td>LDPE</td>
<td>30–60</td>
</tr>
<tr>
<td>PVC (rigid)</td>
<td>30–35</td>
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<tr>
<td>PS</td>
<td>10–20</td>
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<tr>
<td>PC</td>
<td>5–10</td>
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<tr>
<td>PPO/PS</td>
<td>5–10</td>
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<tr>
<td>Nylon</td>
<td>5–15</td>
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<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>Swell</th>
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</thead>
<tbody>
<tr>
<td>Internal head diameter increases</td>
<td>Increases</td>
</tr>
<tr>
<td>Converging tooling</td>
<td>Increases</td>
</tr>
<tr>
<td>Diverging tooling</td>
<td>Decreases</td>
</tr>
<tr>
<td>Parison melt temperature increases</td>
<td>Decreases</td>
</tr>
<tr>
<td>Ram speed increases</td>
<td>Increases</td>
</tr>
</tbody>
</table>

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**Fig. 7-19 Adjustment of die position to prevent parison bending.**

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**Fig. 7-20**

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**Fig. 7-21**

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**Fig. 7-22**
For most intermittent machines, trimming is not an integral part of the blow molder. The part is removed from the machine and trimmed in a secondary operation. The type of operation varies with the particular part. The parts usually cool for several minutes and then are either manually or automatically deflashed. Deflashing is done manually by scoring the flash with trim knives and pulling it off. It can be removed automatically by deflashing dies in presses or by cutting with CNC routers. After the flash is removed, the parting line usually needs to be hand-trimmed with a knife or a torch. Secondary operations such as trimming end bubbles, drilling or punching holes, and attaching component parts are then completed. The deflashing and trimming operation is automatic on most continuous-extrusion blow molders (done by hydraulic presses and steel deflashers).

**TABLE 7-6**

Typical Blow Molder Size and Capacity  

<table>
<thead>
<tr>
<th>Part Weight, lb (kg)</th>
<th>Extruder Output lb/h (kg/h)</th>
<th>Number of Heads</th>
<th>Platen Size, in. (cm)</th>
<th>Clamp Pressure ton (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Continuous Extrusion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under 1</td>
<td>100-500 (45–227)</td>
<td>1-4</td>
<td>24 × 24 (61 × 61)</td>
<td>20 (179)</td>
</tr>
<tr>
<td>1-5</td>
<td>300-1300 (136–590)</td>
<td>1-4</td>
<td>30 × 24 (76 × 61)</td>
<td>33 (295)</td>
</tr>
<tr>
<td><strong>Accumulator Head</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under 1</td>
<td>200 (91)</td>
<td>1-2</td>
<td>18 × 24 (46 × 61)</td>
<td>20 (179)</td>
</tr>
<tr>
<td>5</td>
<td>500 (227)</td>
<td>1-2</td>
<td>30 × 40 (76 × 102)</td>
<td>40 (358)</td>
</tr>
<tr>
<td>15</td>
<td>900 (408)</td>
<td>1-2</td>
<td>42 × 48 (107 × 122)</td>
<td>100 (896)</td>
</tr>
<tr>
<td>35</td>
<td>1300 (590)</td>
<td>1-2</td>
<td>50 × 60 (127 × 152)</td>
<td>150 (1344)</td>
</tr>
<tr>
<td>300</td>
<td>1850 (839)</td>
<td>1-2</td>
<td>60 × 80 (152 × 203)</td>
<td>200 (1792)</td>
</tr>
<tr>
<td><strong>Reciprocating Screw</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Under 1</td>
<td>300 (136)</td>
<td>1-2</td>
<td>15 × 24 (38 × 61)</td>
<td>40 (358)</td>
</tr>
<tr>
<td>10</td>
<td>600 (272)</td>
<td>1-2</td>
<td>30 × 37 (76 × 94)</td>
<td>90 (806)</td>
</tr>
</tbody>
</table>

**TRIMMING SECTION**

For most intermittent machines, trimming is not an integral part of the blow molder. The part is removed from the machine and trimmed in a secondary operation. The type of operation varies with the particular part. The parts usually cool for several minutes and then are either manually or automatically deflashed. Deflashing is done manually by scoring the flash with trim knives and pulling it off. It can be removed automatically by deflashing dies in presses or by cutting with CNC routers. After the flash is removed, the parting line usually needs to be hand-trimmed with a knife or a torch. Secondary operations such as trimming end bubbles, drilling or punching holes, and attaching component parts are then completed. The deflashing and trimming operation is automatic on most continuous-extrusion blow molders (done by hydraulic presses and steel deflashers).

**AUXILIARY EQUIPMENT**

The following support or auxiliary equipment is needed for an extrusion blow-molding operation:

1. A material loading system to convey virgin material pellets and reground material to the extruder hopper on the blow molder. This consists of a vacuum system, hopper loader, and some type of proportioning system to control the ratio of virgin and regrind mix being molded. Most standard plastic pellet material handling systems will work satisfactorily. An accurate proportioning system to control the virgin-to-regrind ratio is required. Variation in this ratio will cause a variety of processing problems.
2. A grinder to grind flash and trim the part is essential because of the amount of flash that is generated by the molding process. Grinders should be able to grind hot flash and may...
need a water-cooled rotor or cutting chamber. The grinder should have an opening wide enough to handle the size of the parts that will be molded. A blower conveying system should be used to remove the regrind from the grinder. The blower helps to cool the cutting chamber.

3. A band saw is needed to cut flash and trim parts. Other types of saws, routers, computer numerical control (CNC) routers, hydraulic punches and presses, and drills will also be needed for trimming parts.

4. Mold temperature control units are also needed. Molds are usually kept as cold as possible. However, to develop certain surface finishes or to get parts to release from the mold, it may be necessary to run a mold hot. In this case, a chiller or central chilling unit will be needed for mold cooling. During high-humidity summer operation, the mold temperature needs to be monitored to avoid condensation on the molds.

**Process Control**

For the blow-molding process, accurate control of time, temperature, and position is an absolute requirement. Temperature control is required on the barrel of the extruder, the mold, the head, all connecting piping, process water, hydraulic oil, and polymer melt. The filling of the head, the ramming of the parison, the wall thickness of the parison, and the press clamp are all position-controlled. The blowing/cooling cycle is controlled by time. All of these process functions can be microprocessor-controlled. Several industry standard systems are available, as well as systems developed by individual equipment manufacturers.

**MOLD DESIGN AND CONSTRUCTION**

Blow molds are generally constructed of cut or cast aluminum because of the superior heat-transfer characteristics of this material and its lower construction cost. Better heat removal results in a faster cycle. Aluminum is easy to machine, resists corrosion, and results in lighter tools which are easier to handle. Cast-aluminum tools are cheaper to construct than cut tools, but are softer, and thus have higher maintenance requirements. Cast aluminum is a good choice for lower-volume jobs and for some specific part configurations. Common grades of aluminum for cut tools are alloys 6061 or 7075. Cut tools are easier to weld and modify if repairs or changes are needed. It is easier to add slides and knockout cut tools. They are 20–30% more expensive than cast tools. Cast molds do not produce parts as accurate because an extra variable, shrinkage of the aluminum during casting, is added to the mold construction.

Other materials used for production molds include beryllium-copper and steel, both of which increase mold construction cost. Beryllium-copper is used for high-volume container applications because it is harder, and therefore pinch areas last longer without repair. It is also corrosion-resistant to PVC. Beryllium-copper inserts are also used in aluminum blow molds around the pinch to reduce maintenance requirements and increase longevity. Kirksite (soft zinc alloy) and spray-metal-polyester tools are used for very low volume and prototype blow molds.

Blow molds can be quite simple in construction or they can be as complex as injection molds. Figure 7-21 shows the basic layout of a blow mold. Four dowel pins are used for mold alignment at the mold closing. The pinch-off area is relieved in the cross-hatched area to allow the flash to be compressed but not keep the mold apart. The depth of this relief should only slightly exceed the thickness of the compressed flash. If the relief is too great, the flash will not have good contact with the mold surface. The poor contact will restrict cooling of the flash, leading to increased cycle time and part distortion. Because the pressure a blow mold must withstand is low compared to that for injection molds, it is not uncommon to make the molds in sections as indicated by the top and bottom insert sections in the figure. The blow pin area at the top (or bottom) of the mold is often a replaceable insert, as shown; this is a wear area because of contact with the blow pin and can be easily damaged. Water lines are shown running directly through the mold, although they may be looped at the top or bottom to facilitate hookup, provided that the external cooling liquid pressure and flow are sufficient.

Figure 7-22 shows mold venting details, which should allow the air in the mold to be forced out quickly and not restrict the inflation of the parison inside the cavity. Plugged or insufficient vents have caused many blow-molding problems. Vents need to be positioned judiciously to avoid any dead spots within the cavity. The size of the vent hole is kept small at the surface of the mold to prevent material blowing into the vent or vent marks showing on the part. A cluster vent is also shown in the figure. Mold surfaces are often sand-blasted to facilitate venting. Figure 7-23a shows details of the pinch design for a typical blow mold. The pinch is slightly flat on the edge to avoid damage and frequent repair, as well as to eliminate the chance of cutting the parison as the part is being blown. Figure 7-23b shows a restriction dam to prevent thinning of the parting line and formation of a potential weak spot.

As a blow-molded part cools in the mold under air pressure, it will cool to the mold dimension. When the part is decompressed and ejected from the mold, it will shrink. This shrinkage must be incorporated into the dimensions to which the mold is built. If the part is not cooled sufficiently prior to leaving the mold, it will shrink more than these nominal values and may not be within the desired final part dimensions. Table 7-7 lists some commonly used shrinkage values. Shrinkage values vary with the processing conditions and particular grades of materials used for a given process. The values in the table should be used only as starting points and may need to be refined for a particular process, material, and set of operating parameters.

**MAINTENANCE**

Guidelines for normal blow-molding equipment maintenance should be provided by the equipment manufacturer. The process equipment is relatively simple. Areas which have proven to require the most attention include the internal surfaces of the head on an accumulator machine, platen bushings, mold dowel pins and bushings, grinder blades, and trimming equipment. Areas of wear on the mold include the pinch area and the pinch plate which seals around the blow pin.
Body

Water lines

Oil-ring seals

Blow-pin insert

Thread insert section

Main body section

Relief area for pinch-off – 0.33 in (8 mm) deep each half, leave 0.02 in (0.5 mm) land

Dowel pins

Assembly screws

Blow-pin seat

Front view

Side view

Back plate

Main body section

Pinch-off water lines

Pinch-off section

Back plate

Pinch-off water lines

Fig. 7-21 Layout of a blow mold.
Fig. 7-22 Mold venting details: front view (left) and side view (right).
This section will discuss the following:

- Parting line and draft angle.
- Blow ratio.
- Nonsymmetrical parts or details on parts.
- Dimensional control.
- Mounting tabs, inserts, hinges, and interlocks.
- Structural and cosmetic considerations.

PARTING LINE AND DRAFT ANGLE

The first decision that a designer has to make, after choosing the blow-molding process to manufacture a part, is the parting line location. The parting line placement should be chosen to minimize the distance the plastic has to stretch and to allow the mold to be built without undercuts or die locks. The parting line location may be influenced by cosmetic considerations since it is always visible on a part.

Round, symmetrical parts are always parted in the center to produce two equal mold halves. No draft angle is required for a round part. Nonsymmetrical and oddly shaped parts should be parted at the most favorable blowing position to minimize thinning of the part wall and to facilitate part ejection. A square or rectangular part is usually parted in the center of the shortest side to reduce the depth the material must be blown. The four corners tend to be uniform in thickness but are the thinnest areas of the part. Parting across the diagonal between opposite corners will result in thicker corners. However, the corners at the parting line will be heavier than the other corners. Parting at the diagonals is seldom done because of higher mold cost and other geometrical considerations which require the parting parallel to a wall of the part. Offset parting lines, which follow the shape of the part, are commonly used to minimize the wall thinning. Offset parting lines increase mold cost but may be required to produce the desired part. Extreme offsets should be avoided since they may cause processing problems such as folds or thin areas.

Once the parting line is established, the draft angle can be applied to the part starting from the parting line to the outside surface of the part. A standard draft angle is 1°. It can be less for parts which are shallow and may need to be increased for parts which have greater depths and more contact on the sidewalls of the mold. Ejectors in the mold reduce, but do not eliminate, the need for draft angles. Parts which are textured on the sidewall may need an additional 1° of draft angle per 0.001 in. (0.025 mm) depth of texture as shown in Fig. 7-24. Large draft angles can make a significant dimensional change to a large part.

Table 7-7

<table>
<thead>
<tr>
<th>Material</th>
<th>Shrinkage, Inches/inch* (centimeters/centimeter) of dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDPE</td>
<td>0.020</td>
</tr>
<tr>
<td>PP</td>
<td>0.018</td>
</tr>
<tr>
<td>TPE</td>
<td>0.016</td>
</tr>
<tr>
<td>HDPE, 25% mica filled</td>
<td>0.013</td>
</tr>
<tr>
<td>ABS</td>
<td>0.005–0.008</td>
</tr>
<tr>
<td>PC</td>
<td>0.005–0.007</td>
</tr>
<tr>
<td>PVC (rigid)</td>
<td>0.003–0.006</td>
</tr>
<tr>
<td>PS</td>
<td>0.005–0.007</td>
</tr>
<tr>
<td>Nylon, 15% glass</td>
<td>0.003–0.005</td>
</tr>
</tbody>
</table>

These values are typical of part shrinkage for materials used in blow molding. Shrinkage numbers will vary with different grades of the same material manufactured by a different process. Operating conditions such as cooling time and temperature will greatly influence the amount of shrinkage that occurs after the part is molded.

*Inch values given; centimeter values are proportionally equivalent.
BLOW RATIO

Blow ratio is the depth of an entire mold cavity, or of a small area of the mold cavity, divided by the smallest dimension of the material available to be blown or stretched. When the term is applied to a material, it defines how well the material will stretch without tearing. When applied to a part or mold, it is a geometrical consideration. The farther the material must be stretched or blown, the thinner it will be.

Round Parts

The blow ratio for round parts is defined as the radius of the largest section of the part divided by the radius of the parison (see Fig. 7-25). It is thus possible to control the blow ratio by changing the diameter of the head tooling used to blow the part. Large differences in the radius of a round part should be avoided to minimize the blow ratio, to blow the parison inside the part, and to avoid any flash on the side of the part. The radius of the parison will need to be smaller than the smallest radius of the part to avoid flash on the sides of the part.

NONSYMMETRICAL PARTS OR DETAILS ON PARTS

Figure 7-26 illustrates an approach to develop an approximate part thickness for nonsymmetrical parts based on the parison thickness and the surface area of the cavity into which the material is to be blown. The approach is similar to determining wall thickness on thermoformed parts.

Figure 7-27 shows how the plastic stretches into a cavity and the wall thickness reduces. The hot material that does not touch the wall of the mold continues to stretch into the mold. It thins more than would be expected because the material that touches the mold freezes and does not stretch much. This causes the wall thickness distribution to be thicker at the top (outside) of the cavity and thinner at the bottom (inside) of the cavity. Figure 7-28 demonstrates the radius guideline “bigger is better” and illustrates the surface distance that material must be stretched for three different radii. As expected, the thickness reduces proportionally the more the material is stretched.

The information described in this section shows that the part is thickest at the parting line and tends to thin at the deeper sections of the cavity or at the greatest distance from the parting line. There are exceptions to this around compressed areas of the mold. In such cases, the clearance between the mold halves will control the thickness of the part, provided there is sufficient material to fill the clearance between the mold halves, the press has sufficient pressure to overcome the resistance of the plastic in these areas,
and the mold has been designed to have sufficient lay-flat area for the excess plastic, and does not hold the mold halves apart. Parts may also be thin at extreme parting line offsets.

**DIMENSIONAL CONTROL**

Blow-molded parts have good exterior dimensional control since the part will replicate the dimension of the mold minus shrinkage of the material. Part shrinkage is a function of:

1. The temperature of the part when it is removed from the mold.
2. The polymer used.

Molds are cut larger than the desired part dimension to compensate for material shrinkage. Filled and engineering polymers have less shrinkage than unfilled polyethylene or polypropylene.

Table 7-8 lists typical exterior molded dimension ranges and the tolerances that normally can be held. These dimensions can be improved if critical dimensions are machined after the part is molded and has cooled. Internal dimensions of blow-molded parts are not as easy to control. This is because the internal dimension represents the mold dimension of the part less the wall thickness of the material at the measuring point. Some internal dimensions can be controlled with a forming pin that compresses the plastic between the mold and the forming pin to provide internal dimensional control. Dimensions can also be controlled at compressed areas in the mold when the plastic is trapped between two mold halves. Forming pins are most effective at the bottom of a mold where the pin can spread the parison and then push up against or into the bottom of the mold to control an internal dimension at the end of a part.

![Fig. 7-26 Cavities may have similar surface areas although they differ widely in length, width, and height. Cavity a has a surface area of 44, while cavity b has an area of 46.](image)

Polymers such as HDPE and PP which are crystalline in structure will continue to increase in crystallinity for hours after molding. As the parts increase in crystallinity, the dimensions will become slightly smaller. This is not significant on small parts but on large blow-molded parts, it can cause a part produced at the limit of a tolerance to become too small after several hours. Hygroscopic plastics, because they tend to absorb moisture, also may change slightly in dimension hours after molding.

**MOUNTING TABS, INSERTS, HINGES, AND INTERLOCKS**

Mounting tabs can be incorporated into blow-molded parts by using either compressed areas in the mold or inserts. Compressed areas need to be nearly perpendicular to the opening of the mold.
and located at the parting line. They can be slightly less than twice the nominal wall thickness of the parison. Holes or slots can be incorporated into the compressed areas by in-mold coring or punching, or by secondary drilling or punching after the part is molded. Secondary operations will result in more accurate location.

Inserts of either plastic or metal for use as threads or mounting tabs can be molded into the part. The insert is designed to allow the plastic from the parison to form around the insert so that it is locked in place. Inserts are held in by a mechanical lock of the plastic around the insert. The part needs to be designed so that the insert can be placed into the mold and so that a die lock is not formed after the part is molded. If a die lock cannot be avoided, slides can be incorporated into the mold. The use of inserts lengthens the molding cycle and results in a slightly higher part cost. Figure 7-29 is a typical design for an insert base.

A variety of hinges can be compression-molded into blow-molded parts. These can consist of male and female sections as shown in Fig. 7-30 or more conventional hinges using a pin. It is also possible to blow a top and bottom part and attach the two parts together with a “living hinge” that is compression-molded between the two parts. This results in a one-piece design for a box or container.

**TABLE 7-8**

<table>
<thead>
<tr>
<th>Above Division of Nominal Dimensions</th>
<th>Below (inclusive)</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>3</td>
<td>±0.3</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>±0.4</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>±0.5</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>±0.6</td>
</tr>
<tr>
<td>18</td>
<td>30</td>
<td>±0.8</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>±1.0</td>
</tr>
<tr>
<td>50</td>
<td>80</td>
<td>±1.2</td>
</tr>
<tr>
<td>80</td>
<td>120</td>
<td>±1.4</td>
</tr>
<tr>
<td>120</td>
<td>180</td>
<td>±1.6</td>
</tr>
<tr>
<td>180</td>
<td>250</td>
<td>±2.0</td>
</tr>
<tr>
<td>250</td>
<td>315</td>
<td>±2.5</td>
</tr>
<tr>
<td>315</td>
<td>400</td>
<td>±3.0</td>
</tr>
<tr>
<td>400</td>
<td>500</td>
<td>±3.5</td>
</tr>
<tr>
<td>500</td>
<td>630</td>
<td>±4.5</td>
</tr>
<tr>
<td>630</td>
<td>800</td>
<td>±5.6</td>
</tr>
<tr>
<td>800</td>
<td>1000</td>
<td>±7.0</td>
</tr>
</tbody>
</table>
Figure 7-31 shows a room air cleaner housing which is constructed of four blow-molded pieces that interlock with a snap-together system. This interlock is easy to blow mold and results in a solid attachment between the panels.

**STRUCTURAL AND COSMETIC CONSIDERATIONS**

Adding ribs or reinforcements to any part will increase its rigidity. In blow-molded parts, by the use of a double-wall design, a significant increase in stiffness can be achieved when the two walls are “tacked off,” thereby increasing the moment of inertia. A variety of designs can be used (see Fig. 7-32). A typical conical tack-off is shown in Fig. 7-33. Ribs are preferred to conical tack-offs when structure is of importance. Staggered ribs can also be used. An important consideration in the rib design is that the blow ratio in the rib area is not excessive. The amount of actual contact area between the two tacked-off walls of the part should be minimized if one of the surfaces is a show surface. Tack-off areas tend to be visible on a show surface if the contact is excessive. If structural considerations are important, more contact area may be needed. Other methods of reinforcing a blow-molded part include insertion or attachment of metal brackets and foam filling of the part.

Blow molding of industrial parts has been limited to those with nonshow surfaces until recently. Now blow-molded parts can be produced with surface quality equal to that of injection-molded parts. For the textures desired for cosmetic parts, it is often necessary to use steel tooling because a sharply engraved surface cannot easily be maintained on aluminum tooling. Moreover, higher mold temperatures and blow pressures are needed on cosmetic parts to achieve the best possible surface replication. Cycle times will also increase, and cosmetic parts generally require more care in handling and trimming after they are molded. Applications for blow-molded show parts include console lids, glove box doors, instrument panels, and spoilers.
In the manufacturing process, product cost and safety should be considered.

**PRODUCT COST**

The cost of a blow-molded product is determined by:

1. Part weight and material.
2. Equipment size and overhead.
3. Calculated cycle time.
4. Finishing operations and labor cost.
5. Packaging and components.

To determine the estimated volume of material required, the outside surface area of the part is multiplied by the nominal wall thickness. The estimated volume is then multiplied by the specific gravity of the polymer to determine the weight of the part. Depending on the part configuration, the outside area of the part may be easy or difficult to determine. Because the recycled material that is reground from flash causes some loss, a scrap factor of about 5% should be added to the part weight calculation; there are always losses associated with any regrinding operation. Color concentrate and additive costs need to be included in the raw material cost.

The part orientation in the mold and the choice of parting line will allow the determination of the approximate mold dimensions and the amount of mold coverage needed to make a part. This information will allow the estimation of head tool size. With an estimate of total shot size (part weight and flash), head tool size, and mold dimensions, it is possible to estimate the size of machine needed for one part. Once production requirements are compared with cycle time, it is possible to determine if multiple cavities or molds are required.

Molds can be stacked or run side by side out of multiple-head machines. The overhead cost of a machine is based on a number of operating factors. Table 7-9 lists typical industry rates charged for various machine types, sizes, and part complexity. These rates reflect building, utilities, and direct and indirect labor costs, excluding only material cost.

The cycle time for a blow-molded part is most influenced by the wall thickness of the part and the length of time to cool the part sufficiently to hold its shape without distorting when it is ejected from the mold. A very general rule for HDPE is one second of cooling for every 0.001 in. \((0.025 \text{ mm})\) of wall thickness. The use of steel tooling, higher mold temperatures, tighter dimensional tolerance, or thick compressed areas will alter this time. Materials with higher specific heats and lower heat-distortion temperatures usually require longer cooling times. Engineered resins with higher heat-distortion temperatures usually require hotter mold temperatures for surface appearance and part ejection. They can be molded with shorter cooling time because of their much higher heat-distortion temperature; as parts become thinner and cooling times reduce, screw output or part trimming and deflashing may become the limiting factor.

An efficiency factor needs to be applied to the cycle time. Typical efficiencies range from 75–99%, depending on the equipment, part complexity, and material being molded.

Most continuous extrusion- and injection-blowing operations are totally automatic and do not require any labor other than packing. Industrial blow-molded products using intermittent equipment usually require at least one operator to deflash and trim parts. Additional operators may be needed, depending on the amount of trimming, drilling, routing, or assembly required. Cycle times

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Fig. 7-33 Typical conical tack-offs.
range from as little as 10 seconds for a thin bottle to four minutes or more for a large heavy-walled industrial blow-molded part.

SAFETY

Safety is a condition of being free (safe) from undergoing or causing hurt, injury, or physical loss to a person(s). This should be the guiding principle in evaluating working conditions. Always follow the equipment manufacturer's recommendations for proper equipment use and comply with safety regulations. Evaluate the following suggestions to determine if it is appropriate to your facility.

The safety precautions for a blow-molding process are similar to those for any industrial or plastic manufacturing operation. Since presses are involved, normal safety guarding and gates—which should stop the press while it is open—are required. Normal safety practices for electric and hydraulic equipment should be used in the design and standard safety operating procedures must be applied by people working around or on the equipment. Technicians may be required to work at heights high above the ground. For this reason, safety guard rails and ladders are also required.

Because of the high operating temperatures, cotton gloves are a minimum requirement for operators. Eye and hearing protection are required for operators in trimming and grinding.

If plastic overheats in the blow molder or air is trapped in the extruder during the extrusion operation, it can splatter or blow out of the molder head in an uncontrolled manner and burn an operator. If a machine head is cold when started and the extruder is melting material under pressure, it is possible to blow a head off the machine, causing considerable damage. Start-up instructions should always specify a heat-up time for all machine components and the operator should check temperatures before the extruder is started. Automatic pressure shut-offs and pressure rupture disks should be incorporated in all extruders.

Cuts from trim knives, burns from hot plastic, falls from slipping on hydraulic oil or plastic pellets on the floor, and sprains from handling large parts are the most common safety problems associated with blow molding. One problem suffered by operators is carpal tunnel syndrome, which can result from repetitive operations such as the trimming and deflashing of parts. Because of increased incidence of carpal tunnel syndrome, additional automation and improved deflashing and trimming equipment are used.

NEW DEVELOPMENTS

This section will discuss the following:

- Coextrusion.
- Flashless blow molding.
- PET blow molding.
- Deep-draw blow molding.

COEXTRUSION

Coextrusion—the simultaneous extrusion of more than one material—has been done for a number of years in continuous blow molding to produce bottles with improved oxygen- and moisture-barrier properties and chemical resistance. Coextrusion is finding
additional applications in gas tanks as a barrier to hydrocarbon emissions and in furniture and automotive interior components where a soft material over a rigid material will produce a nonskid or a soft-touch surface. This process also offers cost savings when a less expensive material can be used in conjunction with a more expensive material, or where regrind or recycled material can be used as an inner layer of a part. This process has been slow to enter the industrial market because the accumulator head machine technology was limited. Companies are now supplying multilayer accumulator-head machines (see Fig. 7-34). Using this technology in conjunction with three-dimensional (3D) blow-molding technology, it is possible to mold two materials of different densities out of the same head, to produce, for example, automotive air-inlet ducts that are rigid in one area and flexible in another area.

**FLASHLESS BLOW MOLDING**

Flashless blow molding refers to producing parts with no side flash (only top and bottom) where flash along most of the side of the part would normally be required. There are two methods of producing a flashless, 3D blow-molded part. One approach, shown in Fig. 7-35, uses an oscillating platen at a 45° angle which is moved two-dimensionally under the head. The parison is sealed on the bottom and laid into the mold cavity. The mold is closed and the part is blown. The second method, shown in Fig. 7-36,

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Fig. 7-34 Cross-section of multilayer accumulator head.

Fig. 7-35 Oscillating platen for flashless part.
Phase 1
• Parison is extruded and gripped.
• Parison is cut off.

Phase 2
• Parison is lowered and the first part of the mold closes.
• The parison is gripped by the parison turning device at the bottom.

Phase 3
• The parison is positioned in the other mold segments by the reversing device at the bottom and the manipulator at the top.
• These mold segments close.
• The article is molded.

Phase 4
• The mold opens.
• The article is removed.

Fig. 7-36 Operation of parison grabber for flashless blow molding.
involves grabbing an extruded parison and manipulating it into the mold. The mold is closed and the part is blown. Either method can produce the same type of high-quality flashless blow-molded parts. Flashless molding reduces labor costs, but increases cycle time and equipment costs over conventional molding.

**PET BLOW MOLDING**

Until the late 1980s, PET bottles could only be injection blow-molded. New resins and some refinement of existing equipment have made it possible to extrusion blow-mold PET. The new resins have a high viscosity, which provides the melt strength needed for the extrusion blow-molding process. Extrusion blow molders accustomed to running PVC have learned to deal with the higher temperatures and difficult drying requirements of PET. Equipment improvements include new barrier screw designs, hydraulic finish calibration, and new steel-insert molds.

Several computer software packages have been developed which predict wall thickness, part temperature, and cooling time required for blow-molded parts. Most of these programs can also be used to predict the same data for thermoformed parts.

An emerging opportunity for blow molding is energy-absorbing unit (EAU) bumper beams for cars and trucks. The advantages of blow molding include light weight parts, lower cost, process simplicity, and flexibility of design. The blow-molded shape is optimum for the structure and reduces the assembly cost by eliminating several parts. The wall thickness can be varied easily to provide the optimum amount of energy absorption at the lowest cost. Parts can also be foam filled, if necessary, without difficulty.

**DEEP-DRAW BLOW MOLDING**

Deep-draw molding is a process by which double-wall blow-molded parts may be produced with up to a 2:1 blow ratio. Many parts that are currently produced in two pieces may be converted to a single part.

The deep-draw process employs a special mold with an actuated core and a folding cavity (see Fig. 7-37). The core and the cavity are hydraulically driven with cylinders. The core extends and retracts while the cavity sides fold on their hinges. Pinch-offs and relief are machined into the cavity sides because material will flow between the sides. These molds can run in most machines with minimal modifications, most notably the addition of a head-mounted prepinch system.

**The Process**

The deep-draw process consists of a sequence of steps:

1. The head-mounted prepinch pinches a bag just as it begins to extrude. The head blow pin preblows the bag as it extrudes so that the parison expands evenly (see Fig. 7-38a).
2. After the parison has been extruded and preblown, the press begins to close the mold (see Fig. 7-38b).
3. The actuated core advances into the parison. The cavity sides then begin to fold around the core as the press continues closing (see Fig. 7-39c).
4. As the press continues to close, the core completes its travel. The cavity sides completely close to form the cavity (see Fig. 7-39d).

5. The press totally closes the mold. The blow needles then fire to blow the part (see Fig. 7-40e).

6. The cycle ends and the press begins to open. The cavity unfolds and the core retracts. The part is then removed and the cycle is repeated (see Fig. 7-40f).

Applications

Deep-draw molding can fabricate many parts that previously could not be blow-molded. A unique process feature is the ability to form outside details that conventionally would be undercuts. The process could be used on a flower planter, for example, that has a realistic brick pattern on all four outside walls. The folding cavity easily molds these features. Water coolers are another example. Traditionally, coolers have been made from blow molded shells, and liners were either injection molded or thermoformed, then bonded together. One maker produces a one-piece double-walled cooler.

Deep-draw molding may also be used to produce round containers. An example is a flower planter that is shaped like half a wooden barrel. Many such containers could benefit from the deep-draw process.

Typical deep-draw molds are produced from steel. The many actions that are associated with the process call for wear-resistant mold materials. The molds could be built from aluminum with steel pinch-offs to provide better cooling.

Fig. 7-39 (c) Core starts to travel and mold starts to close (d) core travel is completed and side walls fold to create “box.”

Fig. 7-40 (e) Mold is closed and then opens. (f) The core returns to starting position.
Cycle Times

Cycle times for deep-draw molds are somewhat greater than those for conventional blow molds. However, the resulting products have many added features that are virtually impossible to produce by conventional processes. Deep-draw molding does have a potential drawback: at every point where the cavity sections meet, a pinch-off witness line is left on the part. This must be considered in the design of new parts.

Deep-draw blow molding opens new doors to blow molders. Developing new products and converting old products will create endless applications. The benefits should be apparent to designers and consumers alike, and the process will give blow molders another alternative to competing processes to further the blow-molding industry.

CONCLUSION

Continuing developments in both equipment and resins are further facilitating the use of blow-molding technology. Manufacturers are determined to integrate many parts into a single part to save assembly costs. Lightweight and flexible blow-molded products—containers, structural parts, intricate ductwork—help manufacturers achieve this objective and firmly establish blow molding in the industrial marketplace.

References


Bibliography


Colby, Paul N., Screw and Barrel Technology, (Spirex Corporation, 1985).


Dreps, J.R., Plastics Engineering, (Brookfield, CT: Society of Plastics Engineers, 1975), p. 34.


Thermoforming is the process of heating and shaping plastic sheet and film. The industry generally classifies material that is less than 0.010 in. (0.25 mm) thick as film; greater thicknesses are considered sheet. The plastic sheet or film is heated to a specified temperature, where it is pliable and flexible, and immediately shaped to the desired configuration using minimal force. When the part has cooled below its heat deflection temperature, it is removed from the shaping mold or fixture, and the selvage used to hold the sheet during processing is trimmed away. Any apertures required in the part are then trimmed out. The selvage is reprocessed for later use.

Thermoforming sheet plastic began in the mid-1930s with the introduction of cast acrylic sheet. Its primary application through 1945 was for production of military aircraft domes, turrets, and canopies. After World War II, new thermoformable plastic resins for sheet extrusion were developed, making new sheet materials available for thermoforming. In the late 1980s and early 1990s, thermoforming has been one of the fastest-growing methods of processing plastics.

Thermoforming has several advantages and disadvantages when compared to other plastic processes.

**ADVANTAGES**

**Tooling Costs**

Thermoforming tooling costs and delivery times are relatively low for three reasons. First, thermoforming compares favorably with other processes because of the low pressures required. When vacuum forming, a maximum pressure of 14.7 psi (101 kPa) is used. With pressure forming, 30–150 psi (207–1034 kPa) is required. Mechanical forming requires even less pressure than vacuum forming. Prototyping and short runs without critical specifications can use molds of wood, plaster, epoxy, fiberglass, or rigid foam. Production molds can be cast epoxy or machined or cast aluminum, preferably temperature controlled.

The second advantage is that the cost of vacuum-and pressure-forming molds does not increase proportionately with size. For example, doubling the size of a mold may increase the tooling cost only 25–50%. This is not the case in high-pressure molding processes.

Finally, thermoforming molds are usually only one-sided, again reducing costs and production times.

**Machinery**

Because the thermoforming process uses low pressures to form the sheet or film, the cost of the forming and heating machinery is lower than that for other processes of equal platen or mold size. When vacuum forming, two pressures are considered: (a) the atmospheric pressure exerted against the mold when forming and holding the sheet in place and (b) the force necessary to lift or lower the mold into the hot sheet before the vacuum is applied. When pressure forming, pressures are still relatively low at 30–150 psi (207–1034 kPa). However, structurally sound press platens are required because they are mechanically locked together. This is to ensure air seals between the hot sheet and the mold on one side, and the pressure vessel on the other.

**Physical Properties**

Thermoforming creates better physical properties in finished parts because, when properly processed, the part is virtually stress free. When the plastic sheet is uniformly heated to the forming temperature and then quickly stretched into or onto the mold for cooling, minimal internal stresses are created in the finished part. In heavy-gage sheet forming, a temperature-controlled mold assures more uniform cooling through both surfaces of the sheet, further reducing the internal stresses.

An additional advantage of sheet forming is that the starting resin, which is used to extrude the sheet through relatively larger orifices than those in injection molding, may have a lower, more viscous melt flow. This resin usually has better physical properties than the high-melt-flow material. Consequently, the extrusion/thermoforming process can take advantage of resins with superior performance.

**Layered Products**

Multiple layers of various materials can be coextruded or press laminated into sheet or film, giving tremendous variety in material properties of the part. For example, a thin-wall package can be thermoformed from a material having an inner surface meeting Food and Drug Administration (FDA) requirements, a barrier layer of water- or vapor-resistant material, a main layer of regrind materials, and a top or outer layer of close-tolerance color-match material. Because some of these materials may be incompatible, other layers of tie or adhesive materials are used to bind them.

**Small Parts**

Small and modest-sized parts formed into intricate shapes with wall thicknesses less than 0.010 in. (0.25 mm) are competitively thermoformed in high volumes. Packaging blisters, clamshells, cups, tubs, and form/fill/seal containers are routinely produced at rates of 200,000 parts per hour per mold, and sometimes more.
CHAPTER 8

THERMOFORMING BASICs

Large Parts

Very large parts are also thermoformed easily and economically compared to other processing methods. Parts that are $8 \times 10 \times 0.5$ in. ($2.4 \times 3.0 \times 13$ mm) in size are quite common, and $10 \times 30 \times 0.5$ ft ($3.0 \times 9.1 \times 13$ mm) parts can be produced with special techniques. A single mold for these large sizes can produce up to 50 parts per shift, depending on the material selection and mold design.

Foam Products

Foam sheets, such as polyethylene and polystyrene, are readily thermoformed from thin to heavy gauge. Typical products are egg cartons, food packaging, athletic pads, automotive insulation panels and various industrial packaging.

Pressure-formed Parts

Pressure-formed parts, such as computer and machine housings, control panels, and enclosures, feature mold-side detail comparable to that of injection molding at 10–20% of the tooling costs with shorter delivery time.

Surface Treatment

Sheet material can be economically laminated or printed with wood grains or novelty patterns and then thermoformed to the required shape, saving postmolding handling and operations such as hot stamping or screen printing.

DISADVANTAGES

Most competing processes begin with pelletized or powdered resin and mold it directly into finished product. Thermoforming begins with a sheet or film, adding to the finished part cost. Details and close tolerances are available only on the mold side, since most thermoforming is done with a single-side mold. Secondary shapes and details must be added to the second surface, or back side, at additional cost.

Finally, because the sheet is clamped and held, it must be larger than the desired shape, requiring excess material for each part and additional labor to trim away this selvage. Apertures must also be trimmed or drilled into the part. This selvage can vary from 15–75% of the original sheet weight, as a result, trim reclamation is important in minimizing final part cost.

THERMOFORMING MATERIALS

There are many thermoplastics and thermoplastic elastomers available for the various thermoforming processes.

Thermoplastics are materials that can be repeatedly softened by heating and hardened by cooling. They are all linear, and many have slightly branched polymers. These polymers consist of long molecules, and each may have noncross-linked side chains or molecular groups. Newly developed thermoplastics are processed normally, but at the end of the process, they are cross-linked with special techniques (for example, a nucleating agent or a mold heated above the forming temperature). Materials can also be cross-linked by radiation, converting them to an undeveloped or full thermoset part with greatly improved physical properties. Thermoplastics comprise approximately 90% of all plastics currently processed.

Any thermoplastic resin that can be extruded or calendared into sheet or film can be thermoformed. However, those with low-heat strength at forming temperature may be difficult to form. Sheet and film are produced by extrusion, coextrusion, continuous casting, extrusion casting, calendaring, compression molding, and autoclave and press laminating.

TYPES OF THERMOPLASTICS

There are two types of thermoplastics: amorphous and crystalline.

Amorphous

Devoid of crystallinity, amorphous thermoplastics have a randomly ordered molecular structure. Their behavior is similar to that of a very viscous, inelastic liquid. Upon heating, an amorphous sheet gradually softens and eventually acquires the characteristics of a liquid, but without a definite transition point from the solid to liquid state. Amorphous materials normally have better hot strength characteristics than their crystalline counterparts and, as a result, form more easily. These resins also require less energy to reach forming temperature and to be cooled. Amorphous plastics never flow as easily as crystalline resins. When cooled, they do not reach a totally “nonflowing” solid state. Therefore, they tend to creep with age when a load is applied. Amorphous plastics include acrylonitrile-butadiene-styrene (ABS), nylon, acryl, the cellulosics, and polycarbonates.

Crystalline

Crystalline thermoplastics, an orderly group of molecules, tend to line up in rigid, precise, highly ordered structures, much like a chain link fence. This gives them good stiffness and creep properties. Most thermoforming crystalline materials are also partly amorphous (for example, polypropylene is about 65% crystalline and 35% amorphous). Unlike amorphous plastics, when a crystalline sheet is heated, it remains stiff until reaching its glass transition temperature ($T_g$). At $T_g$, the material softens.

For high-density polyethylene (HDPE), this softening, which occurs at 257˚ F (125˚ C), is accompanied by a change from a translucent to a clear appearance. This is also the minimum forming temperature of the sheet. As the sheet gains temperature, it rapidly becomes more fluid, indicating the material has reached its ideal forming temperature. Unfortunately, as with most crystalline materials, this is only a few degrees below the melt temperature.

Consequently, much of this material is cold formed at the “oriented” temperature or slightly above. The orienting temperature is halfway between $T_g$ and forming temperature. This can promote internal stresses, causing a decrease in the heat distortion point, warpage, and lower impact strength.

Polypropylene resin suppliers have made considerable advances in reducing the inherent deficiencies of crystalline plastics. Several excellent grades, which exhibit good hot strength at normal forming temperatures (about 330˚ F [166˚ C]), are available.

Compared to amorphous plastics, crystalline materials require more energy to bring them to $T_g$. After this temperature is reached, little additional heat is needed to reach the forming temperature. Crystalline materials include polyamide, polyethylene, polypropylene, polyphenylene sulfide, and acetal.

THERMOFORMING METHODS

Mechanical Forming

This forming method does not use compressed air or vacuum to move and mold the sheet. The necessary forces are applied by manually stretching or bending the sheet or by pushing the sheet from one or both sides with dowels, panels, or various shaped plugs. Plugs are used to uniformly distribute the plastic in the mold. Several mechanical forming techniques are ridge forming, stretch forming, matched molds, and strip heating.

Ridge forming. An outline frame, pushing on the hot sheet from one side and on the panel edges from the opposite direction, creates geometric shapes while touching only the edges. This
process is often used for transparent parts, where good optics are required. The process works best with high-hot-strength materials such as cast acrylic and butyrate; however, polycarbonate and ABS have been successfully formed. Applications include display cases, windows, and light lenses (see Fig. 8-1).

Stretch forming. In this process, the sheet is heated to forming temperature, moved to the mold surface, and then, by pulling on the sheet edges, stretched over the male mold surface. It is then clamped in place for cooling. Acrylic or polycarbonate transparencies are frequently formed by this process. The method is also used when wrapping plastic around a mandrel to form a “U” or coiled shape (see Fig. 8-2).

Matched molds. This process uses two molds with matched or mated surfaces that compress the hot sheet between them. Depending on the material’s elongation, platen press forces are 5–60 psi (34–414 kPa). Some fiber-reinforced materials may require higher pressures. Tooling costs in this process are higher, with longer lead times, because two mold surfaces are needed. Furthermore, the higher operating pressures demand stronger molds. However, with this process, details are molded on both part surfaces, and with properly temperature-controlled aluminum molds, the parts cool more quickly and with fewer residual stresses. Foams and fiber-reinforced materials are typically formed by this process (see Fig. 8-3).

Strip heating. Strip heating is widely used to make single-plane bends in sheet thermoplastic. A tubular heater or coiled nickel-chrome resistance wire (approximately 0.025 in. [0.64 mm] in diameter) is inserted into a slot in the surface of a large platen. The plastic sheet, laid on the platen surface, is warmed in only the narrow straight line of the heater. The sheet is then bent and placed in a jig to hold its shape while cooling. Additional heaters can be aligned in the platen to create multiple bends in the part. For high-production requirements, multiple heater platens and jigs are used to maintain production speed (see Fig. 8-4).

For materials greater than 0.125 in. (3.18 mm) thick, applying heat from both sides of the part eliminates surface blistering. One side is heated for 35–45% of the cycle, the part is flipped for an additional 45–55%, and the first side is again heated for the balance of the cycle. Alignment blocks are fixtured on the platen to ensure accurate location of the sheet over the heater strips.

Straightener, sharper bends are created in thick materials if a 90° V-groove, for right angles, is machined on the inside surface of the sheet prior to heating (see Fig. 8-5).

Vacuum Forming

Drape vacuum forming. The most common thermoforming method is drape vacuum forming. A male or female mold is moved into the hot sheet, and a vacuum is used to remove the resistant air trapped between the sheet and the mold. Atmospheric pressure (14.7 psi [101 kPa]) is used to move the heated sheet into contact.
with the mold, and holds the sheet until it cools below the heat distortion temperature.

In this process, good material distribution, or equal thinning, depends on the following variables:

- Uniform sheet heating.
- Mold temperature.
- Material type.
- Rate of air evacuation (vacuum and/or compressor air).
- Prestretching of the sheet.

By maintaining the mold temperature approximately 10°F (6°C) below the heat deflection temperature of the material, and by using a fast air evacuation (vacuum and/or pressure), the best material distribution is attained. A temperature-controlled mold enhances part quality.

In drape vacuum forming, as the hot sheet comes in contact with any portion of the mold, that area of the sheet cools faster than the untouched area. Hot strength increases where the sheet touches the mold. This causes most of the sheet stretching (and thinning) to come from the untouched area.

There are a variety of methods for prestretching the sheet to ensure uniform material distribution.

Male mold—snap back. This is a common process because the assist box can be made quickly and inexpensively. The assist box is moved into the hot sheet, causing a seal around its perimeter. A vacuum is introduced into the box, drawing the still-hot material into a bowl shape in the box. A photoelectric eye is often used to control the depth of the bowl or bubble. The mold is then pushed into the bubble, allowing the platen on which the male mold is mounted to seal the hot material to the edge of the box. At this time, the vacuum is reversed from the prestretch box to the mold, causing the material to snap back to the mold surface. The box is then moved away from the part to eliminate interference with the cooling fans (see Fig. 8-6).

Male mold—billow plug. This setup is similar to that of the snap back except the box is pressurized, causing the hot material to billow out from the box in a bubble shape. The billow height, about 75% of the mold height, is adjusted with the first few sheets of formed material. The mold is moved into the bubble of material, which wraps itself around the mold until the platen has sealed the material to the box edge. The vacuum is then applied to the mold, drawing the material into contact with the complete mold and platen surface. This process produces a more uniform wall thickness than the snap back but is more difficult to adjust for proper production. Pressure in the box must be controlled by relief valves as the mold is forced into it (see Fig. 8-7).

Female mold—plug assist. When prestretching the material into a female mold, a plug assist is used. The plug is built from wood or syntactic foam, materials with low-heat transfer properties, to the approximate shape of the mold cavity. A clearance of about 0.50 in. (13 mm) is provided between the plug and mold surfaces. The female mold is mounted above the sheet frame to provide a seal around the perimeter of the mold without allowing the sagging sheet to touch the mold surface. The plug is then moved into the hot
sheet, pushing it into the mold cavity. Air that is trapped in the mold causes the sheet to billow around the plug as it is compressed. When the plug has pushed into the mold, stopping just short of touching the bottom of the cavity, vacuum is rapidly applied in the mold, transferring the sheet from the plug to the mold (see Fig. 8-8).

Female mold—billow snap back. When it is impractical to use a plug assist, some prestretching can be achieved by introducing pressurized air into the mold after a seal is made with the hot sheet, creating a bubble away from the mold. A bubble that is about 75% of the cavity depth is recommended. The air pressure is then reversed to pull a vacuum, and the prestretched hot material snaps back into the cavity of the mold. This process adds thickness to the bottom of the part (see Fig. 8-9).

Female mold—billow plug assist. This process is a combination of the previous two methods. It is the best way to achieve reasonably uniform wall thickness in large, deep parts. However, it is often difficult to coordinate all the elements of this procedure to effect a perfect draw of the material. The plug assist should travel into the hot bubble fast enough so that the compressed air in the mold keeps the material against the plug until it has completed its movement. At the same time, the compressed air must be bled from the cavity to prevent “blow outs.”

Free-draw vacuum forming. Free-draw vacuum forming is used when the best optics or surface finish is required. The portion of the sheet that does not touch the forming frame yields optics equivalent to those of the original sheet. In this process, a vacuum box is built with the top opening in the shape of the formed part’s flange or open side. The box is moved into the hot sheet, and a vacuum is introduced in the box. The ambient air pressure pushes the material into the box in a spherical bubble; the deeper the vacuum, the greater the bubble. Only the material in the clamp frame and on the perimeter of the vacuum box touches a mold surface; therefore, the entire bubble remains free of “mold markoff” or distortion. A photoelectric eye is often used to control the vacuum and thus the depth of the part (see Fig. 8-10).

This process is widely used to produce skylights, windshields, viewing windows, and other industrial parts. Close-tolerance dimensions are not possible with this vacuum-forming technique.

Twin-sheet forming. This process is used to form hollow parts. It is competitive to blow molding in forming large, heavy-wall parts. Typical twin-sheet-formed parts are pallets, dunnage containers, double-walled parts that require great rigidity (such as large machine housing walls or platform floors), and air plenums or ducts. For extra rigidity, twin-sheet parts can be filled with rigid foam, or, in some cases, have metal or wood inserts placed in the part during forming.

In twin-sheet forming, two hot sheets are moved between two opposing cavity or female molds and vacuum formed into their respective molds. The molds are then pressed together with the hot-formed sheets between them. The pressure of the two molds squeezing the sheets together effects an excellent bond similar to that achieved by thermowelding. Twin-sheet molds are designed to create a bonded surface around the perimeter of the part, and at various selected areas throughout the part, as required for strength and appearance. The sheet surface must be at forming temperature when the bonding occurs.

Successful twin sheeting relies on the following mold design and construction considerations:

- Blow pins are required, to introduce and remove compressed air from the interior of the part to facilitate interior cooling.
- All mating perimeter and interior surfaces must be parallel and of the proper width to allow material movement during the squeezing process.
- Some molds require electric heating strips behind the mating surfaces to maintain this area of the mold at higher temperatures and effect an acceptable bond.
Twin-sheet forming can be done with light-gage materials (0.010–0.060 in. [0.25–1.52 mm] thick) on continuous roll-fed machinery (see Fig. 8-11) and with two other methods on three machinery designs using heavy-gage materials.

Single-station/single-oven forming machine. In this process, two sheets of material, each not exceeding 0.100 in. (2.54 mm) thick, are clamped together in a single frame with a flat air nozzle projecting between the sheets. The sheets then enter the oven, consisting of upper and lower heaters, and each sheet is heated from one side only. During the heating and forming cycle, hot air is blown through the nozzle between the sheets. This is done to introduce heat to the back side of the sheets, to prevent them from sticking together, and to introduce ambient air to the back side of the sheets during the subsequent forming and sealing sequences (see Fig. 8-12).

When the frame removes the sheets from the oven, molds press into the sheets from opposing sides, vacuum draws the sheets into the molds, and the pressure of the joining molds effects the seal. This is the least desirable method of twin-sheet forming, because the sheets are heated from the sides opposite to the surfaces that require critical bonding temperatures.

Double-ended ovens on a single-station forming machine. This machine has a single forming station with two sets of clamp...
frames, one above the other, approximately 6 in. (152 mm) apart. The frames carry the sheets, one to the right and the other to the left, into two ovens, with top and bottom heaters in each oven.

Again, one mold is mounted above and one below the sheets in the center or forming station. When the hot sheets return to the forming station, the molds move into the sheets, and a vacuum draws the sheets into the molds. The molds then continue into the hot sheets, pressing together to effect the seal. This machine gives more efficient heating and greater control of the bonding surfaces than the single-station/single-oven unit, with approximately the same production rates (see Fig. 8-13).

Four-station rotary forming machine. This machine has a large horizontal wheel with four material clamp frames arranged in a block shape. The wheel rotates the material into the stations in the following order (see Fig. 8-14):

• Station 1: Load and unload.
• Station 2: First-heat oven—top and bottom heaters.
• Station 3: Second-heat oven—top and bottom heaters.
• Station 4: Form station—upper and lower molds.

This machine gives the most efficient heating and greatest control of the bonding surfaces. It also provides simultaneous and continuous use of all stations. More than double the productivity of a single-station machine is attained with no increase in the required number of molds.

Because of the 12–15-second dwell time between heating and bonding the sheets (Stations 2 and 3), engineering thermoplastic grades, such as polycarbonate and polysulphone, are not recommended for four-station forming. The materials cool too fast during the open time before heating and bonding. The process, however, is ideal for polyethylene and works well with polystyrene and ABS.

During the short dwell time of the second sheet, while the first sheet is formed into the lower mold and the mold is lowered awaiting the next hot sheet, robotic arms can reach into Station 4 and insert wood, metal, or other plastic “orphan parts” into cavity areas. These parts, captured between the two formed sheets, are made a part of the final article. The orphan parts can be reinforcing or strengthening sections, or threaded inserts for later use in assembly.

Slip forming. This process works in both match mold and vacuum forming. An oversized sheet is removed from the oven and laid on a mold. When the vacuum is applied or when the opposite match mold presses, the loose sheet is drawn into the mold area and formed (see Fig. 8-15). Slip forming is an excellent method of forming materials that have restricted stretch or elongation, such as polyethylene-backed carpet and fabrics and fiber-reinforced thermoplastics.
Pressure Forming

When pressures greater than atmospheric are required to force the thermoplastic into more intimate contact with the mold surface, or when good optics of a circular part are needed, pressure forming is the preferred manufacturing method.

Free pressure forming—heavy-gage sheet. A forming mold is not required for this process, but close dimensional tolerances and detailed surface shapes are not possible. The process is excellent for viewports, skylights, food covers, and canopies. A pressure box or air platen is used with a clamping frame featuring an inside opening in the shape of the open side of the part. In using a pressure box (see Fig. 8-16), the heated sheet is sealed with the desired-shape clamp frame over the box. Compressed air is used to pressurize the box, thus forcing the sheet into a bubble. The depth is controlled by the air pressure (a pressure greater than 14.7 psi [101 kPa] begins to move the sheet), and the sheet is held in the desired position while it cools. A properly positioned photocell or microswitch is used to control the airflow and hence the depth of the part.

When using an air platen with a low-heat-conducting cover (felt, flocked suede rubber, or cotton flannel), the material surface that rests against the top of the platen is slightly cooled to prevent markoff. When using pressure to assist the vacuum, the material is forced into more intimate contact with the mold. This allows the contact surface of the sheet, closer tolerances, better material distribution, and lower residual stress. Common pressures are 50–60 psi (345–414 kPa); however, up to 150 psi (1034 kPa) may be required on large parts of higher-hot-strength materials or fiber-reinforced materials.

Specially built or adapted forming stations are required in the vacuum forming machine to successfully perform this process. To take full advantage of high-pressure forming, the machine platens must lock together so that the mold and pressure vessel cannot open when fully pressurized. Either mechanical locking platens or hydraulically operated platens with pressurized bags or hoses beneath the lower mold will ensure the seal (see Fig. 8-18).

There is usually a reduced yield when producing fine pressure-formed parts, compared to those made by vacuum forming. This is due to tighter appearance tolerances, such as crisp details and uniform texture surface, and a high level of secondary operations, such as trimming apertures and installing second-surface details on the back side of the part.

All of the previous methods of prestretching the sheet, to ensure uniform material distribution, are applicable to pressure forming with a plate or box.

Pressure-forming molds are more expensive than their vacuum-forming counterparts because of the extra strength required and the greater design detail usually desired in pressure-formed parts. Properly designed and built pressure form molds, run by experienced personnel on the right equipment, can produce parts with an exterior finish equal to that of an injection-molded part.

The majority of pressure-formed parts are machinery and computer equipment enclosures; they generally require Underwriters’ Laboratory (UL) certification of fire retardancy. The most widely used materials are fire-retarded ABS, modified polynaphylene oxide, and polycarbonate.

Pressure box forming—roll-fed thin-gage. For producing parts other than simple blisters, most roll-fed, high-volume forming is run with pressure assist for two reasons. First, the cycle time is controlled by the time required to cool the part on the mold after forming. When using pressure to assist the vacuum, the material is forced into more intimate contact with the mold. This allows the heat to be drawn from the sheet more efficiently. Second, since the
Thermoplastic materials that are extruded into a sheet web and then wound onto rolls are the raw materials used for the continuous roll-fed thermoforming process (see Fig. 8-19). Plastics such as PVC (polyvinyl chloride), high-impact and oriented styrenes, olefins, ABS (acrylonitrile-butadiene-styrene), PET (polyethylene terephthalate), and various foam derivatives of these materials are commonly thermoformed on a continuous basis.

One variation of this process is to skip the conversion of the plastic to roll form and extrude directly into the thermoforming equipment (see Fig. 8-20). A technical advantage of this procedure is that, as the hot extruded plastic travels into a thermoforming machine, the core of the material cross-section remains hot. The machine oven then heats the outer sheet layers so that the temperature across the web thickness becomes stabilized, and the hot plastic flows to form more uniform stress-free walls. However, the decision to extrude directly into the thermoformer creates an additional step in the production process that is susceptible to breakdown.

Most 6 in. (152 mm) diameter sheet extruders have the capacity to outperform a similar-size thermoformer by a factor of four. This excess sheet capacity allows a single extruder to feed several thermoforming machines more economically than dedicating an extruder to each thermoformer.

A roll of plastic material that is 0.003–0.100 in. (0.08–2.5 mm) thick and weighs 150–1000 lb (68–454 kg) is wound on a round cardboard core and placed in inventory. When the plastic is needed at the thermoformer, a shaft with tapered core chucks is used to feed the plastic to the forming station in the roll-fed equipment. As in cut-sheet machines, the forming station in the roll-fed equipment must be heavily constructed to lock the pressure box against the mold.

**CONTINUOUS ROLL-FED PROCESS**

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inserted into the cardboard core (to support it during unwinding) and positioned to enter the thermoformer (see Fig. 8-21).

FEATURES OF A ROLL-FED THERMOFORMING MACHINE
Most roll-fed thermoforming equipment has similar common component subassemblies. These components may differ in engineering elegance, durability, and quality, but their functions are similar.

Unwind Systems
Various types of unwind systems are built into the machine to overcome the inertia of the heavy roll weight; this allows the thermoformer to strip the web with a minimum of effort. The plastic web is guided into the thermoformer by means of an inlet guide. This guide is adjustable to permit setting up any plastic width within the machine capacity.

Web Transport
The plastic web is transported through the thermoforming machine by two parallel transmission chains that impale the edges of the web at its maximum width (see Fig. 8-22). This chain is indexed and intermittently synchronized with the demands of the thermoforming cycle. The index is powered by an air- or hydraulic-cylinder-driven mechanical system or by an electronically controlled electric stepping motor (see Fig. 8-23). Accuracy and repeatability of the index is important to register later thermoformed parts to an in-line trimming operation.

Heating
The web is indexed into an oven that is heated electrically or by natural gas. One or more residence index stations are built into the oven to allow the plastic to reach proper thermoforming temperatures at the cycle rate specified. Most ovens have upper and lower heating banks that are independently controlled (see Fig. 8-24).

The mass of the metal structure that guides the indexing chains through the oven draws heat from the edges of the plastic web; additional edge heaters may be installed to replace the heat deficit. The exit at the end of the oven, which has a relatively large opening, creates a localized heat loss, so many machine designers include an additional heater bank in this area to compensate for this loss.
The forming press is placed at the exit end of the oven, and the molds, plugs, assists, and pressure box are mounted on its platens. The forming press often has two independently operated platens, and they must be extended and locked to resist the opening force generated during pressure forming of the plastic (see Fig. 8-25). The forming press is extended, locked, or retracted by means of pneumatics, hydraulics, or electric stepping motor toggle systems (see Fig. 8-26). The position of the platens on closing triggers the actuation of the vacuum or pressure-forming valves and the plastic part stripping mechanism.

Factors Affecting Accurate Trimming

Once the finished parts are cooled by contact with the mold, they are indexed and ready to be trimmed out of the web. Accurate part trimming requires consideration of several factors:

- Full plastic part shrinkage is not completed during the thermoforming cycle. Parts are ejected from the mold when they
are rigid enough to hold their shape but may not be completely cooled. They are often indexed out of the mold to an in-line trim press when they have achieved only half shrinkage. The trim die designers must allow for this aberration in calculating die dimensions.

- Indexing error occurs on a thermoforming in-line machine when the web indexing system is inconsistent or inaccurate and the formed web does not register with the die.
- Piloting of the formed part relative to the trim die contour is a technique sometimes used to assure part concentricity. The pilot is a protrusion built into the punch or knife-like die that conforms to a rigid portion of the thermoformed part. It can be used to shift the part slightly into true position before the die cuts it free from the web.

TECHNIQUES FOR SPECIAL APPLICATIONS

Mold-related Topics
Trim-in-mold design. Roll-fed thermoforming featuring a trim-in-mold design is a common technique used worldwide (see Fig. 8-27).

The web of plastic unwinds from a roll, is heated in an oven, and indexes to the thermoforming press. The mold and trim dies are fabricated as a single unit so that, after thermoforming, the press platen has an additional closing action that activates the trim die (see Fig. 8-28). This method eliminates the need to transfer the formed part, which is still in the web, to another press for trimming. The concentricity of the trimmed flange to the thermformed shape is very uniform.

When a trim-in mold is designed with many rows of cavities in the index direction, trimmed part removal is difficult. This problem occurs after the finished loose parts are cut from the web. Material handling systems are required to remove these parts from the mold area quickly so the next forming cycle can commence.

Mold cavity types. Male mold cavities are generally less expensive and can be manufactured more rapidly than female cavities. The male molds can reproduce engraving textures and maintain size accurately on the inside face (mold side) of a formed product. The wall is generally thickest at the highest point of the cavity and tapers down from that value to the flange area (see Fig. 8-29).

Female mold cavities can yield the closest center-to-center distance on multiple molds, and when formed with the aid of a plug, provide the most uniform wall thickness. If a plug is not used, the bottom of the cavity yields the thinnest wall section (see Fig. 8-30). The outside wall (mold side) accurately reproduces engraving and texture and precisely reproduces parts from cavity to cavity.

Molds may be either male or female cavities built onto a temperature-controlled mold base. Roll-fed thermoformers require a moving clamp (pneumatically or spring operated) on the entering and exiting faces of the mold base. The rear clamp on the oven side of the mold prevents hot plastic from being pulled into the mold from the oven when the mold is closed. The exit (front) clamp prevents finished (hot) parts from being pulled and distorted on the press closing.

Spacing mold cavities. Mold cavity spacing requires analysis of several factors:

- Steel rule dies require a minimum of wood between the knives to maintain their integrity. These minimum requirements of the trim dies are influenced by the geometry of the die. Round dies can be placed closer together than long rectangular shapes, which leave a weak section in the long-knife direction due to side deflection of the die wall.
- Male molds are designed so that 75% of the part height serves as the flange distance between cavities (see Fig. 8-31). This rule does not take into consideration the draft angle of the side wall, any tiered layering of the part, or rotating 180° the high to low points of adjoining cavities. All of these geometric features help reduce the flange distance between cavities and maintain uniform wall thickness. However, the greatest mold efficiency is achieved by placing the cavities as close together as possible.
- When using a punch and die to trim two rows at one stroke in the index direction, the mold is laid out in even rows of cavities (see Fig. 8-32). This avoids the problem of punching one
CHAPTER 8
CONTINUOUS ROLL-FED PROCESS
row each from two different shots, because a small index error can cause errors in trim concentricity.

- Allowance for the following factors dictates the final mold size (see Fig. 8-33):
  1. There must be perimeter allowance for pressure box walls and sufficient edge distance from the chain rail (which cools the plastic sheet).
  2. Sufficient space is required for mounting assist devices (for male molds) in the pressure box and water-cooled stripper plates for the mold cavities.
  3. When using a punch and die, space for thermoform pusher index nubs for each row of parts in the index direction and space for indexing guides through a die are required. Punch and die index mechanisms drive pusher nubs on each index row to locate the row relative to the die in the trim press.

Female mold plugs. Plugs used on female molds are designed using the following parameters (see Fig. 8-34):

- The plug material consists of thermal insulators or temperature-controlled metal. The plug should reach an equilibrium temperature close to the plastic web temperature. This reduces the likelihood of the plug cooling the sheet as it stretches the plastic in the female cavity prior to thermoforming on press closure.
- The plug geometry should have generous radii at its intersecting planes and be relatively smooth. Plug computer programs are available to guide the designer, but trials on specific applications provide the final design.
- The plug clearance between the side walls and the cavity bottom can be estimated as a starting point. A plug that is too short yields a thin bottom section, while an excessively long plug results in weak side walls. Side wall clearance between plugs and molds may require adjustments to provide uniform part walls.
- Test a single plug in a sample thermoforming machine to refine its geometry before ordering a multicavity mold.

Undercut molds. Undercut molds may require a mechanical knockout for stripping parts. A warm part may strip more easily than a cool one, and this procedure is commonly attempted first. Mild undercuts may be stripped by coating the mold with a baked-on polytetrafluorethylene (PFTE) coating similar to that on a kitchen frying pan.

Mold surface finish. Molds can have various surface finishes. Very highly polished molds may trap air, degrading the resultant part. Molds for polyolefins are often heavily sandblasted to allow the trapped air to vent through the microscopic ridges of the finish. Etching and engraving are also used to achieve different textured finishes.
Aluminum molds. Aluminum mold cavities are machined or cast. Machined molds are milled or turned to a good finish before hand cleanup with abrasive cloths. Cast aluminum cavities can be produced with an acceptable finish if the pattern has a smooth metal finish or simulates a tight-grained wood such as maple or poplar.

Sand casting in fine-grained sand provides better results than plaster or ceramic materials. The gases generated in the hot liquid aluminum are more easily vented through the fine sand to avoid surface blemishes and internal flaws.

Molds for porous materials. Thermoforming molds used for foams or porous synthetic textile materials have conforming male and female cavities with clearance allowed for material thickness. The mold clearance may be set thicker than the original web for closed-foam cell-expanding materials such as foam polystyrene (egg cartons) or may be compressed into a desired wall thickness. Pressure-forming air is not appropriate for foam forming, as it may crush the foam cell, but vacuum is often used to sharply define engraved features.

Porous woven synthetic textiles are formed using generous radii and draft angles on matched tooling. On occasion, a sacrificial film of plastic material is used as a barrier for pressure or vacuum forming. Synthetic textiles have considerable orientation, and behave differently than plastic webs. It is therefore useful to experiment on a sample thermoformer before attempting to build a production tool.

Molds for crystalline plastics. Crystalline plastics, such as C-PET (crystallized polyethylene terephthalate), require high mold temperatures (270–300°F [132–149°C]) to produce a high-heat, dual-ovenable finished plastic food package. This type of crystalline plastic is processed more rapidly on a double-mold setup. The first mold is used to thermoform the part, which is then indexed into the second mold for cooling.

Another technique used in a single mold is to thermoform in the heated mold and index the web onto a cooling plate to reduce part warpage, allowing the plastic to cool before being trimmed.

**Additional Topics**

Contact heating. Contact heating of plastic, and then thermoforming and trimming the finished part in the mold from a roll of plastic, is common when producing clear disposable food containers and packaging (see Fig. 8-35). The contact press contains a heated...
Skin packaging is a thermoforming process in which a product is substituted for a mold (for example, hardware, auto parts, or toys). Multiple or individual products are placed on a porous cardboard that is preprinted and coated with a heat-sensitive dry adhesive. The cardboard with the multiple products is indexed into the thermoforming section of the skin-packaging machine, and a heated, thin clear plastic film comes into contact with the cardboard. A vacuum is applied through the porous cardboard, drawing the hot film around the product and causing it to adhere to the cardboard. The film cools, wrapped tightly around the contours of the product and cemented to the cardboard. The complete packages are trimmed automatically in-line or manually off-line.

Tooling and equipment. Thermoforming tooling for roll-fed equipment consists of a mold and a trim die, which are required for continuous thermoforming from a web of plastic.

This combination of tooling is necessary, since the completed thermoform shot (in single or multiple cavities) is rarely used without trimming the individual parts. Both tools must be considered when analyzing a new part since they interact with each other.

The type of thermoforming equipment available and the quantity of finished parts needed determine the type of thermoforming tools required. Cycle speed on most modern thermoforming equipment is directly related to the cooling efficiency of the mold. In-line heating ovens can preheat the web to optimum thermoforming conditions, drastically reducing the heating time. Indexing time for moving the sheet out of the oven into the forming press remains constant at 0.3–0.5 seconds. Press closing and opening speed totals less than one second, so the remainder of the cycle consists of thermoforming (cooling).

Mold cooling efficiency is increased by using high-heat-conducting metal, such as aluminum, for mold construction, and by following heat transfer rules. The best heat transfer results are obtained by reducing the number of interfaces (such as plating or coating) and minimizing the air gaps that serve as thermal insulators. Fluid coolants circulating through the mold should have a high Reynolds number (signifying turbulent flow) to increase heat transfer from metal to cooling liquid.

Fluid cooling paths through a plate or a cavity should be designed in a parallel rather than a series layout (see Fig. 8-38). Parallel paths, with suitable restrictors that uniformly force the fluid through the multiple channels, provide the most even cooling.
for each cavity. Series paths result in cooler cavities near the fluid entrance and hotter cavities at the exit as the fluid gains heat in passing through the mold.

Thermoforming molds made of epoxy, wood, or other low-heat-conducting materials can restrict machine cycling to the 1–3 cycle per minute range. Additionally, nonmetallic molds become hotter with use, further reducing quality and production output.

Pressure and vacuum forming. Pressure or vacuum forming or combinations of both are options for roll-fed thermoforming equipment. Pressure forming requires a safely designed pressure box that completely encloses the mold; a pressure of 15 psi (103 kPa) or higher is introduced into these boxes (see Fig. 8-39). Vacuum forming does not require a strong pressure box but features simple vacuum sealoff tools around the mold perimeter (see Fig. 8-40). Both methods may require plugs or assist devices to distribute the plastic sheet uniformly before the pressure or vacuum is initiated.

Fig. 8-37 Contact heat mold-die assembly. (Courtesy GN Plastics Co., Ltd.)

Fig. 8-38 Liquid cooling paths for mold temperature control. (Courtesy Mold Systems Corporation)

Fig. 8-39 Pressure forming. (Courtesy Mold Systems Corporation)

Fig. 8-40 Vacuum forming. (Courtesy Mold Systems Corporation)

HOW DIE CHOICE CAN DICTATE THE EQUIPMENT USED

Thermoforming machines that include an in-line trim press (see Figs. 8-41 and 8-42) may feature a spiked chain to index and register the part relative to the die. This type of equipment is available from several domestic and overseas machinery builders. These machines are designed for in-line trimming using knife-like dies (steel rule or forged high dies), which trim the entire multicavity thermoformed shot simultaneously into finished parts.

The trimmed parts may be retained in the web by means of weak uncut bridges (die nicks) so that, after being cut, the finished parts can be transported out of the die station. Finished, formed, and trimmed parts are plucked out manually or automatically and stacked by a part-stripping section once they are indexed out of the die cutting station.
Roll-fed thermoforming trim equipment, which includes a separate trim press in-line with the thermoformer, is also available. The separate trim press is generally a flywheel type of punch press with a self-contained, built-in sheet feed that cuts the parts free so they are ejected horizontally (see Figs. 8-43 and 8-44). The press has a variable stroke speed, so it can be set to accept the output of the thermoformer.

The formed web from the thermoformer is not directly registered into the die but is reindexed by the trim press feed. This arrangement of reindexing the formed parts allows one or two rows of parts to be cut at once, rather than trimming the whole shot at one time. This reduces the cost and size of the trim die and helps produce very accurately cut parts. Generally, only punch and dies can be used with this equipment.

Punch and die trimming in separate presses offers excellent technical advantages, but its economic drawbacks (die cost and long setup time) generally dictate long production runs.

Typical trimming costs for 100,000 parts are shown in Table 8-1.
The die costs shown in Table 8-1 dictate a knife-like die for economic purposes unless future production quantities increase by a factor of about 14. A punch and die might be used for medical or food packages where “angel hair” cannot be tolerated. However, a properly set up sharp forged die may produce an acceptable trimmed edge for critical packaging.

Delivery schedules in the thermoforming industry are often short (4–6 weeks); this factor as well as the number of available sources must be considered. Delivery times are as follows:

- Steel rule die makers generally deliver a new die in 3–10 days and rerule an existing die in 1–2 days (see Fig. 8-45).
- Forged die makers are less numerous and can deliver dies in 2–5 weeks. Manufacturing this type of die requires broad skills: blacksmithing, welding, heat treating, grinding, and layout (see Fig. 8-46).
- Punch and die makers for thermoforming trimming are indeed scarce. Most metal stamping die makers are not equipped to

### Table 8-1

<table>
<thead>
<tr>
<th>Die Type</th>
<th>Cost Details</th>
<th>Cost Per Part</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel Rule Die</strong></td>
<td>Die cost 500</td>
<td>0.0095</td>
</tr>
<tr>
<td></td>
<td>Rerule die (due to dullness) 250</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Setup time (4 hour @ $50 per hour) 200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total cost 950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Die cost per part ($950/100,000 parts)</td>
<td>0.0095</td>
</tr>
<tr>
<td><strong>Forged Die (High Die)</strong></td>
<td>Die cost 1,600</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td>Rerule die 0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Setup time (4 hour @ $50 per hour) 200</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total cost 1,800</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Die cost per part ($1,800/100,000 parts)</td>
<td>0.018</td>
</tr>
<tr>
<td><strong>Punch and Die</strong></td>
<td>Die cost 24,000</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Die maintenance (short run) 0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Setup time (20 hour @ $50 per hour) 1,000</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Total cost 25,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Die cost per part ($25,000/100,000 parts)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

* 1994 pricing
build the heavy dies weighing 1,000–2,000 lb (454-908 kg). They often lack the experience to allow for thermoforming press feeds, shrinkage, and other special features (see Fig. 8-47). Obtaining a single source for these toolmakers ensures the best relationship and minimal development problems.

The types of dies that are used in part trimming are listed in Tables 8-2 and 8-3. The tooling parameters of each die type are tabulated in Table 8-4.

**Economic Implications**

Economic factors concerning tooling cost and delivery cycles (Table 8-4) are based on the type of machines used for both thermoforming and trimming. The parts produced per shift are related to the sophistication of tooling.

Small thermoforming orders are often produced using epoxy molds; the shot is guillotine-cut and manually trimmed on steel rule die cutters into finished parts (see Figs. 8-48 and 8-49). This system is used for low-volume production runs of 500–2,000 shots and lower tooling costs.

Highest-quantity parts per shift are thermoformed on a roll-fed off-line punch and die line with a large bed area that accepts the full sheet width. As they are produced, the parts automatically stack for easy packaging. The high tooling cost and setup time require long production runs to amortize costs.

**Trim Quality**

Trim quality is judged by the lack of angel hair (see Fig. 8-50) clinging to the trim line and the accuracy of trim to formed part. Angel hair is small slivers of plastic material that need to be shaved from the trimmed edge.

Form and trim in the mold produces accurately registered parts and small quantities of angel hair if the die is carefully maintained. Knife-like dies are unable to achieve the same low angel

![Fig. 8-47 Punch and die. (Courtesy Fortune Mold Corporation)](image-url)

<table>
<thead>
<tr>
<th>Type of Die</th>
<th>Comparison of Costs $</th>
<th>Typical Delivery (Days)</th>
<th>Quality of Trim</th>
<th>Die Hardness (Rockwell “C”)</th>
<th>Life Strikes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel rule die</td>
<td>200–800</td>
<td>2–10</td>
<td>Fair</td>
<td>35</td>
<td>10-50,000</td>
</tr>
<tr>
<td>Knife-like forged die</td>
<td>600–5,000</td>
<td>7–35</td>
<td>Good</td>
<td>45</td>
<td>*25-100,000</td>
</tr>
<tr>
<td>Punch and die</td>
<td>10–40,000</td>
<td>45–110</td>
<td>Best</td>
<td>59</td>
<td>*50-250,000</td>
</tr>
</tbody>
</table>

*Can be resharpened by customer

<table>
<thead>
<tr>
<th>Type of Die</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel rule die</td>
<td>Lowest cost die, rapid delivery, many die suppliers available.</td>
<td>Dies cannot be sharpened, shortest die life, dulls rapidly, quality of trimmed parts deteriorates rapidly, center to center errors cannot be corrected.</td>
</tr>
<tr>
<td>Knife-like forged dies</td>
<td>Trim edges stand up 4-6 times as long as steel rule dies, dies can be resharpened, center to center die errors can be corrected.</td>
<td>Few die suppliers available, delivery time is longer than steel rule dies.</td>
</tr>
<tr>
<td>Punch and die</td>
<td>Highest quality trimmed edge, self-stacking trim out, lowest cost per packout, longest production die life, can be resharpened.</td>
<td>Most expensive die type, can have the longest press setup time, few die suppliers, center to center die errors cannot be corrected.</td>
</tr>
</tbody>
</table>
hair contamination that a punch and die assembly produces over a long production cycle.

Scrap Ratio

Total scrap ratio is governed by the mold area, with the most efficient use of available material on the largest mold size. For example, a 10 in. (254 mm) wide web may require 1 in. (25 mm) of edge width scrap on each side under the chain rails for transport through the thermoformer, a 20% scrap/web ratio. A 36 in. (914 mm) wide web with a similar scrap width has a 5.5% scrap/web ratio. A similar principle governs the front-to-rear dimensions of the mold.

SECONDARY OPERATIONS PERFORMED ON INDIVIDUAL CUT PARTS

Rim Rolling

Rim rolling of disposable drinking containers yields a smooth edge. This process is common on the majority of cups manufactured in the United States and Canada. Cups are rim rolled continuously at rates exceeding 600 cups per minute through a heated atmosphere into a group of rotating helical threaded screws, which roll the heated cup rim edges (see Fig. 8-51).

Printing

Printing of cups or containers in multiple colors is achieved at high rates on machines that use turretted mandrels. These mandrels rotate synchronously with each of the multicolor printing heads.

Decorative Parts

Decorating finished parts is accomplished by silk screening or hot stamping various foils. Off-line equipment, ranging from manually operated to automated installations, is commercially available.

Post-trimming

Post-trimming of parts includes punching various-shaped holes (elongated, round, or rectangular) or cutting a thermoformed part along its side walls. These secondary operations are economically feasible for short production runs.
Heat Sealing
Heat sealing of two thermoformed parts is most often accom-
plished using PVC plastic with a dielectric heat sealing machine
(using radio frequency waves). Packaging for high-value rack
merchandising and reusable book-like storage for audio and video
tapes is fabricated by heat sealing (see Fig. 8-52).

Blister Sealing
Blister sealing of clear thermoformed packages to printed
cards whose surfaces are treated with a heat-activated adhesive is
done on a thermally heated platen machine. Most of this heat seal-
ing occurs at the customer’s facility; however, many thermoform-
ing operations contain contract packaging sections. These opera-
tions provide full-service drop shipping to regional distribution
warehouses as well as to retail stores.
Sheet-fed thermoforming refers to heavy-gage products molded from precut thermoplastic blanks. These sheets are of sufficient thickness that they cannot be rolled and continuously fed into the machine. Material less than 0.100 in. (2.5 mm) thick is generally roll fed. Any material thickness can technically be molded on a sheet-fed machine, depending on the quantity and economics. Very low volumes of light-gage parts are run more economically on a sheet-fed machine because the setup is less time consuming. Sheet-fed parts are likewise larger in all dimensions and the end markets are radically different.

Sheet-fed plastic can use the same types of heaters as roll-fed material (ceramic, infrared, quartz, etc.). The dwell time (oven time) is proportional to the plastic’s thickness and type. Crystaline materials require more heat than amorphous materials. With longer dwell times, sheet-fed machines use gas-fired infrared heat. Considerable savings are realized with this method for very large parts.

**SHEET-FED MACHINERY**

**Single-station Machine**

A single-station machine consists of one molding station and one oven. The precut sheet is loaded into a clamping frame that securely holds all four sides of the sheet while it is heated and molded. The secured blank is manually slid into the oven until the material reaches forming temperature, which is predetermined by the blank thickness. A preset timer with an audible alarm notifies the operator that the sheet is at forming temperature; it is then manually moved to the forming station, molded, and cooled there. After cooling, the part is removed from the clamping frame, another sheet is loaded and slid into the oven, and the process is repeated. Single-station machines can be of the manual type described here, or semiautomatic to the extent that the operator needs only to load the precut blank and unload the molded part.

**Dual-station Machine**

Dual-station machines have molding stations at each end of a shared oven; the oven can be fixed or moving. This type of machine has a higher throughput, because while one station is in the cooling phase, the other is heating a second sheet. Optimum production is achieved for parts that require the same type and gage sheet. The thicker sheet dictates the overall molding cycle.

**Multiple-station Machine**

Multiple-station rotary machines have the highest throughput for sheet-fed parts. These machines have one molding station, one load/unload station, and either one or two ovens arranged in a triangular or block shape. The extra oven can be a preheat station or be used to heat another blank for twin-sheet thermoforming. The material clamp frames are in a large horizontal wheel that rotates the material from station to station. Part cooling or mold temperature control becomes the guiding factor that controls the mold cycle time.

**Oven Controls**

Molding stations for sheet-fed machines have reached a high level of electromechanical sophistication integrated with multiple-zoned ovens. The sheet is loaded on a lift table that has adjustable stops for repeatable positioning of the sheet into the clamp frame. The lift table also retrieves the formed part when the cycle is complete. This type of molding station frees the operator for less physically demanding tasks, such as quality control checks and secondary operations.

The ultimate molding station has a vacuum cup assembly that automatically picks up the sheet from the material stack and loads it into the clamping frame. This machine has a separate station with a gravity-feed roller system that is positioned under the clamp frame to convey parts to a downline workstation.

Computerized oven controls integrated with state-of-the-art molding stations provide the maximum thermoforming versatility. These ovens have up to 100 zones, each controllable from 0–99% input. Individual zone settings provide the molder the ability to use zone, shading, and profile heating techniques. The complete oven pattern can be saved in memory and recalled for later use on the same or different job. This repetitiveness supports part-to-part and job-to-job consistency.

Zoning allows the molder to activate only the needed zones according to the mold size; this results in energy savings. Heat patterns that run multiple tools with dissimilar materials and/or gages, and run a large machine with small molds are two advantages of this technique.

**Shading** is the ability to produce a consistent temperature from the perimeter of the sheet to its center. This reduces sheet sag, uses less energy, and decreases heating and cooling times.

Heating the sheet to conform to the mold design is accomplished through profile heating. Better material distribution and thinner starting gage are the greatest benefits of this oven control.

Heating the sheet from both sides significantly reduces oven dwell times. This is enhanced by using an infrared noncontact pyrometer. Cold-air drafts and fluctuations in electrical amperage can affect a hot sheet and part acceptability.

**POSTOPERATIONS ON VACUUM-FORMED PARTS**

After the part is demolded, postoperation finishing is usually required. In the first of these operations, the part is separated from the blank. Single-dimension horizontal trimming is first done with a small-diameter saw blade or router bit mounted in a high-speed router. The part is fed through the cutter until it is separated from the blank. Other methods include using a shear, bandsaw, or knife. Trimming plastics follows the same rules for machining metals, that is, speeds and feeds. The number of teeth per inch, the speed of the router, and the speed at which the operator feeds the part through the blade determine whether the cut is clean and only needs minimal deburring, or if the cut shows signs of plastic melting. In higher production quantities, this type of trimming is done with a steel rule, forged rule, or match die. The resulting trim leaves a tiny return edge; this is acceptable in products such as luggage, since this edge is covered by decorative trim or a valance. High-speed horizontal trimming can be accomplished by a multi-axis router, which gives the same or better edge finish with increased operator safety.

Drilled or slotted holes on low-volume parts are accomplished by a drill and fixture. The fixtures can be made of plywood, acrylic, aluminum, or steel. Any soft material has a short life when used as a drill fixture, but can be enhanced through the use of hardened drill bushings inserted into the base material. Higher
volume parts, fixtured for multiaxis trimming, are drilled in conjunction with the trimming, since most of these systems have double-ended routers or tool changers.

The parts can be decorated in several ways. Painting with resin-compatible coatings suggested by the resin manufacturer is the most successful approach to a durable finish. The quality of the final color and texture are quite controllable, giving the molder flexibility on low to moderate volumes.

Certain types of electrical enclosures require electromagnetic interference (EMI) or radio frequency interference (RFI) shielding. Sprayable nickel or copper coatings supply standard EMI/RFI attenuation. For more stringent requirements, sprayable silver or chrome plating on the part’s interior provides the ultimate shielding.

Thermoformed parts that are vacuum or pressure formed can be hot stamped or silk screened with the same equipment used for decorating injection-molded parts. When silk screening vacuum-formed parts, particular attention should be given to parts with a haircell finish. The screening inks can be too low in viscosity and seep out from under the screen, yielding a part with a poor quality finish.

SECONDARY OPERATIONS ON PRESSURE-FORMED PARTS

Trimming and decorating pressure-formed parts are basically the same as those for vacuum-formed components, except corner reinforcements, bosses, and standoffs are added. Pressure-formed parts are thinner in the corners, even with the use of temperature control plus assists and zoned heating. These corners can be reinforced with structural adhesive; a dime-sized patch usually suffices. However, the patching material must not melt the base material when it exotherms, and must be compatible with the shielding material if one is used.

Bosses and standoffs, with or without threaded inserts, can be glued into spot faces created in the plastic by an end mill. Close tolerancing of these features depends on the accuracy of the machine forming the facing. The highest accuracy is achieved with computer numerical controlled (CNC) equipment, and the choice of adhesive is important. Solvent-based glues can attack the plastic and permeate its face.

Assembly Considerations

Attachment and assembly of thermoformed parts, either to themselves or to metals, are normally handled on a per-job basis. Mechanical fasteners such as rivets, bolts, and screws require oversized holes. To prevent undue stress and broken parts, 0.015–0.030 in. (0.38–0.76 mm) diameter or larger holes are required. If the parts see a wide range of temperatures, thermal expansion can quickly fatigue parts.

This also applies to all types of adhesives, solvent bonding, ultrasonic welding, spin welding, or any other method where two materials of different thermal coefficients are fastened.

PART PRICING PARAMETERS

The basis for part costing starts with the raw blank, and sizing the blank requires some experience. A good starting point for a male geometrical feature, such as a five-sided box, is its length, plus three times the height, plus two times clamping equals the length of the blank. The width follows the same procedure: width, plus two times the height, plus two times clamping.

If that same box were a female, the rules become the length, plus the height, plus two times the clamping and width plus the height, plus two times clamping. Sizing and gaging of the blank for parts is an art form with few hard and fast rules. Trial and error, plus use of finite element analysis (FEA), contributes greatly to the part estimator’s success. The use of plugs, helpers, and variable heat patterns determines the final part’s wall thickness in relation to its starting thickness and sheet or film blank size.

Once the sheet size and gage have been calculated, the best approach to costing is to contact the potential sheet supplier and request a firm quote. The formulas used to calculate blank weight are entirely dependent on the specific gravity of the resin plus pigment or any other additives, such as flame retardants or ultraviolet light inhibitors. The sheet supplier also will provide a price for trim scrap or regrind that can be recycled.

Rejection percentage is normally 2–5%. As the degree of difficulty of molding and postoperations increases, the potential for molding and trim rejects subsequently rises.

Guidelines for estimating the cycle time are based on the thickness of the blank and the type of plastic. Each mil or 0.001 in. (0.025 mm) of thickness requires about one second of heat. For example, a 0.125 in. (3.18 mm) thick sheet requires about two minutes to reach forming temperature in a machine with upper and lower heaters. It takes a similar time to cool that part. Certain types of heaters reduce the oven times by as much as 40%. Coupled with temperature-controlled tools and spray mist cooling, these guidelines substantially overstate the cycle times attainable with modern equipment.

Formed part trimming is calculated from time and motion studies. Postoperations, such as threaded inserts and standoffs, gluing of walls and reinforcements, painting, shielding, and decorating are added to the base costs and marked up appropriately. The cost of packaging the finished part is a final consideration.
LAMINATION

COATINGS

PAINTING PLASTICS

The introduction of plastics into industry in the mid-1800s marked the beginning of a new era in engineering and commodity substrates. Over the years, plastics technology has grown into a major market. Plastics are considered a practical and economical alternative for metal, metal alloys, glass, ceramic, and wood structures.

Plastics substrates are divided into three categories according to their polymer properties: thermosetting plastics, thermoplastic substrates, and elastomers.

- Thermosetting plastics consist of polymers that, when heated and formed into a part, are cured or cross-linked into a permanent shape. The cross-linking is irreversible, and although the part can be softened by heat, it cannot be returned to its original flowable state.
- Thermoplastic substrates differ from the thermosetting plastics because they do not cross-link when heated. If the final part is reheated, the thermoplastic returns to its original flowable state. Repeated heating and cooling can cause degradation of the polymer.
- Elastomers are plastics that exhibit flexibility and elastic deformation. Natural rubber is an example of an elastomer. Elastic deformation is the ability of a substrate to deform under stress and to recover when that stress is removed. In contrast, thermoplastics and thermoset plastics exhibit plastic deformation, the deforming under stress that does not recover when the load is removed.

Plastics substrates can have in-mold color and texture, and a wide range of gloss; however, organic coatings produce all of these features with better consistency and quality. Organic coatings are made in any color and are held within the tolerances required by most industries. Plastics substrates often have swirl patterns, porosity, knits, and other surface defects from processing; organic coatings fill and hide these defects. Organic coatings meet all the appearance requirements of the manufacturers; they also enhance the quality of the product with the protective properties of the finish.

Painting Considerations

The solvent sensitivity, adhesion characteristics, and heat distortion temperature of plastics substrates make it more difficult to paint plastics than metal parts. For example, the best reducing solvents for paints are often the most aggressive solvents in attacking sensitive plastics. Consequently, the strength of the solvent used is balanced against its evaporation rate to achieve an acceptable compromise for reducing the paint yet not degrading the plastic. In some instances, an aggressive solvent is used in an air-atomized application as long as it is fast evaporating, used in moderation, and accompanied by a suitable amount of slower-evaporating, less-aggressive solvent. Table 9-1 lists some solvent effects on several plastics substrates.

Adhesion characteristics change dramatically from plastic to plastic (for example, ABS to polyphenylene oxide) and from one grade of plastic to another. In addition, plastics have a lower surface tension than metals that are normally painted and consequently are harder to wet and obtain adhesion. Adhesion is generally achieved by using a polymer with a resin similar to the substrate. For example, polyester resins offer good adhesion to polyesters and polyester-based fiberglass-reinforced materials.

Baking temperatures for plastics are lower than those for metals. Table 9-2 lists the maximum baking temperatures of common plastics substrates and the adhesion characteristics of conventional coatings and low-volatile organic compounds (VOC) coatings.

Application Procedures

Applying organic coatings to plastics substrates requires knowledge of plastic types and the coatings that are used. Procedures vary with different substrates and coatings. Before the coating is applied, proper substrate pretreatment is applied to remove mold releases, oils, or other surface contaminants. A solvent wipe removes most contaminants, but caution is essential when selecting a solvent. Certain solvents degrade the plastic, causing loss of strength, blisters, or poor adhesion when coated. Sanding is another method occasionally used to ensure that the plastic surface is clean; it is also used to smooth rough substrates.

Spraying is the most popular method of applying coatings onto plastics substrates. When electrostatic methods are used, the part is rendered conductive using a hygroscopic ionized-salt solution that is applied using dip or spray techniques. Roller coating is commonly used for painting flat surfaces and for producing woodgrain patterns. Flow coating is used to apply basecoats and topcoats for vacuum-metalized plastic parts.1

The Contributors of this chapter are: Edward Bernheim, President, Exxene Corporation; Jack Gabower, President, Vacuum Platers, Inc.; Fred E. Heine, Vice President, Acromark; Roger Lepoutre, President, Meytec, Inc.; Alan Low, Market Manager, Husky Injection Molding Systems.

The Reviewers of this chapter are: John D. Blizzard, R&D Specialist, Dow Corning Corporation; Jim Cuchiara, UV Printing.
### CHAPTER 9

**COATINGS**

<table>
<thead>
<tr>
<th>Table 9-1: Solvent Effects on Some Sensitive Plastics</th>
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<tbody>
<tr>
<td><strong>Evaporation Rate</strong></td>
</tr>
<tr>
<td><strong>Ketones:</strong></td>
</tr>
<tr>
<td>Acetone</td>
</tr>
<tr>
<td>Methyl ethyl ketone (MEK)</td>
</tr>
<tr>
<td>Methyl isobutyl ketone (MIBK)</td>
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<tr>
<td>Diisobutyl ketone (DIBK)</td>
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<tr>
<td>Cyclohexanone</td>
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<tr>
<td><strong>Esters:</strong></td>
</tr>
<tr>
<td>Isopropyl acetate</td>
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<tr>
<td>n-Butyl acetate</td>
</tr>
<tr>
<td>Cellosolve acetate</td>
</tr>
<tr>
<td>Isobutyl isobutyrate</td>
</tr>
<tr>
<td><strong>Aromatic hydrocarbons:</strong></td>
</tr>
<tr>
<td>Toluene/xylene</td>
</tr>
<tr>
<td>Alcohols, glycol ethers, aliphatics (as clears)</td>
</tr>
</tbody>
</table>

* As a group, ketones and esters are aggressive; aromatics are moderately aggressive; and aliphatics, alcohols, and glycol ethers are nonaggressive.
** 1 = aggressive; 4 = no effect.

<table>
<thead>
<tr>
<th>Table 9-2: Adhesion and Paintability of Various Plastic Substrates</th>
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</thead>
<tbody>
<tr>
<td><strong>Substrate</strong></td>
</tr>
<tr>
<td>ABS</td>
</tr>
<tr>
<td>Acrylic</td>
</tr>
<tr>
<td>Cellulosics</td>
</tr>
<tr>
<td>Polyolefins</td>
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<tr>
<td>Nylon</td>
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<tr>
<td>Polycarbonate</td>
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<tr>
<td>Modified PPO</td>
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<tr>
<td>Polystyrene</td>
</tr>
<tr>
<td>Vinyls</td>
</tr>
<tr>
<td>Urethanes</td>
</tr>
<tr>
<td>Xenoy</td>
</tr>
<tr>
<td>Polyesters</td>
</tr>
<tr>
<td>Phenolic</td>
</tr>
</tbody>
</table>

* Treatment required.
** Nonsupported.
START-UP CHECKLIST FOR PAINT SPRAY LINES

Pretreatment/Cleaning
The following items are essential for proper pretreatment and cleaning:
- Heaters on and set at proper temperature.
- Pumps on.
- Rinse stage overflows operating properly.
- Solutions at proper concentrations.
- Bypass discharge valves set at correct pressures.
- Chemicals available and properly stored.
- Operator safety equipment provided.
- Spray nozzles functioning properly.

Ovens
Oven parameters are set for optimum operation:
- Ovens and adjacent areas free of combustibles.
- Purge timers properly set.
- Cure oven and all zones set at proper temperature.
- Dry-off oven on and set at proper temperature.
- Exhaust fans operating.

Paint and Paint Mix Area
This area sets the foundation for proper painting operation:
- Ground wires in place and secured.
- Drums, tanks, and other containers properly vented.
- Exhaust systems operating.
- Required colors available.
- Agitators on and adjusted to proper speeds.
- Paint at proper application viscosity and temperature.
- Paint pumps on and adjusted properly.
- Proper fluid filter pressure.
- Safety equipment provided.

Application Equipment
The following application equipment preparation is essential:
- Proper cleaning and maintenance performed.
- Area free of obstructions.
- Ground wires in place and secured.
- Air wires in place and secured.
- Air make-up and exhaust systems operating properly.
- Fluid lines and applicators purged of wash solvent.
- Paint flowing to applicators.
- Applicator positioning, fluid pressures, flow rates, atomizing air pressures, and spray patterns correct.
- Safety equipment provided.

Conveyers
Conveyers require proper preparation:
- Free of obstructions for the entire length.
- Guards in place.
- Proper lubrication performed, but not excessive.
- Hooks and fixtures properly hung.
- Speed set correctly.

On-load Area
The on-load area is prepared as follows:
- Area free of obstructions.
- Schedule available.
- Proper hooks and fixtures available.
- Proper ware staged.
- Safety equipment provided.

Off-load Area
The off-load area is prepared as follows:
- Area free of obstructions.
- Packing instructions available.
- Packing containers and labels available.
- Safety equipment provided.

Final Check
The final items complete a walk-through check for paint line start-up:
- Pretreatment/cleaning tanks at proper temperature.
- Ovens at proper temperature.
- Conveyor at proper speed.
- Faulty equipment repaired or replaced.
- All interlocks and safety equipment functional.
- Access to emergency shut-down devices clear of obstructions.

TRANSPARENT COATINGS

Substrates
Several engineered optically clear plastics are available:
- Polycarbonate. Polycarbonate is a highly impact-resistant plastic whose surface is very soft. Although it needs coating protection against scratching and weathering, it is the plastic of choice in many applications.
- Acrylic. This material is an economical plastic that can become brittle over time and is usually coated for protection from cracking. Even though it is harder than polycarbonate, coating is still required to protect it from scratching.
- Acetate. Acetate is one of the original plastics. It has high resistance to chemicals but is soft. Furthermore, thermal coating is difficult because of its low melting point.
- Polyacrylate. This material is a soft but weather-resistant, dark yellow plastic. It is stable when used outdoors. Because it is soft on the surface, it is usually coated.
- Polyester. Polyester is a soft but durable plastic that also requires coating. It has a relatively high melting point.

Each of these plastics performs differently but requires coating to maintain its properties.

Cures
Thermal cure. Oven curing is an old process, and some plastics do not oven cure well because of their low melting points. Coatings that heat cure on plastics are formulated with care, and the maximum oven temperature is 250° F (121° C). Oven design is important as some thermal-cure coatings are solvent based. Safety precautions are important because health and fire dangers from solvents are present. Every solvent has a threshold limit value, the maximum amount of solvent a worker may be exposed to during an eight-hour shift. Proper ventilation is required to remain below this exposure limit. Ovens are designed with different heat zones, and some have nonair atmospheres. For example, an inert oven atmosphere helps heat transfer to the substrate.

UV and EB cure. Ultraviolet (UV) light- and energy-beam curing are popular because they provide fast cures. Cure times of less than 30 seconds are common. These coatings are 100% solids, ensuring no solvent danger. Because there may be sensitization problems from some monomers, employee care is important.
Since these coatings are 100% solids, their viscosity is often high. As a result, solvents may be added to coat complex parts.

Types of Coatings

Clear coating types can be either hard, exterior weathering, basecoat, thermoformable, antiglare, barrier, antifog, antistatic, or tinted.

Hard coatings. Plastics, especially polycarbonate and acrylic, do not have long service lives because of their inherent softness. Polycarbonate is especially soft. Uncoated polycarbonate is easily scratched with a fingernail. Other plastics are harder, but there is no clear plastic that is acceptably hard for general applications. A surface coating is often necessary to avoid excessive marring and scratching that occurs during normal use. For instance, glasses are judged for scratches by rubbing over a sandy surface. A hard coating provides good surface properties to minimize wear parameters. Its smoothness reduces friction and increases wear and life. The coating should provide superior chemical resistance. It should resist all cleaners, common acids, and solvents, including acetone and ethyl acetate. Without a coating, the chemical resistance of plastics is suspect. Acrylics are attacked by aromatic solvents, and polycarbonate is marked by many common materials. Some applications for coated sheet stock and molded plastic parts are LCD covers, lenses, laboratory safety plates, and light covers.

Exterior-weathering hard coatings. There are several types of exterior-weathering hard coatings. They have the common link of either dissolved UV absorbers or UV-absorbing systems chemically linked to the polymeric structure. This coating is necessary on plastics and provides a ten-year life in most applications.

This type of coating is modified to reduce the aging processes of yellowing and cracking. The coating is applied to sample parts, which are then exposed to Arizona and Florida weather. Among the tests used are:

- Carbon arc.
- Cabinet weathering tester (QUV).
- Xenon arc.
- Accelerated exterior test (EMMAQUA).

These coatings are used widely in the plastic glazing and automotive industries.

Basecoats for deposition. Hard coatings are also used to offset a problem that vacuum metallizers have when coating plastics. When a plastic substrate, such as polycarbonate, is metallized, the result is generally uneven and has little scratch resistance. The thin film coating is often easily removed. A special type of hard coating (normally silicone) is used. This is slightly porous at the surface and grasps the metallizing film, providing good adhesion. The coating also provides an exceptionally even surface that metallizes easily.

Thermoformable coatings. Hard coatings may be flexible enough to thermoform after application. Such a coating eliminates the problems of fabricating and machining uncoated plastics. The coating must have exceptional flexibility because the bend in the coating is permanent. The coating must have good adhesion, especially at the bend. This type of coating is used on all parts that are exposed to bending. Its flexibility properties are also useful in thin-film applications and nonformed parts.

Antiglare coatings. Antiglare coatings, also called low-gloss coatings, reduce reflection on plastic part surfaces. These coatings contain inert particulate that stay at the coating surface.

This particulate increases light refraction and absorption and decreases reflection. This type of coating has good abrasion resistance, but it is less effective than a similar clear coating. Since the inert material stays at the surface, this type of coating is more easily scratched. Low-gloss coatings can be antistatic. Antiglare coatings have excellent chemical resistance and are used for LCD displays, signs, and electronic applications. The coating properties are generally measured in terms of gloss, which is evaluated with a 60˚ gloss meter. Typical gloss levels are as follows:

- 0: Film screens.
- 40: Heavy gloss reduction, often has clarity problems.
- 55: Normal gloss reduction.
- 75: Light gloss reduction.
- 90: Very light gloss reduction.

Higher gloss provides better clarity, and the converse is true.

Barrier coatings. There are many requirements for coatings that are barriers to water, liquids, or gases. Many of the previously mentioned coatings behave as barriers; however, few coatings do it completely.

Antifog coatings. Water droplets cause a loss of visibility. Most fogging, when viewed through a microscope, consists of extremely small water droplets. Antifog coatings absorb water or reduce the surface tension of water droplets, causing water to sheet. When water sheets, it is transparent.

Antifog coatings are softer than some coatings. Self-healing is an important property for antifog coatings. A self-healing coating levels its own scratches immediately or over time. This enables a softer coating to outlast a harder one because a scratched harder coating does not repair itself. Antifog coatings are mainly used in the safety and recreation industries; they are also applied in the electronics industry.

Antistatic coatings. Antistatic coatings can reduce static and prevent dust buildup. They are more effective when they are grounded. These coatings, which are highly chemical and abrasion resistant, are often applied to the plastic used on clean-room walls. They are also used for plastics that contact sensitive parts.

Tinted coatings. Most plastic coatings can be dyed or pigmented; dyed coatings are the most common. Introducing dyes into coatings affects the amount of light that is transmitted through the coating. Other than light transmission, the physical properties are generally unchanged. However, most dyes have poor UV light stability. This problem is minimized by introducing specific UV absorbers. Tintable coatings are useful in optical stores, where eyeglasses are tinted to suit an individual’s taste. These coatings absorb dye and dye can be removed from them. They must maintain their properties even after the dye absorption process.

Neutral-density coating. This is a tinted, low-gloss coating that is adjusted in color and hue to reduce optical transmission. These coatings are normally gray, but there are some underlying hues, permitting maximum contrast enhancement. This coating has monitor and television applications.

Water-spreading coating. This is coating that sheets large amounts of water. Because it air dries, this coating is used in greenhouses and other structures where water must drip into designated areas.

Formulations

This section covers four coating types: polysiloxane (silicone), heat-cure polyurethanes, light-cure acrylates, and epoxies and silyl epoxies.

Inorganic in nature, polysiloxane coatings have the following properties:

- Thermally cured at temperatures that are low enough for use on plastics.
• Hardest coatings available for plastics.
• Good clarity.
• Excellent chemical resistance.
• Can be formulated for weatherability.
• Stable over the life of the plastic.

Heat-cure polyurethane properties are as follows:
• Somewhat hard, tacky coating.
• Cure thermally, can be UV cured, or can be cured at ambient temperatures.
• Excellent weathering properties.
• Self-healing properties.
• Good chemical resistance.
• Good clarity.

Light-cure acrylates display the following properties:
• Cure quickly.
• Fair to good hardness.
• Good clarity.
• Fair to good chemical resistance.
• Some problems with weathering.

Silyl epoxies are a composite of polysiloxanes and some unique epoxy resins. Epoxies and silyl epoxies exhibit the following properties:
• Cure thermally or air dry.
• Are softer than equivalent silicones.
• Display superior chemical resistance.
• Have superior adhesion for many substrates that are uncoatable with other coatings.
• Exhibit good clarity.

Means of Application

Dipping. Dipping is relatively easy and coats both sides of the part at one time. Hand dipping is rarely used because the coating builds up at the bottom of the part. A better way of dipping is to use a phased withdrawal from the coating at a steady rate of 1–6 in/min (25–152 mm/min). This yields an even coating thickness and prevents buildup at the bottom of the part. Faster withdrawals permit thicker coatings, and the converse is true.

Flow coating. Flow coating is used when coating only one side of a part. The coating is generally thinner than that for dipping. One-side coating is done for several reasons:
• To print the back side of a sheet.
• To ultrasonically weld a part.
• To permit a coating combination; for example, to hard coat one side and antifog coat the other.

Flow coating consists of passing a filtered coating stream across the top of the part and allowing it to run off. Unfortunately, it is a slow process, and the coating may be uneven from top to bottom. However, the process produces the cleanest parts. Flow coating is like washing the part; all particulate runs off with the flow. Flow-coated parts may require more time for flow and run-off compared to other processes.

Spraying. Spraying can produce an even coating as long as the spray pattern and rates are repeated consistently. This process is called reciprocation. Spraying demands a very clean environment, because the spray cone captures all particulate in its path. Spraying, done in a clean-room environment, is useful for many of the same applications as flow coating. The other advantage of spraying is that complex parts can be coated evenly.

Testing Before Application

When testing for solids, a weighed amount of coating (if the coating is water or solvent based) is heated to evaporate the volatiles. The amount of solids left, divided by the original coating weight (multiplied by 100) yields the percent of solids.

Viscosity, which describes the coating thickness, is measured by many methods. The simplest method is to use a Zahn Cup, a measured cup with a hole in the bottom. A finger is placed over the hole at the bottom of the cup, and it is filled with coating until it overflows. The operator’s finger is removed from the hole, and a stopwatch is started. The viscosity result is the time required for a break in the fluid stream.

Specific gravity is defined as weight per unit volume. It is excellent for initial evaluation.

Testing After Curing

Adhesion. Adhesion is tested by cutting a 100-square hatch on the part surface. A piece of tape is then placed over the hatch and pulled off vigorously, and the adhesion is rated on a scale of 1–5. A rating of one demonstrates complete removal of the coating. A five rating has no coating removal.

Hardness. Hardness is often measured by taking a 1 in. (25 mm) circle of steel wool and placing a specified amount of downward pressure on the coated surface. Fifty strokes with the steel wool are completed. The results are reported at the highest poundage that showed no scratching.

There are other hardness tests. A Taber abrader test uses two CS-10F abrasive-weighted wheels placed on a rotating part for 100–1000 cycles. The result is measured as a haze change by a hazometer. There are also hardness tests that use weighted falling sand, but few of these give instantaneous results.

The only test with instantaneous results is the pencil test. A complete set of pencils from soft to 8H are gathered and sharpened. The hardest pencil that does not scratch the part defines the hardness. All the above are excellent tests for various properties, but it is important to differentiate between hardness and wear.

Other tests, which often depend on the rigorousness of the application, are listed as follows:
• Humidity. A part is exposed to 100 hours in a humidity cabinet at 100°F (38°C). The test is passed by withstanding the previously mentioned adhesion test.
• Boiling water. A part is placed in boiling water for two hours. The previous adhesion test provides pass/fail criteria.
• Room temperature impact. Tests range from falling ball bearings to pellets fired from air rifles.
• Discoloration. The part should have no noticeable color change.
• Workmanship. The part should show no scratches, cracks, dirt, grease, pits, hairs, burrs, bubbles, or carbon.
• Luminous transmittance and haze. Optical properties are measured with a hazometer.

Potential Disadvantages of Coating Systems

Impact resistance loss. Structural damage to the surface can occur if a coating is improperly formulated. Solvent or monomer effects can reduce impact resistance, flexibility, and other properties. Excessive temperature or too much light exposure can also cause impact resistance loss, color changes, and other problems.

Inadequate adhesion. Poor adhesion assures coating pull-up and weathering failure. The best test for adhesion is the standard crosshatch test.

Blemishes. Blemishes are avoided by strictly enforcing cleanliness in the process.
CHAPTER 9

COATINGS

Damage by environment. Temperature should damage the substrate long before it damages the coating. Melting the substrate destroys the coating. Humidity can have an effect on many coatings and is a standard test for coating evaluation. Sunlight can yellow coatings. Any coating destined for exterior use is evaluated by QUV or xenon arc testing. Chemical resistance is also tested.

Cleaning
Most plastic parts are cleaned before they are coated. If plastic is film masked, residual adhesive may be present. If a plastic part is exposed to factory conditions before it is coated, mold release or other substances can come to the surface. Packing materials can leave particulate and other residue. Some problems that are caused by inadequate cleaning are loss of adhesion, contamination of the coating, and particulate. Two types of cleaning systems are popular: water-based and solvent-type.

With water-based detergents, the typical cleaning steps are as follows:

1. Detergent in ultrasonics.
2. 50:50 detergent and water in ultrasonics.
3. Tap water wash.
4. Distilled water.
5. 50:50 distilled water and alcohol.
6. Alcohol.
7. Drying.

Solvent cleaning is also possible if proper ventilation is available. However, the contaminated solvent requires reclaiming.

Equipment
Electron beam curing systems, UV light configurations, and ovens are choices for curing laminations. However, with any facility, the following items are essential:

• Laminar airflow. If air is flowing out of the coating facility, dust has less chance of contaminating the process.
• Air filtration. Cleaner air provides better-quality parts.
• Chemical handling. Flammability and health concerns are essential.
• Versatility. Any setup should function in several ways to accommodate a changing marketplace.

HOT STAMPING
Hot stamping is a means of decorating, using heat and pressure to transfer an image from a carrier to a substrate. Used for generations to decorate leather and paper products, hot stamping of plastics only began in the early 1950s. Today, hot stamping is commonly found in every market that has a plastic product. Appliance, automotive, cosmetic, furniture, hardware, houseware, high-tech, and the toy industries design products with hot stamping as a suitable product enhancement method and a fast means of applying decorative finishes at minimal cost.

Foils
Foils are a basic element of hot stamping. They consist of a sophisticated combination of multilayer coatings comprised of a release layer, color layer, and adherence base. Metallic foils replace the color layer with vacuum-metallized aluminum, which is tinted yellow to give a gold appearance. Foil substrates, primarily Mylar®, are coated on smooth rollers on a coating machine. Textured rollers, used on the color coat, apply a first pigment color, leaving a spotty image on the carrier. The foils are then rerun with a second color on a smooth roller, resulting in a multicolored transfer foil. Today, these multicolor foils appear as woodgrains, marble, textured leather grains, and a variety of other imaginative finishes.

In the last decade, innovations, such as additional coatings between the release and color coatings, have resulted in high-such coatings, making the transferred image impervious to the environment. Ticking and brushed effects are obtained by scratching or treating the Mylar carrier prior to coating. Aluminum vacuum metallizing is often substituted with the introduction of chrome, providing a much tougher coating and different appearance for automotive industry uses. Adherence coating polymers have maintained pace with the new engineering plastics, making hot-stamping foils available for most materials.

Reprinted transfers or heat transfers eliminate the need for multistamping operations. Using the same chemistry as foils, these multicolor transfers allow a cost-effective method of multicolor product identification with hot stamping. Heat transfers have the color coat applied to the carrier in the form of an image, with tight registration maintained with each subsequent color; this results in a multicolored transfer. Unlike conventional foil, these transfers are registered exactly over the product prior to the hot-stamping process.

Tooling
Tooling, or fixtures, the next essential item for quality hot stamping, are manufactured from a variety of materials. The most common is aluminum, which is easy to machine and alter after completion. Other materials include urethane and epoxy, which are molded from a part. Most tooling is for single-station hot-stamping systems, requiring only one fixture. Rotary tables with multiple fixtures increase productivity by as much as 200%. Automatic ejection systems further improve efficiency. Alternately, high-productivity tooling can consist of magazine feeding or automatic loading. With long projected runs, completely automated systems are common in the hot-stamping field. Specialized, dedicated hot-stamping systems and tooling are used in the automotive, houseware, and appliance industries.

Dies
Dies are also an essential part of hot stamping; they are produced from metal or silicone rubber. Metal dies are made from a variety of materials, with the number of impressions required determining the best material. Short runs are often hot stamped with “line-type” lead slugs. Photographically etched dies of zinc, magnesium, or brass are excellent for medium runs of several thousand impressions. Long-run applications and those with high abrasion characteristics, such as peripheral marking, should have dies of a hardened material. Metal dies impress an image into the part surface, giving a debossed appearance.

Silicone dies are used for tipping raised areas on molded parts and also in place of metal dies. By producing an inexpensive mold, the silicone rubber is formed into an image die, which has advantages in slightly compensating for variations in the product's molded surface, and a true surface image is made without embedding into the product. Aside from dies molded from artwork, dies are molded from engraved molds or forms. These dies, often referred to as cast dies, are beneficial in cases where it is impossible to mount the die to a backing or mounting block, such as in tight corners on an automotive dashboard. Cast dies also increase the flexibility of hot stamping by molding dies that duplicate the part surface. Molds are easily reworked, and improper die matching is corrected with a new die cast reflecting changes in the product surface.

Silicone is also a major factor in large-area hot stamping. Roll-on hot stamping is a method where a roller coated with silicone rub-
ber is passed across a surface, transferring the foil to the product. The silicone is either bonded on aluminum cores, which are returned to the manufacturer for recoating, or molded in the form of silicone sleeves, which are placed over a core at the end user’s plant.

**Stamping Presses**

Hot-stamping machines are available in a variety of styles. The majority of these presses are the vertical type, applying direct up-and-down pressure to the surface that is hot stamped. An example is shown in Fig. 9-1. They are available in simple hand-operated, air, hydraulic, or motor driven versions. Each has its advantages and application limitations.

**Press size.** Press size is an important factor. It is governed by a combination of die area and pressure capacity, with die size limited to the overall impression area and not necessarily related to the product size. The pressure, or pressing capacity, is also related to the die or impression area. A general rule is to provide 500 lb (227 kg) of pressing force for each solid square inch (6.4 square cm) of stamping area. Since many hot-stamping requirements are for small letters spread over a larger area, presses with low tonnage ratings and large die areas are common.

The most common vertical hot-stamping presses are air or air/oil powered. These presses provide stamping pressures from 0.25 ton (2 kN) to over 20 tons (178 kN) and die areas from $1 \times 3$ in. ($25 \times 76$ mm) to more than $2 \times 3$ ft ($0.6 \times 0.9$ m). The pressure is developed through air cylinders, hydraulic cylinders with intensifiers, or mechanical devices driven by air cylinders. The most versatile is the direct-acting cylinder, because it develops pressure upon point of contact with the work surface. Since most plastic products vary, any machine that can compensate for variations is superior to one that cannot.

**Heated head.** Each vertical press has a heated head to which a hot-stamping die is mounted. The head contains heaters and a probe from the temperature control. Units with higher watt density/in.$^2$ (watt density/mm$^2$) provide faster initial warmup and faster die recovery in a production application. Temperature control is critical and is the best means of heat control available. Solid-state controls are used in the majority of cases with standard hot-stamping presses, maintaining variations within 20˚ F (11˚ C).

Attached to the heated head is the foil advance mechanism. This holds the foil roll, guides it between the die and product, and advances it following each press cycle. This foil advance mechanism generally travels with the head of the press, allowing it to clear the product when it is loaded and unloaded. For small advances, foil is indexed by a mechanical system consisting of a ratchet or clutch and gear with rack device. For longer advances, an air cylinder or air foil advance is used, consisting of an air cylinder connected to a rack and driving a gear on an overriding clutch.
Long advances are driven by motors that are timed by an encoder. The function is to feed the used portion of foil, placing an unused portion between the die and part surface.

An elaboration of the standard foil advance is the preprint feeder. This sophisticated foil advance mechanism allows the exact registration, or controlled feed length, of the preprint transfer. These systems have electric eye or tractor feeds for repeat registration to advance the transfer to repeatability within 0.005 in. (0.127 mm). The preprint feeder may be an external attachment to an existing press or combined as part of a standard foil advance.

**Press frames.** The frame is also an essential part of the press, as it provides the desired press pressure. Frames are available as castings, weldments, or assemblies. The two most common styles are C-frame and four-post. The latter has many advantages with respect to deflection, but it can become restricting when trying to place a large part between the posts. As a result, four-post hot-stamping frames are often limited to high-tonnage, large-die-area parts. The C-frame, less expensive and somewhat less restricting, is the most common.

**Roll-on machines.** Roll-on, or linear-contact, hot-stamping machines have revolutionized the hot-stamping industry. A roll-on machine is shown in Fig. 9-2. Whereas vertical presses were suited for large areas with high-density copy only at high pressure and ideal conditions, the roll-on type of machine permits total coverage of large areas. Typical applications include applying woodgrain foils to large flat surfaces, such as television cabinets, furniture panels, and similar items. The principle is to lay the foil onto the surface by a continuous motion with a roller instead of a flat die. Air entrapment or voids, due to minor sinks, are eliminated; the roller fills the minor voids as it passes across the part surface.

There are various types of roll-on machines. Each machine has a heated silicone roller, foil advance, and a means of presenting the part to the roller. The most common roll-on unit has a continuous moving belt. The belt, silicone roller, and foil are all timed to travel at the same speed, ranging from 5–40 ft/min (1.5–12 m/min). Belt-type roll-on machines are used for a variety of applications, including hot-stamping flat panels, plastics sheets that are later vacuum formed and used in automotive trim, or particle boards for the furniture industry.

Roll-on increases production. Roll-on machines, with their continuous motion, have increased production of injected-molded parts with raised letters that require “tipping” or highlighting the characters with foil. Applications, such as molded plastic letters or license plate frames previously hot stamped by a vertical press, are done on a roll-on press at significantly increased production rates. Aside from the increased production speed, lower reject rates are obtained along with a higher recovery rate of parts rejected because of poor hot stamping. Vertical stamping of parts with sinks normally results in poor quality, but with the roll-on process, since the roller falls into slight recesses or sinks, there is no mashing of the other characters to obtain the desired marking.

Roll-on variations. Variations of the roll-on machine generally fall in the area of part presentation. When the part is large or requires internal support under the marking surface, a reciprocating table can replace the belt, providing a surface on which to mount various fixtures. These machines run slower, adding time for the table to return to the start position. One variety of this roll-on machine has moving pallets that travel in a continuous motion through the roller assembly and then around the outside to repeat the cycle. Another variation is the moving roller. Instead of moving the part under the roller, the part is held stationary, and the roller carriage moves across the product surface. The effects are generally the same; however, the part can be moved away from the roller carriage to change it while the roller is reciprocating to the start position. With this type of machine, the foil is held in a stationary position across the product surface during the marking cycle. This type of machine provides utilization of a preprinted transfer, and the foil is advanced and positioned over the product before the roller moves.

Another variation of roll-on marking combines the requirements of the basic concept with the peripheral-type machine for banding larger items, such as powder boxes (see Fig. 9-3). The
Peripheral hot stamping. Peripheral hot-stamping machinery applies hot-stamping foils or transfers around the circumference of cylindrical or conical shapes. Where the vertical press is limited to approximately 90° of the periphery using a concave die, the peripheral machine is used to apply greater coverage. Typical applications include dials, odometer wheels, lipstick tubes, and similar items. In products requiring registered marking, such as dials, the peripheral machine uses a flat hot-stamping die, with the part supported on a mandrel that is interconnected to the die head. Depending on the machine design, the head or the mandrel moves, with the part rotated by a rack and gear or other similar system. The foil also travels at the same rate as the head, passing across the surface of the rotating dial. An alternate method places the foil and head in a stationary position, and the mandrel and its supporting block traverse under the die on a moving carriage.

Peripheral marking is also performed on round containers that have a strong wall to support the marking without internal support. An example is a mascara tube, which can be hot stamped on the previously described machine with the head in a stationary position and a series of moving rollers interconnected to a chain drive assembly. The parts are placed on the rollers and pulled under the stationary heated head of the press, transferring the hot-stamped image.

DECORATION

Many plastic products are decorated after molding by printing, silk screening, or other methods. This requires additional handling, and in some cases the surfaces are specially prepared so the inks adhere to the plastic. Such decoration is often satisfactory; however, a better finish is desirable in some cases. If a better finish is desired, inserts are preprinted on a moldable material that is compatible with the base material of the finished product.

The technology originated with the thermoset compression molding of quality dinnerware that was made primarily of urea-formaldehyde. In this process, blanks are preprinted by a high-quality multicolor printing process (halftone lithography). The mold (in a vertical machine) is loaded with the plastic and closed, and curing is started. When the part is nearly cured, the mold is opened, the printed blank is inserted, and the mold is reclosed to finish the curing cycle. During this time, the plastic blank melts onto the base plastic, but the inks remain on the product surface. The finished products then display a decoration that is superior in appearance to conventional printing, and the surface is highly wear resistant.

In compression molding, the normal molding cycle of a dinner plate is about one minute, and the insertion time is only a few seconds; this does not substantially add to the product cost. The operator may have time to serve two or more machines. Similar methods are used in injection molding, but the cost factor makes this process prohibitive.

With injection molding, the process is somewhat different. The blank is inserted prior to closing the clamp and injection. This dictates the mold and machine complications previously mentioned. In many methods, the insertion adds to the molding process, where a paper insert is prepositioned during the molding cycle above the cavity. As the mold opens and the molded product pulls out with the core prior to ejection, the new inserts slide into position in front of the cavity, ready for movement into it by the core as the mold recloses. This is done without loss of cycle time.

Figure 9-4 shows another method of insert molding that does not slow the molding cycle. The mold consists of a core, cavity, and punch. A printed strip is introduced (from the left in this figure) and pulled through the mold when opened, and the punch is withdrawn. As the mold closes, the core enters the cavity normally, and then the punch advances, thereby blanking out the decoration shape. The blanked-out portion of the strip sticks to the punch as the mold is now fully closed, and injection can begin. The blank is forced by the plastic against the punch and molds a decoration that is as good as the printing process used to produce the strip. As the mold opens, the punch is first withdrawn to permit its advance to the next decoration, and the product is ejected from the core.

While this method produces attractive tops, it cannot be used for product sides. Also, the strip is fairly expensive, and few applications for this system are economically viable.
COATINGS

CHAPTER 9

METAL DEPOSITION

PLATING PLASTICS

Plating is successfully performed on many plastics, including ABS, polypropylene, polysulfone, modified polyphenylene oxide, polycarbonate, polyester, and nylon, to provide a decorative finish or a hard surface for wear and corrosion resistance. Plating can improve physical properties of the plastic part, such as tensile and flexural strength and the heat deflection temperature. Because of their light weight and ease of design, plastics are used in many applications to replace zinc die castings, brass, and steel. The total cost to plate plastics is competitive with that of metals.

Product design of plated parts is particularly critical in determining the success of the plating operation. Basic plastic design practices are followed to achieve good molding in the unplated product, and it is advisable to have the design reviewed by the plater. Because the proper choice of resin for plated products is important, the resin supplier is consulted while the product is in the design stage.

The mechanism by which the electroplated metal adheres to the plastics substrate is a widely debated subject. One group proposes that the adhesion is mainly mechanical. Anchoring points for the metallic coating result from undercuts or shallow pits from preplate etching procedures. Another group proposes that a chemical bond occurs as a result of the conditioning treatment.

Various specifications and tests are standardized by the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO). These standards facilitate world trade, improve productivity, make mass production techniques possible, and lead to consumer satisfaction. Table 9-3 lists the standards published by the ASTM for electroplated plastics.

Preplate Cycle

Since plastics are nonconductive, they are first processed through a preplate cycle, during which a metallic coating is deposited by an electroless plating process to make the plastic part conductive. The preplate cycle consists of etching, neutralizing, catalyzing, accelerating, and electroless plating. A typical cycle for plating ABS plastics is shown in Fig. 9-5. The actual cycle is dependent on the type of plastics processed and the end application.

Depending on their condition, parts may require alkaline cleaning and/or conditioning before etching. If these two preliminary steps are performed, multiple rinses are recommended between steps.

Etching. The etch bath consists of a highly concentrated acid solution of equal concentrations of chromic acid and sulfuric acid. This solution chemically oxidizes selective areas on the plastic part. The holes produced by the oxidizing action are absorbing sites holding small metallic particles that serve as activators for electroless plating. The hole size influences adhesion and other

<table>
<thead>
<tr>
<th>ASTM Standard</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 532</td>
<td>Specification for the Appearance of Electroplated Plastics Surfaces</td>
</tr>
<tr>
<td>B 533</td>
<td>Test Method for Peel Strength of Metal Electroplated Plastics</td>
</tr>
<tr>
<td>B 553</td>
<td>Test Method for Thermal Cycling of Electroplated Plastics</td>
</tr>
<tr>
<td>B 554</td>
<td>Measurement of Thickness of Metallic Coatings on Nonmetallic Surfaces</td>
</tr>
<tr>
<td>B 604</td>
<td>Specification for Decorative Electroplated Coatings of Copper/Nickel/Chromium on Plastics</td>
</tr>
<tr>
<td>B 727</td>
<td>Preparation of Plastics Materials for Electroplating</td>
</tr>
</tbody>
</table>

* American Society for Testing and Materials
physical properties. The type of etchant used is determined by the type of plastic that is etched. After etching is completed, the part is thoroughly rinsed.

To obtain the best etching, the temperature, time, and water levels of the bath are carefully monitored. In general, the etch bath is maintained at a temperature of 145–155°F (63–68°C), the parts should remain in the bath for 5–8 minutes (depending on the part geometry), and the water level is consistently maintained.

Neutralizing (sensitizing). The neutralizing bath, containing mild acids or alkaline solutions along with complexing or reducing agents, chemically neutralizes the acid used in the etching bath. A common solution for ABS plastic parts contains a mixture of an acid and a reducing agent, such as sodium bisulfite. The bath is usually maintained at 100°F (38°C), and the parts are immersed for 1–2 minutes.

Catalyzing (activating). In the catalyzing step, a catalytic film is deposited on the oxidized part surface to prepare it for subsequent electroless metal deposition. Palladium is generally used as the catalytic film and may be deposited in either a one- or two-step procedure; the one-step procedure is more popular.

One-step. In the one-step catalyzing procedure, the plastic parts are immersed in a solution of colloidal stannous chloride and palladium chloride containing excess hydrochloric acid. The solution is maintained at a temperature of 68–85°F (20–29°C), and the parts are immersed for 1–3 minutes. Rinsing in water leads to the surface formation of metallic palladium nuclei surrounded by stannic hydroxide, which is removed by accelerating.

Two-step. In the two-step catalyzing procedure, the parts are initially immersed in a solution of stannous chloride at a temperature of 68–77°F (20–29°C) for 1–3 minutes. After a second thorough rinsing, the parts are immersed in a solution containing palladium chloride. The palladium ions react with the stannous ions to form palladium metal and stannic chloride. After a thorough rinsing, the parts can be coated with nickel or copper by autocatalytic deposition.

Accelerating. The accelerator bath removes the stannic or stannous hydroxide, or excess stannous chloride that remains on the part surface after the one-step catalyzing procedure. It also chemically accelerates the catalytic film to ensure rapid and complete coverage with electroless deposits. Generally, the bath contains hydrochloric acid or a solution of an acid salt.

The accelerator bath is maintained at a temperature of 100–120°F (38–49°C). The optimum time for processing is one minute because “skip plating,” due to a loss of absorbed palladium, could result from leaving the part in the bath too long.

Electroless plating. The electroless plating bath is the final step in the preplate cycle. A thin metallic film, 0.0001–0.0002 in. (0.0025–0.005 mm) thick, is deposited on the plastics parts. The deposit can be nickel or copper, depending on the intended application. Electroless-plated copper may improve the performance of electroplated plastics in a wet corrosive environment.

The electroless nickel bath is usually maintained at 68–122°F (20–50°C). The parts are left in the bath for 5–10 minutes, depending on the desired quality and thickness of the coating. Thicker coatings may be applied by low-current-density electroplating from nickel or copper strike baths.

Plating Cycle

After the plastic parts are electroless plated in the preplate cycle, they are then electroplated. A typical electroplating cycle consists of a strike bath, acid copper bath, semibright nickel bath, bright nickel bath, and a chromium plating bath.

Strike bath. The copper or nickel strike bath is used to electroplate a more conductive coating over electroless copper or nickel. In this bath, the plastic parts are given a negative charge, and the anode baskets filled with copper or nickel receive a positive charge. Copper strike baths are generally of the copper sulfate or pyrophosphate type, and nickel strike baths are generally of the Watts or sulfamate type.

The strike bath is operated over a wide range of temperatures. The time that the parts are immersed in the bath is dependent on the thickness requirements. Plating time is generally 5–10 minutes.

Acid copper bath. In this bath, the plastic part gets its first layer of decorative metallic film. The copper plated on the part is generally bright and has a high luster. The brightness achieved in this bath determines the overall appearance of the plated part. This copper layer acts as a cushion between the nickel and chromium layers and absorbs the stress that occurs when the plastic expands under those layers.

The electrolyte used is copper sulfate, with sulfuric acid added to improve electrical properties. Organic brighteners are added on a regular basis. The acid copper bath is usually kept at 70°F (21°C). Plating time is normally 25–30 minutes.

Semibright nickel bath. The semibright nickel bath is similar to a nickel strike bath in operation and is generally required in automotive applications. Coating parts with a semibright plating followed by bright nickel plating is referred to as double-layer (duplex) nickel plating. The double-layer nickel coating is usually
The plating bath is regularly analyzed for its constituents. Variables such as pH, temperature, or brightener level fluctuate and may require more careful manual control or, in some instances, automatic controllers. The Hull cell is a useful piece of test equipment. It is used to evaluate the plating bath performance over the range of current density used in production. This device indicates current density range, the general appearance of the deposit, the presence of impurities (if such are detrimental), and the effect of additions to the bath. Possible corrective measures can be evaluated in the Hull cell and then incorporated in the bath. Additions to plating baths are small and frequent as opposed to large and infrequent. Permanent records of all additions are maintained. Hull cell tests are run on a daily basis, and samples of the plating solution are sent to the brightener supplier periodically to verify analytical results. Most major metal finishing suppliers offer this service free of charge.

Troubleshooting electroplating processes requires common sense and use of the process of elimination. It is important to start with the basic aspects of the process and then proceed to the more complex aspects. The basic aspects of plating that are checked include temperature, voltage, amperage, polarity, process cycle time, and pH and chemistry of the solution. The next step is to determine if all the parts display the problem or only a select few are affected. If all the parts are not affected, current density is checked, and substrate preparation procedures are monitored. If cleaning problems are evident, an additional cleaning step can be manually performed before placing the parts in the plating solution. Metal finishing suppliers can also give assistance as they maintain a staff of trained service engineers to provide troubleshooting service to customers. Table 9-4 lists the common problems of various plating processes, along with the possible causes and suggested solutions.3

**TABLE 9-4**

Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor adhesion</td>
<td>Inadequate cleaning.</td>
<td>Check age, concentration, and temperature of cleaner. Use standards or established methods of precleaning specific plastics.</td>
</tr>
<tr>
<td>Parts not acidified before entering nickel bath.</td>
<td>Pass parts through clean, diluted solution of hydrochloric or sulfuric acid salts.</td>
<td></td>
</tr>
<tr>
<td>pH out of range (too high or too low).</td>
<td>Check and adjust pH of nickel bath.</td>
<td></td>
</tr>
<tr>
<td>Nickel too stressed (may be due to metallic contamination or excess brightener).</td>
<td>Check for metallic contamination. Use high-pH treatment followed by low current density dummying to remove metallic impurities. Check for organic contamination. Add activated carbon to bath before high-pH treatment. Adjust brightener level as required.</td>
<td></td>
</tr>
<tr>
<td>Chromium contamination.</td>
<td>Reduce hexavalent chromium with careful addition of sodium bisulfate and low current density dummying.</td>
<td></td>
</tr>
<tr>
<td>Nitrate contamination.</td>
<td>Use high current density dummying to destroy nitrates.</td>
<td></td>
</tr>
</tbody>
</table>

(continued)
### TABLE 9-4—(continued)

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor adhesion or laminated deposit</td>
<td>Current interrupted.</td>
<td>Test rectifier meters for output reliability. Check busbars for cleanliness and tight connections. Use established method for plating nickel on nickel when current is interrupted.</td>
</tr>
<tr>
<td>Poor adhesion involving peeling from copper</td>
<td>Nickel over nickel without proper activation.</td>
<td>Check nickel activation.</td>
</tr>
<tr>
<td>Poor adhesion involving peeling from copper</td>
<td>Replating without complete stripping of chromium.</td>
<td>Check chromium stripping procedure and check for complete stripping before plating.</td>
</tr>
<tr>
<td>Poor adhesion involving peeling from copper</td>
<td>Deposit highly stressed.</td>
<td>Make stress determinations on the nickel deposit. May require purification of the bath to remove inorganic and organic impurities.</td>
</tr>
<tr>
<td>Poor adhesion involving peeling from copper</td>
<td>Excess iron in solution.</td>
<td>Use high-pH treatment followed by low current density dummying.</td>
</tr>
<tr>
<td>Deposit too highly stressed</td>
<td>Failure to remove brightener film from copper plate.</td>
<td>Cathodically clean alkaline copper deposit and rinse carefully. Treat in 2–5% sulfuric acid before nickel plating.</td>
</tr>
<tr>
<td>Deposit too highly stressed</td>
<td>Copper tarnished in rinsing process.</td>
<td>Use room temperature rinse water before nickel plate. Shorten rinse time after copper deposit.</td>
</tr>
<tr>
<td>Deposit too highly stressed</td>
<td>Contamination with zinc, lead, or cadmium.</td>
<td>Use high-pH treatment followed by low current density dummying.</td>
</tr>
<tr>
<td>Deposit too highly stressed</td>
<td>Iron content too high.</td>
<td>Use high-pH treatment followed by low current density dummying.</td>
</tr>
<tr>
<td>Deposit too highly stressed</td>
<td>Brighteners out of balance or too concentrated.</td>
<td>Perform Hull cell test to check brightener levels or send to brightener supplier. To reduce brightener level, add activated carbon to bath and perform high-pH treatment. Adjust brightener level as required.</td>
</tr>
<tr>
<td>Deposit too highly stressed</td>
<td>pH out of range.</td>
<td>Check pH and adjust accordingly.</td>
</tr>
<tr>
<td>Deposit too highly stressed</td>
<td>Chloride content too high.</td>
<td>Check for chloride content. Remove required amount of solution and replace with water.</td>
</tr>
<tr>
<td>Pitting of deposit</td>
<td>Solution contaminated with grease or oil.</td>
<td>Perform carbon and/or high-pH treatments followed by dummying. Adjust brightener level as required.</td>
</tr>
<tr>
<td>Pitting of deposit</td>
<td>Solid particles in solution.</td>
<td>Check anode bags. Filter bath through carbon bags.</td>
</tr>
<tr>
<td>Pitting of deposit</td>
<td>pH too low.</td>
<td>Check and adjust pH to proper value.</td>
</tr>
<tr>
<td>Pitting of deposit</td>
<td>Metal too low.</td>
<td>Analyze for metal content and adjust accordingly.</td>
</tr>
</tbody>
</table>

(continued)
## TABLE 9-4—(continued)  
Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitting of deposit</td>
<td>Inadequate agitation.</td>
<td>Increase agitation.</td>
</tr>
<tr>
<td></td>
<td>Temperature too low.</td>
<td>Check temperature and adjust.</td>
</tr>
<tr>
<td></td>
<td>Boric acid low.</td>
<td>Analyze for boric acid and adjust concentration.</td>
</tr>
<tr>
<td>Deposit dark</td>
<td>Metallic contamination, especially copper. (Zinc and cadmium first produce a bright, stressed deposit, then, at higher levels, black streaky deposits.)</td>
<td>Analyze bath for contaminant metals. Use low current density electrolysis to reduce metallic impurities.</td>
</tr>
<tr>
<td>Deposit streaky</td>
<td>See &quot;deposit dark.&quot;</td>
<td>Reduce chromium with careful addition of sodium bisulfate and low current density dummying.</td>
</tr>
<tr>
<td></td>
<td>Chromium contamination.</td>
<td>Use high current density dummying to destroy nitrate.</td>
</tr>
<tr>
<td></td>
<td>Nitrate contamination.</td>
<td>Perform Hull test to determine brightener level. Add activated carbon to bath and perform high-pH treatment to reduce brightener level.</td>
</tr>
<tr>
<td></td>
<td>Brightener imbalance.</td>
<td>Perform Hull test to determine brightener level. Add activated carbon to bath and perform high-pH treatment to reduce brightener level.</td>
</tr>
<tr>
<td></td>
<td>pH out of range.</td>
<td>Check and adjust pH to proper value.</td>
</tr>
<tr>
<td></td>
<td>Inadequate agitation.</td>
<td>Increase agitation.</td>
</tr>
<tr>
<td></td>
<td>Low wetting agent concentration.</td>
<td>Determine surface tension and adjust wetting agent as required.</td>
</tr>
<tr>
<td></td>
<td>Wrong wetting agent. (Wetting agents for mechanical agitation are usually different than those for air agitation.)</td>
<td>Analyze bath for proper wetting agent. Obtain recommendations from supplier.</td>
</tr>
<tr>
<td>Deposit rough</td>
<td>Solid material in solution.</td>
<td>Examine anode bags carefully and correct. Increase filtration rate.</td>
</tr>
<tr>
<td></td>
<td>Smut not removed in cleaning.</td>
<td>Wipe workpieces with clean tissue to check for smut before plating. Use proper procedures for smut removal.</td>
</tr>
<tr>
<td></td>
<td>Excessive current density.</td>
<td>Check current density and correct.</td>
</tr>
<tr>
<td></td>
<td>Boric acid content too high (usually also associated with low temperature).</td>
<td>Analyze bath for boric acid content. Check and correct bath temperature.</td>
</tr>
<tr>
<td>Deposit hazy</td>
<td>Organic contamination.</td>
<td>Check for organic contamination. Add activated carbon to bath and then perform high-pH treatment. Adjust brightener level as required.</td>
</tr>
<tr>
<td></td>
<td>Immersion deposit on substrate (usually from processing multiple alloys through the same acid dip).</td>
<td>Analyze acid dip for contaminant metals and replace if necessary. Do not use same acid dip for multiple alloys.</td>
</tr>
</tbody>
</table>
CHAPTER 9
METAL DEPOSITION

TABLE 9-4—(continued)
Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit hazy</td>
<td>Iron content too high.</td>
<td>Analyze bath for iron content. Use high-pH treatment followed by low current density dummying.</td>
</tr>
<tr>
<td></td>
<td>pH out of range.</td>
<td>Check and adjust pH to proper level.</td>
</tr>
<tr>
<td></td>
<td>Inadequate cleaning.</td>
<td>Check precleaning procedures. Correct and improve where necessary.</td>
</tr>
<tr>
<td>Failure to plate</td>
<td>Faulty electrical system.</td>
<td>Check rectifier output meters and current delivery to anode/cathode bars. Clean corrosion from anode/cathode bars.</td>
</tr>
<tr>
<td></td>
<td>Contamination with chromium or nitric acid.</td>
<td>Analyze bath for chromium or nitric acid contamination. Refer to suggestions under &quot;poor adhesion.&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bright Acid Copper Plating*</td>
</tr>
<tr>
<td>Burning at high current density</td>
<td>Low-copper content. Low chloride levels.</td>
<td>Analyze bath for copper and chloride content. Correct as required.</td>
</tr>
<tr>
<td>Dullness in low current area</td>
<td>Excess chloride.</td>
<td>Analyze bath for chloride content. If chloride content is too high, precipitate excess chloride with silver sulfate and then filter.</td>
</tr>
<tr>
<td></td>
<td>Brightener imbalance.</td>
<td>Carbon treat to remove brighteners, then add proper brightener balance.</td>
</tr>
<tr>
<td>Loss of brightness</td>
<td>Lack of brightener.</td>
<td>Perform Hull cell test to determine brightener level. Correct brightener level in Hull cell and then correct entire bath proportionately.</td>
</tr>
<tr>
<td></td>
<td>Organic contamination.</td>
<td>Carbon treat to remove contaminants and then correct brightener level.</td>
</tr>
<tr>
<td>Ridging or gas streaking</td>
<td>Brightener imbalance.</td>
<td>Carbon treat to remove brighteners and then adjust brighteners to proper level.</td>
</tr>
<tr>
<td></td>
<td>Insufficient agitation.</td>
<td>Increase solution agitation.</td>
</tr>
<tr>
<td>Brown deposits at low current</td>
<td>Excess brightener.</td>
<td>Carbon treat to remove excess brighteners and adjust brighteners to proper level.</td>
</tr>
<tr>
<td>Rough deposit</td>
<td>Suspended matter in solution.</td>
<td>Inspect anode bags and replace if necessary. Increase filtration rate or decrease filter pore size.</td>
</tr>
<tr>
<td>Coarse, granular deposit</td>
<td>Low-acid content.</td>
<td>Analyze bath for acid content. Add sulfuric acid as required.</td>
</tr>
<tr>
<td></td>
<td>Temperature too low.</td>
<td>Check bath temperature and adjust as required.</td>
</tr>
<tr>
<td></td>
<td>Current density too high.</td>
<td>Check current density.</td>
</tr>
<tr>
<td>Deposit soft</td>
<td>Low-acid content.</td>
<td>Analyze bath for acid content. Add sulfuric acid as required.</td>
</tr>
</tbody>
</table>

(continued)
### TABLE 9-4 (continued)
Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposit soft</td>
<td>Bath too warm.</td>
<td>Check bath temperature and adjust.</td>
</tr>
<tr>
<td></td>
<td>Current density too low.</td>
<td>Check current density and adjust to recommended level.</td>
</tr>
<tr>
<td>Deposit hard and/or brittle</td>
<td>Too much free acid.</td>
<td>Analyze bath for free-acid concentration.</td>
</tr>
<tr>
<td></td>
<td>Solution too cold.</td>
<td>Check bath temperature and adjust accordingly.</td>
</tr>
<tr>
<td></td>
<td>Organic contamination. Excess brightener.</td>
<td>Treat solution with activated carbon and then filter. Adjust brightener level.</td>
</tr>
<tr>
<td></td>
<td>High-iron contamination.</td>
<td>Analyze bath for iron content. Raise pH and then blow clean air through solution to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>precipitate iron. Filter bath.</td>
</tr>
<tr>
<td>Poor throwing power</td>
<td>Low acid.</td>
<td>Analyze bath for acid content. Add sulfuric acid to increase content.</td>
</tr>
<tr>
<td>Low conductivity</td>
<td>Temperature too low.</td>
<td>Check bath temperature and adjust as required.</td>
</tr>
<tr>
<td></td>
<td>Low acid.</td>
<td>See &quot;poor throwing power.&quot;</td>
</tr>
<tr>
<td></td>
<td>Low copper.</td>
<td>Analyze bath for copper content and increase as required.</td>
</tr>
<tr>
<td>Anodes bright and crystalline</td>
<td>Free acid too high.</td>
<td>Analyze bath for free-acid content. Add copper carbonate as required.</td>
</tr>
<tr>
<td>Anodes polarized</td>
<td>Low acid content.</td>
<td>Analyze bath for acid content. Add sulfuric acid to increase content.</td>
</tr>
<tr>
<td></td>
<td>Insufficient anode area.</td>
<td>Compare actual anode area versus recommended area and correct.</td>
</tr>
<tr>
<td>Anodes polarized with green deposit</td>
<td>High chloride contamination. (Note: plate will also be seriously affected.)</td>
<td>Analyze bath for chloride content. Add silver sulfate to reduce chloride content as recommended and then filter solution to remove silver chloride.</td>
</tr>
<tr>
<td>Poor chromium coverage</td>
<td>Rectifier failure.</td>
<td>Check rectifier meters for stable operation. AC ripple should not exceed 5%. Rectifier should operate at 75% rated amperage.</td>
</tr>
<tr>
<td></td>
<td>Poor electrical connections.</td>
<td>Check electrical connections for tightness and contact.</td>
</tr>
<tr>
<td></td>
<td>Inactive anodes.</td>
<td>Check coating on anodes. A yellowish lead chromate coating indicates that the anode is inactive; a black-brown lead peroxide coating is on active anodes. Make sure proper current is used. When plating inside diameters, use largest anode possible.</td>
</tr>
</tbody>
</table>
TABLE 9-4—(continued)
Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor chromium coverage</td>
<td>Incorrect bath temperature.</td>
<td>Check bath temperature. Check bath agitation.</td>
</tr>
<tr>
<td></td>
<td>Incorrect bath concentration.</td>
<td>Mix bath thoroughly and take bath sample. Analyze chromium and sulfate content. Adjust accordingly.</td>
</tr>
<tr>
<td></td>
<td>Improper racking.</td>
<td>Check rack-to-fixture connections. Incorporate shields or robbers in racking to direct current to specific areas.</td>
</tr>
<tr>
<td></td>
<td>Poor cleaning or rinsing.</td>
<td>Check temperature of rinsing water and maintain between 70 and 75° F (21 and 24° C).</td>
</tr>
<tr>
<td>Copper or nickel roughness.</td>
<td></td>
<td>Check copper or nickel plate for roughness.</td>
</tr>
<tr>
<td>Passive nickel.</td>
<td>Dip nickel-plated part in 50% by volume solution of hydrochloric acid. If part brightness increases, correct nickel plating bath.</td>
<td></td>
</tr>
<tr>
<td>Chloride contamination.</td>
<td>Dummy with high anode current density and agitation or treat with silver oxide.</td>
<td>Dummy with high anode current density and agitation or treat with silver oxide.</td>
</tr>
<tr>
<td>Improper current density.</td>
<td>Adjust current density to solution temperature and concentration.</td>
<td>Adjust current density to solution temperature and concentration.</td>
</tr>
<tr>
<td>Incorrect chromic acid to sulfate catalyst ratio.</td>
<td>Add sulfuric acid to lower ratio and barium carbonate to increase ratio.</td>
<td>Add sulfuric acid to lower ratio and barium carbonate to increase ratio.</td>
</tr>
<tr>
<td>Impurities.</td>
<td>Limit metallic impurities to less than 0.5 oz/gal (3.75 g/L). Increase chromic acid concentration.</td>
<td>Limit metallic impurities to less than 0.5 oz/gal (3.75 g/L). Increase chromic acid concentration.</td>
</tr>
<tr>
<td></td>
<td>Incorrect bath temperature.</td>
<td>Correct bath temperature.</td>
</tr>
<tr>
<td></td>
<td>Improper bath concentration.</td>
<td>Analyze chromium and sulfate content. Correct if necessary.</td>
</tr>
<tr>
<td></td>
<td>Inactive anodes.</td>
<td>Check anode color. Inactive anodes are coated with a yellowish lead chromate.</td>
</tr>
<tr>
<td></td>
<td>Incorrect anode length.</td>
<td>Anode should be 2–4 in. (51–102 mm) shorter than cathode. Mask anodes that are too long with suitable insulator or cut to proper length.</td>
</tr>
<tr>
<td></td>
<td>Current interruption.</td>
<td>Check racking of parts and electrical contacts.</td>
</tr>
<tr>
<td></td>
<td>Improper racking.</td>
<td>Check rack to fixture connections. Incorporate shields or robbers in racking to direct current to specific areas.</td>
</tr>
<tr>
<td></td>
<td>Improper solution level.</td>
<td>Place work 3 in. (76 mm) below surface of plating solution.</td>
</tr>
</tbody>
</table>
### Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burned chromium deposits</td>
<td>High current density.</td>
<td>Adjust current density to solution temperature and concentration.</td>
</tr>
<tr>
<td></td>
<td>Sulfate concentration or other catalyst too high.</td>
<td>Add barium carbonate to bath to lower sulfate concentration. Ratio should be 2:1.</td>
</tr>
<tr>
<td></td>
<td>High or low concentration ratio.</td>
<td>Check ratio and adjust accordingly.</td>
</tr>
<tr>
<td>Dull chromium deposits</td>
<td>Dull or passive nickel.</td>
<td>Correct nickel brightener concentration. Increase current density in nickel bath.</td>
</tr>
<tr>
<td></td>
<td>Excessive ripple in current.</td>
<td>Check rectifier operation. Ripple should not exceed 5%.</td>
</tr>
<tr>
<td></td>
<td>Current interruption.</td>
<td>Check racking of parts and electrical contacts.</td>
</tr>
<tr>
<td></td>
<td>Incorrect bath temperature.</td>
<td>Correct bath temperature.</td>
</tr>
<tr>
<td></td>
<td>Improper bath concentration.</td>
<td>Take Baume reading of bath and correct.</td>
</tr>
<tr>
<td></td>
<td>Low current density.</td>
<td>Adjust current density to bath temperature and concentration. Check rinsing procedures.</td>
</tr>
<tr>
<td></td>
<td>Impurities.</td>
<td>Limit metallic impurities to less than 0.5 oz/ gal (3.75 g/L). Increase chromic acid concentration.</td>
</tr>
<tr>
<td></td>
<td>Excess fluoride catalyst or fluoride contamination.</td>
<td>Add boric acid to reduce catalyst or use high anode current density dummy.</td>
</tr>
<tr>
<td></td>
<td>High or low concentration ratio.</td>
<td>Check ratio and adjust accordingly.</td>
</tr>
<tr>
<td>White blotching</td>
<td>Film of immersion nickel on workpiece.</td>
<td>Rinse workpiece thoroughly.</td>
</tr>
<tr>
<td></td>
<td>Passive nickel.</td>
<td>Check nickel plating bath for proper concentration.</td>
</tr>
<tr>
<td></td>
<td>Excessive ripple in current.</td>
<td>Check rectifier operation. Ripple should not exceed 5%.</td>
</tr>
<tr>
<td></td>
<td>Bipolarity caused by rapid work movement in automatic machines.</td>
<td>Reduce speed of work movement through machine.</td>
</tr>
<tr>
<td></td>
<td>Bipolarity caused by dead entry into chromium.</td>
<td>Use live lead at reduced current.</td>
</tr>
<tr>
<td></td>
<td>Bipolarity caused by dead exit from nickel tanks.</td>
<td>Use live exit-lead from nickel.</td>
</tr>
<tr>
<td></td>
<td>Impurities, especially chloride.</td>
<td>Check rinsing procedures.</td>
</tr>
<tr>
<td>Deposit roughness</td>
<td>Poor basis metal finish.</td>
<td>Reject parts with rough finish.</td>
</tr>
<tr>
<td></td>
<td>Copper or nickel roughness.</td>
<td>Check copper or nickel plating for roughness.</td>
</tr>
<tr>
<td>Poor chromium adhesion</td>
<td>Poor nickel adhesion.</td>
<td>Refer to solutions for bipolarity conditions under &quot;white blotching.&quot;</td>
</tr>
</tbody>
</table>

(continued)
### Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>No chromium plate</td>
<td>Rectifier failure.</td>
<td>Check operation of rectifier. Rectifier should operate at no less than 75% rated amperage.</td>
</tr>
<tr>
<td>Poor electrical connections.</td>
<td>Missing anodes.</td>
<td>Check for replacement of anodes after they have been removed.</td>
</tr>
<tr>
<td>Missing anodes.</td>
<td>Check nickel bath.</td>
<td>Adjust current density to bath temperature and concentration.</td>
</tr>
<tr>
<td>Low current density.</td>
<td>Incorrect catalyst concentration.</td>
<td>Adjust current density to bath temperature and concentration.</td>
</tr>
<tr>
<td>Incorrect catalyst concentration.</td>
<td></td>
<td>Analyze chromium plating solution and adjust accordingly.</td>
</tr>
<tr>
<td>Hard Chromium</td>
<td>Poor substrate finish.</td>
<td>Adjust current density to bath temperature and concentration.</td>
</tr>
<tr>
<td>Poor chromium brightness</td>
<td>Excessive reverse etching.</td>
<td>Check ratio and adjust accordingly.</td>
</tr>
<tr>
<td>Excessive reverse etching.</td>
<td>Correct bath temperature. Check bath agitation.</td>
<td></td>
</tr>
<tr>
<td>Improper bath temperature.</td>
<td>Take Baume reading of bath and correct.</td>
<td></td>
</tr>
<tr>
<td>Improper bath concentration.</td>
<td>Adjust current density to bath temperature and concentration.</td>
<td></td>
</tr>
<tr>
<td>High concentration ratio.</td>
<td>High trivalent chromium.</td>
<td>Check color of chromium solution; a black color indicates trivalent chromium contamination. Electrolyze chromium plating solution.</td>
</tr>
<tr>
<td>Magnetic particles.</td>
<td>Attach a magnet to a piece of wood and then drag through solution to remove particles.</td>
<td></td>
</tr>
<tr>
<td>Excessive reverse etching.</td>
<td>Adjust current density to bath temperature and concentration.</td>
<td></td>
</tr>
<tr>
<td>High current density.</td>
<td>Improper concentration ratio.</td>
<td>Check ratio and adjust accordingly.</td>
</tr>
<tr>
<td>Improper concentration ratio.</td>
<td>Correct bath temperature.</td>
<td></td>
</tr>
<tr>
<td>Uneven chromium deposit</td>
<td>Improper bath temperature.</td>
<td>Correct bath temperature. Check bath agitation.</td>
</tr>
<tr>
<td>Poor fixturing.</td>
<td>Check rack design and contacts. Use shields to direct current to specific areas.</td>
<td></td>
</tr>
<tr>
<td>Incorrect anode length.</td>
<td>Anode should be shorter than cathode. Mask anodes that are too long with suitable insulator.</td>
<td></td>
</tr>
<tr>
<td>Improper anode-cathode relation.</td>
<td></td>
<td>For outside-diameter plating, anode-cathode distance should be approximately 4 in. (100 mm). For inside-diameter plating, the distance should be from 0.5–1 in. (13–25 mm).</td>
</tr>
</tbody>
</table>
TABLE 9-4—(continued)  
Troubleshooting Guide for Electroplating

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Suggested Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor chromium adhesion</td>
<td>Improper cleaning or rinsing.</td>
<td>Follow recommended cleaning procedures.</td>
</tr>
<tr>
<td></td>
<td>Improper reverse etching.</td>
<td>Do not reverse etch in plating bath.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Current used in reverse etching should be proportionate to work area. Work should be at bath temperature before applying current.</td>
</tr>
<tr>
<td></td>
<td>Current interruption.</td>
<td>Check racking of parts and electrical contacts.</td>
</tr>
<tr>
<td>Burned chromium deposits</td>
<td>Etching in alkaline cleaner.</td>
<td>Check cleaner concentration.</td>
</tr>
<tr>
<td></td>
<td>Improper fixturing.</td>
<td>Rack should be made from copper for best results. Check rack design and content.</td>
</tr>
<tr>
<td></td>
<td>Improper anode-cathode relationship.</td>
<td>See &quot;uneven chromium deposit.&quot;</td>
</tr>
<tr>
<td></td>
<td>Improper solution level.</td>
<td>Work should be 3 in. (76 mm) below surface of plating solution.</td>
</tr>
<tr>
<td></td>
<td>Improper anode length.</td>
<td>Anode should be shorter than cathode.</td>
</tr>
<tr>
<td></td>
<td>Inadequate stop off anodes.</td>
<td>Correct bath temperature.</td>
</tr>
<tr>
<td></td>
<td>Improper bath temperature.</td>
<td>Mix bath thoroughly and take sample to obtain Baume reading. Adjust accordingly.</td>
</tr>
<tr>
<td></td>
<td>Low-bath concentration.</td>
<td>Mix bath thoroughly and take sample to obtain Baume reading. Adjust accordingly.</td>
</tr>
<tr>
<td></td>
<td>High-current density.</td>
<td>Adjust current density to bath temperature and concentration.</td>
</tr>
<tr>
<td></td>
<td>Impurities.</td>
<td>Adjust sulfate and/or fluoride ratio to proper level.</td>
</tr>
<tr>
<td></td>
<td>Excess catalyst or chloride contamination.</td>
<td>Adjust sulfate and/or fluoride ratio to proper level.</td>
</tr>
<tr>
<td>Lack of chromium hardness</td>
<td>Incorrect bath temperature.</td>
<td>Check bath temperature and agitation.</td>
</tr>
<tr>
<td></td>
<td>Improper bath concentration.</td>
<td>Take Baume reading of bath and correct.</td>
</tr>
<tr>
<td></td>
<td>High ratio.</td>
<td>Check ratio and adjust.</td>
</tr>
<tr>
<td></td>
<td>Insufficient deposit thickness.</td>
<td>Check deposit thickness.</td>
</tr>
<tr>
<td>Pitting</td>
<td>Poor basis metal and rework.</td>
<td>Check metal prior to plating.</td>
</tr>
<tr>
<td></td>
<td>Improper cleaning.</td>
<td>Check cleaning procedures.</td>
</tr>
<tr>
<td></td>
<td>Incorrect catalyst concentration.</td>
<td>Analyze chromium plating solution and adjust accordingly.</td>
</tr>
<tr>
<td></td>
<td>Incorrect fume suppressant.</td>
<td>Eliminate use of fume suppressant that lowers surface tension.</td>
</tr>
<tr>
<td>No chromium plate</td>
<td>Rectifier failure.</td>
<td>Check operation of rectifier.</td>
</tr>
<tr>
<td></td>
<td>Poor electrical connection.</td>
<td>Check connections for good contact.</td>
</tr>
</tbody>
</table>

*(continued)*
**Sputtering**

Sputtering is the deposition of materials under a vacuum onto prepared substrates to produce specific films for both decorative and functional applications. Sputtering differs from vacuum metallizing (evaporation) in that the material is removed from a solid cathode or target instead of being vaporized by a heating source. Rapidly moving gas ions in the vacuum chamber strike a negatively biased target, ejecting metal atoms through a transfer of momentum (Fig. 9-6). Subsequently, the ejected target atoms strike and adhere to the substrate surface, forming a thin coating that has the same composition as the target. The process dates back to 1852, when W. R. Grove, while studying the electrical conductivity of gases, observed that metallic deposits formed on glass walls. However, it was not until 1950 that the ionization phenomenon was understood.

Because the coating material is passed into the vapor phase by a mechanical process rather than a chemical or thermal process, virtually any material is a candidate for coating. Most types of metal can be successfully sputtered, including chromium, stainless steel, titanium, aluminum, copper, brass, tungsten, molybdenum, gold, silver, and tantalum. Alloys and compounds are also sputtered without altering their original compositions. New compounds are created by sputtering with a gas background that reacts with a metal or metal alloy to form new materials such as oxides, carbides, and nitrides. Semiconducting and insulating materials are sputtered by applying a radio frequency potential to the target.

Sputtered coatings are deposited on both conductive and nonconductive substrates; some metals and nylons may require a primer or pretreatment before sputtering. Basecoats are generally applied to the substrates when a bright finish is required. Most sputtered deposits are from 0.002–0.040 in. (0.050–1 mm) thick.

### Advantages and Limitations

- **Sputtering is a nonpolluting, controllable process.**
- **A versatile tool for both decorative and functional finishing.**
- **As previously stated, a wide variety of metals and alloys are successfully deposited.**
- **The coatings adhere better than conventional vacuum metallized coatings.**
- **The primary limitation to sputtering is the slow deposition rate, but newer sputtering methods have resulted in faster rates.**

### Applications

- **Sputtered coatings are used in decorative, decorative/functional, and functional applications.**
- **In decorative applications, the coatings are primarily for aesthetic purposes.**
- **Typical parts include toys, cosmetic caps, and picture frames.**
- **In decorative/functional applications, the coatings provide aesthetic value along with resistance to corrosion and impact, reflectivity, durability, and adhesion.**
- **These coatings are often used for appliance endcaps; automotive grills, wheel covers, and hubcaps; fixtures for plumbing, marine, and electrical use; and knobs, buttons, and door hardware.**
- **Typical functional applications include electromagnetic interference shielding, semiconductor fabrication, transparent conductors, printed circuit boards, optical and magnetic storage media, electrical connections, architectural windows, solar control film, and barrier coats.**

### Sputtering Methods

- **The sputtering process is used for surface coating or etching.**
- **Some of the more common coating methods are planar diode, triode, magnetron, and ion gun sputtering.**
- **Direct current discharges are generally used for sputtering conductive substrates; a radio frequency (RF) potential is applied to the target to sputter nonconductive substrates.**
- **Reactive sputtering is performed with the addition of small, controlled quantities of a reactive gas, such as oxygen, to the argon stream.**

**Planar diode sputtering.** A planar diode is a two-component system. The sputtering target is the cathode, and the coated substrate is the anode (see Fig. 9-7). When a negative potential of several hundred to a few thousand volts is applied to the cathode, a glow discharge (plasma) ignites within the vacuum chamber after the appropriate pressure level is reached. The plasma usually consists of argon gas ions.

With this simple arrangement, deposition rates are low, and it is difficult to avoid contamination in the film. To produce results that can be duplicated, it is necessary to control residual gas pressure. Because of the low deposition rates, the base pressure required before backfilling is less than $1 \times 10^{-7}$ torr (1.3 $\times$ 10$^{-5}$ Pa). However, the low-base pressure is not practical in a production environment. The advantages of diode sputtering are as follows:

- **Refractory films can be deposited.**
- **Insulating films can be deposited.**

The limitations of diode sputtering are:

- **Good film adhesion is only possible with a few materials.**
- **Low base pressures are required.**
- **The source material must be available in sheet form.**
- **Special holders are required to maintain low substrate temperatures.**
- **Deposition rates are usually less than 4 in./min (0.1 m/min).**

**Triode sputtering.** In triode sputtering, the apparatus consists of three electrodes: an anode and target, and an additional electron
source (see Fig. 9-8). The chamber is held at the required pressure, and electrons are generated by a thermionically heated filament. The electrons are accelerated toward the anode, where they ionize a larger portion of the gas molecules. The process that takes place in the triode system is known as electron-supported discharge, because it relies on the abundance of electrons generated by the heated filament to ensure sufficient ionizing collisions. The abundance of electrons allows the plasma to operate and sputter material at pressures considerably lower than diode sputtering.

The advantages of low-pressure triode sputtering when compared to diode sputtering are:
• Higher deposition rates.
• Decreased ratio of sputtering gas molecules to sputtered atoms, which enhances film density and purity.
• More consistent straight-line deposition from target to substrate, making it possible to use masks to define film patterns.

However, use of the heated element as a source of free electrons creates the following limitations when compared with diode sputtering:

• The thermionic elements make reactive sputtering with chemically reactive gas impractical or even dangerous.
• The filament contributes to contamination and is subject to burnout.

**Magnetron sputtering.** In magnetron sputtering, a magnetic field is applied over the sputtering target to confine the high-density plasma. The argon ions in the plasma are accelerated to the target, which is negatively biased. The collision of the ions with the cathode ejects particles of the target material with mean kinetic energies of 4–6 eV. The coated substrate is positioned in front of the target, and the particles that strike the substrate condense to form an adherent coating (see Fig. 9-9). A number of target configurations are commercially available, such as the planar magnetron and cylindrical-post magnetron; planar targets are more suitable for in-line or semicontinuous process operations, and cylindrical targets are better for batch processes.

High sputtering rates and efficiencies are possible with magnetron sputtering, because a greater percentage of the current is now carried by the argon gas. Because of the higher sputtering rates, the sputtered material is made to cover larger areas. Magnetron sputtering typically takes place at pressures midway between diode and triode sputtering methods.

**Ion gun sputtering.** Ion gun sputtering is a method that extracts ions from a Kaufman source and impinges them on a target that becomes eroded; the eroded atoms are then deposited on the substrate. The Kaufman source uses a magnetically enhanced low-voltage discharge that is similar to a cold-cathode gage.

The ions are extracted through a series of screen grids and dumped into a low-gas-density chamber, where they are further accelerated at the target. Since the gas density or pressure is low, few if any collisions take place, resulting in higher-energy ions striking the target. Because the background pressure is low, less argon is included in the coating. This method is used for sputtering, etching, and ion implantation; however, it is not used for production applications.

**Process Description**

Sputtering is performed on rigid and flexible substrates. Rigid substrates are sputtered in batch or in-line multichamber equipment, whereas flexible substrates are sputtered in semicontinuous equipment.

**Batch process.** A typical sputtering cycle consists of precleaning, racking, pumping down, backfilling with argon gas, sputtering, and unloading. For plastics and some metals, an organic basecoat and topcoat may be applied as a separate operation or combined in a production cycle. The basecoat helps level the surface of the part, thereby increasing brightness and improving deposit adhesion. The basecoat also reduces the amount of outgassing that occurs under vacuum conditions. The topcoat, which is generally transparent and colorless, protects the metallic deposit from abrasion and improves corrosion resistance. The topcoat can also be tinted to provide a variety of color shades.

Cleaning. Cleaning is discussed only in general because different procedures are required for different circumstances. Some factors that influence the cleaning method used are substrate material, coating specifications, and the type of cleaning equipment that is readily available. The main purpose of cleaning is to reduce surface contamination to an acceptable level. Since all chemical solutions leave some level of contamination on the surface, sputter cleaning is performed before sputtering.

Process. After the parts are loaded onto the racks and placed into the vacuum chamber, the chamber is closed, either by lowering the vessel onto the base plate or by closing the door. The mechanical pump is then activated, and the system is pumped down to approximately 0.1 torr (13.3 Pa). At this point, the roughing pump is shut off, and the high-vacuum valve is opened to allow the high-vacuum pump to evacuate the system to less than $1 \times 10^{-4}$ torr ($1.3 \times 10^{-4}$ Pa). After the required pressure is attained, the chamber is backfilled with an inert gas that is easily ionized, such as argon, to a pressure range of $1 \times 10^{-3}$ to $2 \times 10^{-3}$ torr ($13–0.26$ Pa). Ionization occurs when a high negative voltage is applied to the target. The ionized gas molecules strike the target, causing ejection of the atoms. The ejected atoms eventually strike and adhere to the substrate surface. After the sputtering is completed, the chamber is vented to the atmosphere. The sputtering time depends on the required film thickness; typical times range from 1–20 minutes.

Equipment. The sputtering system consists of vacuum chambers and pumping systems, as well as the sputtering sources, power supplies, and a feed and control system for the sputtering gas. The vacuum chamber in the batch process can be vertically or horizontally oriented; it is approximately 47–55 in. (119–140 cm) in diameter and 59–87 in. (150–221 cm) in height or length. Parts are loaded onto racks that are rotated during sputtering to increase the uniformity of the deposited film. A mechanical pump and one or more high-vacuum pumps—such as diffusion, turbomolecular, cryogenic, or a combination of these—reduce the pressure to approximately $1 \times 10^{-6}$ torr ($1.3 \times 10^{-6}$ Pa) prior to backfilling the chamber to a pressure of approximately $2 \times 10^{-4}$ torr (0.26 Pa).

**In-line sputtering.** In-line sputtering, like roll sputtering which is discussed later, is a production-oriented process because large quantities of parts are coated in relatively short times. Architectural glass, semiconductor wafers, flat-panel displays, and automotive grills are commonly sputtered in an in-line system.
A diagram of an in-line sputtering system is shown in Fig. 9-10. In this system, the parts are placed face up on coating platens and then fed into the entrance chamber; this chamber cycles between atmospheric pressure and a vacuum environment. A transport system moves the platens from chamber to chamber. Generally, at least one conditioning chamber is required to allow outgassing of the substrates. The length of the conditioning chamber depends on the amount of outgassing required; outgassing is dependent on the type of coated material, the exposed surface area, the length of time that the material is in the chamber, and the substrate temperature. Additional chambers can be incorporated in the system to ensure that residual gases and atmospheric traces are eliminated.

Before sputtering, the parts can be heated or sputter etched. Heating is used to remove gases that were physically absorbed by the substrate surface, and sputter etching is used to remove thin oxide films or other surface contaminants. Planar magnetron sources are generally used because they have higher deposition rates than planar diode and triode sources.

The number of sputtering sources and the type of target material used vary with the individual coating process. The sputtering source can be oriented to sputter down, up, or sideways. In-line systems are designed to accommodate multiple sources, either of the same material to increase the production rate, or of different materials to deposit a multilayer coating. Following sputtering, the platens move from a vacuum environment to atmospheric pressure through a buffer-and-exit chamber. The main advantage of in-line systems is that the parts and the coating chamber are conditioned prior to sputtering. Another advantage is the ability to unload and reload a hatch of parts while sputtering another batch.

Roll sputtering, or semicontinuous sputtering, is a process used to deposit functional coatings on flexible substrates such as plastic films. The coating may be applied to either one or both sides of the substrate depending on the roll coater design. Typical applications of sputtered coatings on flexible substrates include transparent, electrically conductive films for liquid crystal displays, electroluminescent displays, touch panels, and membrane switches; electrostatic imaging film for document processors and copiers; electronic shielding; solar energy control films; and high-density magnetic recording media.

Process. In a typical roll coater, the roll of plastic film is mounted on the unwind mandrel, and then the entire roll is placed inside the vacuum chamber. The film is next threaded through idler drive and tension control rolls, passed through the sputtering regions, and attached to the rewind mandrel. The pumping system is activated, and the vacuum chamber is evacuated to a pressure of approximately $1 \times 10^{-6}$ torr ($1.3 \times 10^{-4}$ Pa). After the required pressure is attained, the chamber is backfilled with an inert gas (argon) to a pressure of approximately $2 \times 10^{-3}$ torr (0.26 Pa).

During sputtering, the flexible substrate passes through a cloud of charged particles at a specific rate. Positively charged ions in the plasma (cloud of charged particles) strike the negatively biased target, causing ejection of the metal atoms toward the substrate surface. The ejected atoms strike and adhere to the substrate surface, forming a thin coating. Electrons contained within the plasma help ionize the incoming argon gas, thereby increasing the deposition rate. After the entire roll is coated, the vacuum chamber is opened and the roll removed.

Equipment. A typical roll coater consists of a vacuum chamber, sputtering sources and targets, a pumping system, and a winding system. Most production roll coaters can handle rolls up to 80 in. (2 m) wide and films up to 0.030 in. (0.76 mm) thick. Both planar diode and magnetron sources are used in roll coaters; however, magnetron sources are preferred because of the low heat load generated during sputtering. The sputtering source is generally oriented around a drum. Targets of pure elements, alloys, and compounds are sputter deposited. New compounds are also deposited by adding reactive gases into the vacuum chamber during sputtering. Multiple sources deposit multilayer coatings consisting of a variety of materials.

The pumping system of the roll coater is large enough to handle the air that is released when the roll is unwound in the vacuum chamber during sputtering. To minimize outgassing (release of trapped air), materials with high vapor pressure may require a separate unrolling and then reloading onto another mandrel while in a vacuum. Outgassing can cause cloudy films and brittleness, and reduced adhesion, electrical conductivity, and reflectivity. The winding system feeds the film over the various rollers and in front of the sputtering source while maintaining a constant speed and tension until the entire roll is coated.4

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![Fig. 9-10 Schematic of in-line magnetron sputtering system for coating architectural glass panels. (Courtesy Airco Temescal)](image-url)
VACUUM-METALLIZED PLASTICS

Vacuum-metallized plastic uses range from Christmas ornaments to automotive headlamp reflectors, CDs to cellular phones, and toy car bumpers to NASA space helmets.

Many plastic parts used in visible or decorative applications require a shiny metallic appearance. Other components may need a conductive or reflective surface as a prerequisite to their function. Perishable food products, such as potato chips, are packaged in bags with an aluminum barrier coating to protect against moisture, oxygen, and light. Table 9-5 is a list of the various uses for metallized plastics.

The vacuum coating industry is often divided into three categories: decorative, functional/optical, and web coating. The coating equipment for each segment generally operates on the same basic principles but varies based on specific applications.

As mentioned earlier, Grove noticed that cathode material can deposit on surrounding surfaces. Subsequently, Faraday and Edison tried experiments using this ionizing technique. World War II led to the development of the diffusion pump. This made the high-vacuum process commercially feasible. The postwar era saw both the plastic and vacuum-metallizing industries gain acceptability and gradually replace electroplated metals in many applications. Today literally billions of plastic components and millions of ft² (m²) of plastic film are coated annually.

Vacuum deposition is a physical, rather than electrochemical, method of depositing a metallic film onto a plastic substrate. The deposition takes place within a vacuum vessel or chamber, where the solid material is melted and then becomes gaseous when reaching its vapor point. Gas molecules traveling by line of sight subsequently condense on the surface of the plastic part, forming a relatively conformal and uniform coating.

Vacuum System

A vacuum system consists of an airtight chamber where the deposition process occurs. All systems have multiple vacuum pumps that evacuate the chamber to the process pressure required. The systems have valves and gates between various sections to isolate and control the vacuum pump-down process. A work-holding fixture that slides in and out of the chamber is used to rack the parts. A power supply and evaporation source melt the material that is deposited onto the plastic components.

Vacuum chambers are as small as one 1 ft (305 mm) in diameter and 1 ft (305 mm) high. They can be small or large custom-built systems as large as 5000 ft² (464 m²) and process over 1000 ft² (93 m²) of web material per minute.

All systems are essentially batch-type operations, but many applications have evolved into semicontinuous cycles with microprocessor controls.

Figure 9-11 shows a typical 72 in. (183 cm) batch coater that is the “workhorse” of the industry and suitable for most applications.

The functional equipment is usually much smaller than chambers used in decorative and web coating and has the most sophisticated controls. Basic vacuum systems cost from $50,000 to $150,000, and large, semicontinuous systems can exceed $10 million.

Vacuum Pumps

Three types of pumps are normally used to achieve the high vacuum necessary for metallizing. The pumps, arranged in a series, are connected by valves. The first stage of the operation uses a mechanical rotary piston pump along with a Roots-type booster pump. About 99% of the air in the chamber is removed, lowering the pressure to 100 millitorr (13.3 kPa). This is the rough pumping stage.

Figures 9-12 and 9-13 illustrate a mechanical pump and a Roots-type blower, a combination known as a mechanical booster. These pumps are reliable and maintain a constant pumping speed. Air pumps function similar to water pumps with vacuum capability down to 100 millitorr (13.3 kPa); this is known as viscous or turbulent flow.

Below this pressure, molecular flow occurs, and one or more diffusion pumps (Fig. 9-14) are valved into the system to further reduce the pressure to the desired level. This is called the high-vacuum or diffusion stage and is the point where the vaporization cycle occurs. In large diffusion-pumped systems, a holding pump (a small mechanical pump) is used to back up the diffusion pump. This holds the diffusion pump’s pressure to a high vacuum when it is not working on the system during loading, unloading, and the roughing stage.

Decorative Coatings

Decorative vacuum metallizing usually requires a paint application system and bake or curing ovens in addition to the vacuum evaporation system. The following steps are used in a decorative application to “first-surface metallize:”

1. Rack parts on workholding fixtures.
2. Apply basecoat by dip, spray, or flow-coat method.

<table>
<thead>
<tr>
<th>Decorative</th>
<th>Optical</th>
<th>Electrical</th>
<th>Web Coating/Packaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auto trim/medallions</td>
<td>Automotive lighting</td>
<td>Audio/videotape</td>
<td>Barrier coatings</td>
</tr>
<tr>
<td>Appliance trim</td>
<td>Architectural glass</td>
<td>Capacitors</td>
<td>Laminated film</td>
</tr>
<tr>
<td>Cabinet and window trim</td>
<td>Camera lenses and filters</td>
<td>Electrical contacts</td>
<td>Hot-stamp film</td>
</tr>
<tr>
<td>Casket hardware</td>
<td>Compact discs</td>
<td>EMI/RFI shielding</td>
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<tr>
<td>Clock bezels</td>
<td>Jet canopies</td>
<td>Integrated circuits</td>
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<tr>
<td>Cosmetic caps</td>
<td>Mirrors–1st and 2nd surface</td>
<td>Resistors</td>
<td></td>
</tr>
<tr>
<td>Custom jewelry/giftware</td>
<td>Reflectors</td>
<td>Solar cells</td>
<td></td>
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<td>Fishing lures</td>
<td>Sunglasses</td>
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<tr>
<td>Furniture trim</td>
<td>Telescopes</td>
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<td>Labels</td>
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<tr>
<td>Lamps and lighting</td>
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<tr>
<td>Novelty items</td>
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<tr>
<td>Picture frames</td>
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<td>Signs</td>
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<td>Toys</td>
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</tbody>
</table>

TABLE 9-5
Uses of Metallized Plastics
Fig. 9-11 Typical 72 in. (183 cm)-diameter vacuum coater. (Courtesy Stokes Vacuum, Inc.)
3. Solvent flash-off and bake or oven cure basecoat.
4. Load basecoated part racks onto metallizing carriage and insert into vacuum chamber.
5. Pump down and initiate vapor deposition cycle in metallizing chamber.
6. Unload metallized parts and topcoat.
7. Unload parts from workholding fixtures.
8. Inspect and pack parts.

To achieve brilliant blemish-free coatings, the plastic parts must be clean and free of any surface contaminants. Molding is done without using mold release agents. Operators handling parts should wear white inspection gloves, and parts are immediately put into polybags or boxes lined with polybags to avoid soil and dust in the workplace.

Parts are held securely as they go through various coating and metallizing processes. Spring clips are normally used, mounted on individual rods or reels that are compatible with the processing equipment. Part design is important because clip marks or scars can be left where the part is attached to the rack. The attachment points cannot be visible in the part application. Close attention is paid to critical tolerance surfaces. Parts are not affixed to the rack in these areas, since basecoat buildup is hard to control.

Various masking devices, plugs, and caps may be used to shield critical areas. A destatic blow-off is used to eliminate dust and static buildup on parts before further processing.

Basecoating is a painting operation (as is topcoating). Basecoat lacquers are applied by conventional methods, and parts may be flow-coated, sprayed, or dipped. Paint equipment manufacturers have developed special coating equipment for the metallizing industry that mates paint application systems with the vacuum systems.

Basecoating acts as an adhesion-promoting layer and fills in minor surface imperfections, giving the plastic parts a smooth surface. Some plastics outgas in a vacuum, and the basecoat seals the surface.

The coating is fully cured, using either batch or conveyered ovens. Curing times normally run from 30 minutes to two hours, depending on the type of resin coating and its curing temperature.

After the basecoat is fully cured, the racks of parts are loaded onto carriages of stationary or planetary design (see Fig. 9-15); these carriages hold the racks inside the vacuum chamber. Most chambers are cylindrical and are mounted horizontally for easy insertion of the carriage. After the carriage is inserted, the door is closed, and the pumping cycle begins.

All metals, most alloys, a large variety of oxides, and other compounds can be metallized. However, aluminum is the most common metal in decorative and functional applications because of its physical properties, economic considerations, and the equipment it requires.

Buss bars with tungsten wires or filaments run down the center of the chamber. Aluminum canes, clips, or ribbons are attached to the filaments. The carriage drive rotates the parts around the diameter of the chamber. When the electrical current to the filament is turned on, the filaments are heated by resistance. When
the filament temperature reaches 1220° F (660° C), the aluminum melts and flows along (wets) the filament. The aluminum vaporizes (flashes off) the filament when the filament temperature reaches 2100° F (1149° C). The aluminum vapors leave the filaments in straight lines and strike the parts as they are rotated on the carriage. The vapors condense on the parts, since the parts are much cooler than the filaments.

Planetary rotating workholding carriages are used when it is necessary to expose all part surfaces to the aluminum vapors. Contours and recessed areas are covered, because the coating is still fluid when it condenses and forms a uniform layer on the part. The flashing takes about 10 seconds while heat-up and prewet cycles take about 20 seconds.

The vacuum is broken by closing pump valves and allowing air into the chamber through another valve until atmospheric pressure is attained. The carriage with the now-metallized parts is removed from the chamber, and the parts are ready for topcoating.

Controls for the evacuation and vaporization sequences may be manual, semiautomatic, or completely automated. Automatic sequencing eliminates the cost of an operator and human errors.

Resistance firing is not the only method of metal vaporization from tungsten wires or refractory crucibles. Sputtering, electron-beam vaporization, ion plating, high-frequency resistance, radiant heating, and induction heating are other techniques for specific applications.

An organic topcoat is used to protect the thin layer of metal from wear and abrasion; it also offers chemical resistance. A proper topcoat is essential in obtaining the brilliantly polished aluminum appearance desired. The various aspects of topcoating are an art or science in achieving the desired finish over the mirror-like metallic coating. In addition to simulating all the bright metallic finishes, satiny or subdued effects are achieved by using semigloss rather than clear topcoats. The topcoat can be clear or tinted and can appear as copper, brass, gold, and colored metallic finishes.
Tinted coats are always spray coated, unless a special effect is desired. The pigments’ higher specific gravity causes them to accumulate in recesses when flow coated. Areas where the coat is thicker, such as edges, are also darker due to particle attraction. Flow-coated topcoats are clear, and the dip is dyed in a resin-die solution to attain the proper tint and film color uniformity.

Clear UV-curable coatings are recent developments in topcoating technology that provide extremely durable coatings for exterior uses. However, the capital cost for UV application systems approaches $500,000. The systems are application specific, requiring a tremendous volume of work load.

Vacuum-metallized plastics have met the following nonvisual test requirements as well:

- Tape adhesion, which requires a minimum of 95% coating retention when the tape is applied to a cross-hatched surface.
- Humidity, with 96 hours of exposure at 100˚ F (38˚ C) and 100% relative humidity with no loss of adhesion, blistering, or other appearance changes.
- Gravelometer, for abrasion resistance, with parts withstand- ing a minimum rating of five when tested per SAE J400 at 0˚ F (–18˚ C).
- Thermal cycle exposure at 170˚ F (77˚ C) for 20 hours, followed by room temperature, followed by 20 hours at 20˚ F (–29˚ C), and finally four hours at room temperature. The cycle is repeated three times, and the parts can show no evidence of adhesion loss, cracking, or other appearance changes.
- Cleanability, with the topcoats resisting attacks from a wide variety of cleaners and solvents.
- Wear, with all coatings exceeding requirements for abrasion resistance of the topcoat and metal film.
- Salt spray, with no blistering or corrosion in scribed areas, and no loss of adhesion after 336 hours of neutral salt spray. (Lines are scratched through the coating down to the substrate in a cross-hatched pattern.)
- No blistering or corrosion in scribed areas, and no loss of adhesion after 48 hours of copper-accelerated salt spray (CASS).
- Weatherometer, with exposure to UV light for up to 1600 hours without evidence of topcoat deterioration or appearance change.

A variety of malfunctions may occur. Table 9-6 lists common problems and corrective actions.

Substrate selection is given serious consideration, and virgin plastics are always used to avoid contaminates in regrind material. The material is stable in a vacuum and must not evolve gases or vapors when exposed to the deposition vapors. Outgassing causes darkened deposits with poor adhesion on the process parts and causes excessive gas load on the pumping system. Although all plastics can be metallized by basecoating with an impervious lacquer layer, a better solution is to select a more compatible resin. The most popular resins include high-impact polystyrene, ABS, acrylic, polycarbonate, PC-blend polyesters, and polypropylene.

Polyethylene requires a primer or flame treating to assure good adhesion before basecoating. Many of the higher-temperature thermosts and engineered plastics can be successfully coated using specially formulated basecoat resins suited for higher-temperature service requirements. Some resins, such as nylon, are difficult to process because they are relatively hygroscopic or emit plasticizer when baked or in a vacuum; this causes substrate embrittlement.

**Functional Coatings**

Functional coatings are often divided into two categories, reflective/optical and conductive/dielectric. Although functional coatings are probably less than 25% of the vacuum coating industry,
<table>
<thead>
<tr>
<th>Problem</th>
<th>Results In</th>
<th>Suggested Corrective Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contamination</td>
<td></td>
<td></td>
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<tr>
<td>On plastic surface</td>
<td>Loss of adhesion</td>
<td>Cratering</td>
</tr>
<tr>
<td></td>
<td>Lint and dust specks</td>
<td>Bubbles, pimples</td>
</tr>
<tr>
<td>In coatings</td>
<td>Loss of adhesion</td>
<td>Humidity or solvent blush</td>
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<tr>
<td></td>
<td>Delamination to basecoat</td>
<td>Lint and dust specks</td>
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<td></td>
<td>Delamination to topcoat</td>
<td>Cratering</td>
</tr>
<tr>
<td></td>
<td>Iridescence, Newton fringe</td>
<td>Bubbles, pimples</td>
</tr>
<tr>
<td>In air or dryer</td>
<td>Delamination to basecoat</td>
<td>Lint and dust specks</td>
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<td></td>
<td>Delamination to topcoat</td>
<td>Cratering</td>
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<tr>
<td></td>
<td>Iridescence, Newton fringe</td>
<td>Bubbles, pimples</td>
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<tr>
<td></td>
<td>Humidity or solvent blush</td>
<td></td>
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<tr>
<td>In wash solution</td>
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</tr>
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<td>Lint and dust specks</td>
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</tr>
<tr>
<td>Coatings</td>
<td>Loss of adhesion</td>
<td>Humidity or solvent blush</td>
</tr>
<tr>
<td>Improper formulation</td>
<td>Delamination to basecoat</td>
<td>Lint and dust specks</td>
</tr>
<tr>
<td></td>
<td>Delamination to topcoat</td>
<td>Cratering</td>
</tr>
<tr>
<td></td>
<td>Iridescence, Newton fringe</td>
<td>Bubbles, pimples</td>
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<tr>
<td></td>
<td>Increase air capacity, time, and/or temperature</td>
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<tr>
<td>Undercured basecoat</td>
<td>Loss of adhesion</td>
<td>Cratering</td>
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<td></td>
<td>Delamination to basecoat</td>
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<td></td>
<td>Delamination to topcoat</td>
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<tr>
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<td>Iridescence, Newton fringe</td>
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<tr>
<td>Undercured topcoat</td>
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<td>Humidity or solvent blush</td>
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<tr>
<td></td>
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<td>Bubbles, pimples</td>
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<td>Improper thinner ratio</td>
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<td>Humidity or solvent blush</td>
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<td>Delamination to topcoat</td>
<td>Cratering</td>
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<td></td>
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<td>Movement of basecoat to plastic</td>
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<td>Cratering</td>
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<td></td>
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<td>Delamination to basecoat</td>
<td>Iridescence, Newton fringe</td>
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<td>Delamination to topcoat</td>
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<tr>
<td></td>
<td>Humidity or solvent blush</td>
<td>Bubbles, pimples</td>
</tr>
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<td></td>
<td>Lint and dust specks</td>
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</tr>
<tr>
<td>Moisture sensitive</td>
<td>Delamination to basecoat</td>
<td>Humidity or solvent blush</td>
</tr>
<tr>
<td></td>
<td>Delamination to topcoat</td>
<td>Lint and dust specks</td>
</tr>
<tr>
<td></td>
<td>Iridescence, Newton fringe</td>
<td>Cratering</td>
</tr>
<tr>
<td></td>
<td>Bubbles, pimples</td>
<td></td>
</tr>
<tr>
<td>Vacuum chamber</td>
<td>Delamination to basecoat</td>
<td>Iridescence, Newton fringe</td>
</tr>
<tr>
<td>Metal oxidation</td>
<td>Delamination to topcoat</td>
<td></td>
</tr>
<tr>
<td>Outgassing of fixtures</td>
<td>Delamination to basecoat</td>
<td>Iridescence, Newton fringe</td>
</tr>
<tr>
<td></td>
<td>Delamination to topcoat</td>
<td></td>
</tr>
<tr>
<td>Low vacuum</td>
<td>Delamination to basecoat</td>
<td>Iridescence, Newton fringe</td>
</tr>
<tr>
<td></td>
<td>Delamination to topcoat</td>
<td></td>
</tr>
<tr>
<td>Back streaming of oils</td>
<td>Iridescence, Newton fringe</td>
<td></td>
</tr>
<tr>
<td>Thick film buildup</td>
<td>Delamination to basecoat</td>
<td>Iridescence, Newton fringe</td>
</tr>
<tr>
<td>Oven cure too high or long</td>
<td>Iridescence, Newton fringe</td>
<td></td>
</tr>
<tr>
<td>Plastic</td>
<td>Crazing, blush</td>
<td></td>
</tr>
<tr>
<td>Molding imperfections</td>
<td>Bubbles, pimples</td>
<td></td>
</tr>
</tbody>
</table>
it is the fastest-growing sector. Most of the research and development work is carried out in this area because it is application rather than process oriented.

Functional coatings are often deposited directly onto the plastic substrate, eliminating the basecoat used in decorative vacuum coating. A variety of surface modifications alter the “wettability” and increase the surface tension of the plastic to promote better adhesion bonds. Mechanical abrasion, chemical etching, irradiation, flame, and plasma treating are methods used to increase adhesion. Plasma treatments with reactive and nonreactive gases are most often used with vacuum processing, because this is done within the same vacuum cycle as the deposition process.

Multiple-evaporant sources and a variety of reactive process gases are used and introduced into the systems to deposit oxides, nitrides, alloys, compounds, and multilayered films for specific applications.

In optical coatings, aluminum is again the most popular deposition material because of its high reflective properties. Gold offers the highest reflectivity followed by silver, but because of their cost, gold and silver are only used in highly technical applications. Aluminum remains the coating of choice for compact discs, auto headlamps, flashlights, mirrors, telescopes, and a variety of other reflectors.

Very thin semitransparent films are used as light filters, beam splitters, and solar reflectors, and as coatings for architectural glass, sunglasses, microscopes, and camera lenses. MgF2 is used to produce a nonreflective coating, and SiO is overlaid to provide additional scratch and abrasion resistance. Rhodium, chromium, and nickel-chromium coatings are also used in severe atmospheric exposures, although their reflectance is slightly below that of aluminum.

Table 9-7 lists metals and compounds that are used as conductors, capacitors, and resistors and for other electric/electronic applications.

As a conductor, aluminum is most often used because it has the maximum electrical conductivity per unit weight deposited. All the noble metals (gold, platinum, copper, and silver) may be

<table>
<thead>
<tr>
<th>Coating Material</th>
<th>Application</th>
<th>µm</th>
<th>Coating Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Conductor (a)</td>
<td>0.01–0.2</td>
<td>0.0004–0.008</td>
</tr>
<tr>
<td>Bi</td>
<td>Conductor (b)</td>
<td>0.05–0.5</td>
<td>0.002–0.02</td>
</tr>
<tr>
<td>Cd</td>
<td>Conductor</td>
<td>0.05–1</td>
<td>0.002–0.04</td>
</tr>
<tr>
<td>Cr (c)</td>
<td>Resistor</td>
<td>0.002–0.1</td>
<td>0.00008–0.004</td>
</tr>
<tr>
<td>Nb (d)</td>
<td>Superconductor</td>
<td>0.05–0.1</td>
<td>0.002–0.004</td>
</tr>
<tr>
<td>Cu</td>
<td>Conductor</td>
<td>0.01–0.2</td>
<td>0.0004–0.008</td>
</tr>
<tr>
<td>Ge (d)</td>
<td>Semiconductor</td>
<td>0.5–10</td>
<td>0.02–0.4</td>
</tr>
<tr>
<td>Au</td>
<td>Conductor</td>
<td>0.01–0.2</td>
<td>0.0004–0.008</td>
</tr>
<tr>
<td>In</td>
<td>Conductor</td>
<td>0.05–0.2</td>
<td>0.002–0.008</td>
</tr>
<tr>
<td>Pb</td>
<td>Conductor</td>
<td>0.05–0.2</td>
<td>0.002–0.008</td>
</tr>
<tr>
<td>Mo</td>
<td>Conductor (e)</td>
<td>0.05–0.2</td>
<td>0.002–0.008</td>
</tr>
<tr>
<td>Ni</td>
<td>Conductor</td>
<td>0.05–0.2</td>
<td>0.002–0.008</td>
</tr>
<tr>
<td>Pt (f)</td>
<td>Conductor</td>
<td>0.01–0.2</td>
<td>0.0004–0.008</td>
</tr>
<tr>
<td>Se</td>
<td>Semiconductor</td>
<td>0.5–10</td>
<td>0.02–4</td>
</tr>
<tr>
<td>Si (d)</td>
<td>Semiconductor</td>
<td>0.5–10</td>
<td>0.02–4</td>
</tr>
<tr>
<td>Ag</td>
<td>Conductor</td>
<td>0.01–0.2</td>
<td>0.0004–0.008</td>
</tr>
<tr>
<td>Ta (f)</td>
<td>Resistor</td>
<td>0.01–0.2</td>
<td>0.0004–0.008</td>
</tr>
<tr>
<td>Sn</td>
<td>Superconductor</td>
<td>0.05–0.2</td>
<td>0.002–0.008</td>
</tr>
</tbody>
</table>

Metal Compounds

<table>
<thead>
<tr>
<th>Coating Material</th>
<th>Application</th>
<th>µm</th>
<th>Coating Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al2O3 (f)</td>
<td>Capacitor</td>
<td>0.1–2</td>
<td>0.004–0.08</td>
</tr>
<tr>
<td>Cadmium sulfide</td>
<td>Semiconductor; photoconductor</td>
<td>0.1–2</td>
<td>0.004–0.08</td>
</tr>
<tr>
<td>Cerium oxide</td>
<td>Capacitor</td>
<td>0.1–2</td>
<td>0.004–0.08</td>
</tr>
<tr>
<td>Silicon oxide</td>
<td>Capacitor; insulator</td>
<td>0.1–2</td>
<td>0.004–0.08</td>
</tr>
<tr>
<td>Tantalum oxide (g)</td>
<td>Capacitor</td>
<td>0.01–0.2</td>
<td>0.0004–0.008</td>
</tr>
<tr>
<td>Titanium oxide (h)</td>
<td>Capacitor</td>
<td>0.03–0.2</td>
<td>0.001–0.008</td>
</tr>
<tr>
<td>ZnO</td>
<td>Semiconductor</td>
<td>0.1–2</td>
<td>0.004–0.08</td>
</tr>
</tbody>
</table>

(a) Good counterelectrode for capacitors.
(b) Good counterelectrode for rectifiers.
(c) Adheres exceptionally well to glass.
(d) Difficult to obtain purity desired.
(e) Good conductor for high-temperature applications.
(f) Difficult to vaporize except by electron-bombardment heating.
(g) Produced by anodizing tantalum films.
(h) From thermal oxidation of titanium metal.
used for thin-film integrated circuits using silicon monoxide and magnesium fluoride as dielectric layers. A number of metallized and dielectric films are often deposited. Gold and silver are frequently used where highest conductivity and corrosion resistance are essential.

Nickel-chromium and platinum alloys are deposited for electronics because of their resistive elements. Certain oxides, such as tin oxide and In-TiO₂, are also used. The resistance of these films is inversely proportional to their thickness.

Metallized plastics are also used for suppressing electromagnetic interference (EMI), radio frequency interference (RFI), and electrostatic discharge (ESD) in electronic devices such as computers, cellular phones, and electronic instruments. This is normally done by depositing the metallic coating inside the injection-molded case. Thin-film thermoformed vacuum-metallized inserts are also used in electronic devices in a variety of methods. They can be mounted at the board level over integrated circuits and power supplies that cause interference to replace metal assemblies. Clamshells can encapsulate entire or multiple board assemblies. Formed metallized liners are fit inside the instrument case, eliminating the coating on the case.

Vaporization of many optical and electrical films becomes elaborate, and extremely close control is required for their deposition techniques. All are normally done in clean-room conditions and require specialized equipment.

**MULTILAYER PROCESSES**

**DRY ADHESIVE FLAT BED LAMINATION**

This process originated in the 1970s with the advent of joining fusible interlinings as a reinforcement for garments in the apparel industry. Continuous-fusing machines replaced intermittent flat bed presses, and the era of horizontal lamination was initiated with the availability of thermoplastic films, webs, and powders used as adhesives to weld various industrial-type substrates. Modern lamination equipment manufacturers are usually former manufacturers of fusing machines, but the two markets are different in their end uses and equipment characteristics.

**Flame Lamination and Other Systems**

When polyurethane foams are exposed to a flame, the surface of the foams (ether- or ester-based) is melted, creating an adhesive film that permits laminating a textile cover onto the hot melted foam. This method remains popular because of the speed of the process. Its limitation resides in having to use foam and burn some of it off; this creates air pollution. Laminating with solvents is slowly phasing out because of air quality concerns. Cold lamination with solvent-based or water-based adhesives does not necessarily require the use of foam, but there are similar ecological consequences and higher energy costs.

To process different types of adhesives, there are several types of equipment that relate to heat, time, pressure, and in some instances, cooling. Calenders operate with drums that are heated with oil or electricity. They offer a large heating surface area that heats from one side only, with the disadvantage of heating the adhesive through only one of the substrates. They are also limited to the thickness and flexibility of the total assemblies that are laminated. A high degree of temperature control is more difficult to achieve. The adhesive must flow and can be softened to join the substrates.

With flame lamination and calender lamination, production runs are longer, and at start-up, waste becomes a factor before the heat, time, and pressure requirements are stabilized. Hot-air or steam systems offer other limitations regarding heat control, which is the most important element of a flexible and efficient laminating system. When the principles of efficient fusing—proper contact heat, duration of heating, and pressure—are applied to a laminator, the best formula is approached with horizontal contact heat lamination.

**Contact Heat Horizontal Laminator**

The most important criterion in selecting proper heat settings is the heat resistance of the various substrates. Once the lamination has taken place, determining the heat resistance the assembly needs to satisfy the end use of the laminated assembly is essential.

The choice of the adhesive is important. Thermoplastic materials and their presentations vary. Furthermore, blends of thermoplastic materials are now available.

Double-sided films also exist with two different adhesives. Adhesive weights are selected to achieve the appropriate adhesion results between the substrates. Costs of the chemical formulas are considered. Each supplier offers its speciality, such as low melt points, webs versus films, and powders instead of films or webs. The ideal laminator can laminate all types of substrates, in any thickness, in any width, and with all types of adhesives.

Laminating equipment is selected with the following characteristics in mind:

- The proper width for the processed materials.
- Appropriate height elevation between the top and bottom heating zones, allowing thick assemblies.
- Controllable and recordable heat with good adaptability to change and with no more than 4–9˚ F (2–5˚ C) variance across the horizontal heat zones.
- A heating zone with sufficient length to allow the adhesive system to flow between the different substrates at a good production speed.
- Proper cooling at the end of the heating zone to cure the adhesive system prior to roll-up of the completed assembly, and to allow prelamination of adhesives.
- A laminator that can use powder, webs, or film based on the chosen adhesives (which can change with different uses).
- Equipment that is easily maintained with adequate diagrams and parts lists.
- A supportive locally based supplier who warrants the quality of engineering by supplying, before the sale is completed, a complete list of references.
- Equipment that has a history of materials used during its construction. A visit to the manufacturer is recommended.

**FILM AND SHEET FORMING**

The basic methods for producing film or thin sheets are calendaring, extrusion, blowing, and casting. The method chosen for a particular application is determined by the type of thermoplastic that is processed.

**Calendering**

Calendering, illustrated in Fig. 9-16, is the formation of a thin sheet by squeezing a thermoplastic material between rolls. In principle, it is a continuous “extrusion” process in which a pair of
CHAPTER 9
MULTILAYER PROCESSES

9-33

Mating rolls establishes the thickness and surface characteristics of the formed sheet.

The material, composed of resin, plasticizer, filler, and color pigments, is compounded and heated before it is fed into the calender. The sheet thickness produced depends on the roll spacing and the speed of the finishing rollers that stretch the plastic material. Before the sheet (film) is wound, it passes through water-cooled rolls. Vinyl, polyethylene, cellulose acetate films and sheeting, and vinyl floor tile are calendering products.

Extrusion

In making sheets of polypropylene, polyethylene, polystyrene, or ABS, an extrusion process is used. This process is illustrated in Fig. 9-17. After the material is compounded, it is placed in the feed hopper. The material is heated to 320–425°F (160–218°C) and forced into the die area at pressures of 24 ksi (165 MPa) by the screw conveyor. The sheet thickness is controlled by a combination of the choker bar and the die opening. After extrusion, the sheet passes through oil- or water-cooled, chromium-plated rolls before it is cut to size. Extruded plastic sheet and film materials range in thickness from 0.001–0.126 in. (0.03–3.2 mm). Material that is less than 0.01 in. (0.3 mm) thick is called film.

Blown Tubular Extrusion

The blown tubular extrusion process produces film by first extruding a tube vertically through a ring die and then blowing it with air into a large-diameter cylinder. The blown cylinder is air cooled as it rises, and then it is flattened by driven rolls before reaching the winder. This technique is used to produce thin film such as that used in trash bags and packaging materials.

Film and Cell Casting

In film casting, the plastic resins are dissolved in a solvent and spread on a polished continuous belt or large drum and conveyed through an oven; here, the resins are cured and the solvent is removed. In cell casting, a cell is made up of two sheets of polished glass, separated according to the desired film thickness. Gaskets retain the liquid catalyzed monomer. The cell is heated to the desired temperature in an oven, where it is held until curing is completed. Cell casting is used for producing acrylic transparent sheets.

References


Bibliography

Rotational molding, also called rotomolding or rotational casting, is a thermoplastic processing method for producing hollow parts, from the most simple to the very complex.

**THE BASIC PROCESS**

Rotational molding consists of six steps:

1. A predetermined amount of plastic, either in powder or liquid form, is deposited in one half of a mold.
2. The mold is closed.
3. The mold is rotated biaxially inside an oven.
4. The plastic melts and forms a coating over the inside surface of the mold.
5. The mold is removed from the oven and cooled.
6. The mold is opened and the hollow part is removed.

Polyethylene powders are the most widely used rotational molding material. Vinlys, both liquids and powders, are the second most widely used rotational molding material. Many other types of plastics are rotationally molded, but are used less often.

**APPLICATIONS**

Rotational molding produces parts for many different industries including automotive, furniture, industrial equipment, lawn/garden, marine, materials handling, road/highway, sporting equipment, medical, toys, and transportation.

- **Agriculture**
  Vegetable growing trays, feeding/watering troughs, chemical tanks.

- **Consumer Products**
  Baby strollers, child car seats.

- **Containers**
  Storage tanks, 55-gallon drums, carboys, septic tanks.

- **Furniture**
  Children’s beds, chairs, planter pots, tables.

- **Industrial Equipment**
  Tool carts, equipment housings, safety helmets, battery containers, fluid reservoirs.

- **Lawn/garden**
  Garden tool carts, composting bins.

- **Marine**
  Boats, kayaks, sailboards, canoes, boat bumpers.

**Medical**

Syringes, dental chairs, testing equipment housings, anesthesia/oxygen masks, ear syringes, squeeze bulbs.

**Materials Handling**

Stackable pallets, forklift containers, shipping containers.

**Road/Highway**

Safety barricades, lane markers, litter bins, portable toilets.

**Sporting Equipment**

Bike seats, athletic pads, footballs, juggling pins, helmets.

**Toys**

Playhouses, outdoor gym equipment, balls, rocking horses, picnic tables, wading pools, pool floatables, doll parts.

**Transportation**

Camper tops, motorcycle saddlebags, bicycle trailers, tool chests for trucks, truck bed liners, air ducts, fuel tanks, seat back head-restraint covers.

**ADVANTAGES AND LIMITATIONS**

Key advantages of rotational molding:

- Molds are relatively inexpensive.
- Rotational molding machines are much less expensive than other types of plastic processing equipment, such as injection molding machines and blow molding machines.
- Different parts can be molded at the same time.
- Straight-wall parts can be made (no draft angles).
- Very large hollow parts can be made.
- Parts are stress-free.
- Very little scrap is produced.

Limitations of rotational molding:

- Cannot make high-tolerance parts.
- Large flat surfaces are difficult to achieve.
- Molding cycles are long.
- A limited number of resins are successfully processed.

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*The Contributor of this chapter is: Philip T. Dodge, Quantum Chemical Company.*

*The Reviewers of this chapter are: Glenn L. Beall, President, Glenn Beall Plastics, Ltd.; Charles D. Frederick, Executive Director, Association of Rotational Molders; Robert McMillan, Vice President, General Manager, New England Plastics Corporation.*

*Sponsored by: Association of Rotational Molders.*
CHAPTER 10

THE BASIC PROCESS

There are many process and materials variables for rotational molding, which gives the process considerable design flexibility.

MATERIALS TESTING AND PREPARATION

The rotational molding process starts with materials preparation. For powders, this preparation can include the grinding of pellets and the dry blending of colored powders.

Rotational molding powders are purchased from materials suppliers. Molders can also buy resin pellets and produce their own powders. There are three key powder properties: mean particle size, apparent/bulk density, and pourability.

Particle size analysis. This process uses a series of stacked screens. A 100 g powder sample is placed in the top screen, which has the largest mesh. A cover is placed over the top screen and a pan below the bottom screen and the stack is mechanically shaken. The amount of powder retained by each sieve is measured. (ASTM D-1921)

Mean particle size (MPS) in microns is determined by:

\[ \text{MPS} = \frac{\sum (P_i \times D_i)}{100} \]

where:

- \( P_i \) = percent of powder retained in each sieve
- \( D_i \) = average particle size in microns on each sieve

Pourability. Checking for pourability uses the same funnel for determining apparent density. The density of powders is determined by pouring a powder sample through a funnel. The funnel has a top opening of 3.6 in. (9.1 cm), is 4.5 in. (11.4 cm) high, and has a wall inclination of 20˚ and a bottom opening of 0.4 in. (1.01 cm). The funnel is placed in a ring holder and a 3.9 in. (9.9 cm) measuring cup is placed below it, with its top 15 in. (38 cm) below the bottom of the funnel. The bottom of the funnel is closed by holding a flat material against it and the funnel is filled with 115 cc of powder. The bottom of the funnel is opened and all the powder flows into the cup. Apparent density (g/cc) is determined by dividing the net weight of powder by the net volume of the powder in the cup by 100. Apparent density (lbs/ft\(^3\)) is determined by multiplying sample weight by 0.6243. (ASTM D-1895)

Pourability checking for pourability uses the same funnel for determining apparent density. A powder sample weighing 100 times the material’s molded specific gravity is poured into the funnel. The flow time(s) for the powder through the funnel is multiplied by the material’s molded specific gravity is poured into the funnel. The bottom of the funnel is opened and all the powder flows into the cup. Apparent density (g/cc) is determined by dividing the net weight of powder in the cup by 100. Apparent density (lbs/ft\(^3\)) is determined by multiplying sample weight by 0.6243. (ASTM D-1895)

Optimum particle size. This will vary depending on the material rotationally molded and processing requirements. A mean particle size of 500 micron (35 mesh) powder is the norm for polyethylene.

Rotational molding powders generally are mechanically ground without refrigeration. If the material’s properties are affected by the heat generated during grinding, the polymer (polypropylene) pellets are refrigerated (using liquid carbon dioxide, liquid nitrogen or “dry ice” (compressed carbon dioxide)).

Key physical properties of rotational molding powders are dry flow (also called pourability), particle distribution, and bulk factor. Testing for these properties is done in accordance with ASTM D-1895. Dry flow describes the relative flow property of a powder at ambient conditions. Shorter flow times indicate better flow. Particle size, distribution, shape, and surface condition also influence flow properties.

Generally, rotational molding materials contain all the additives that are needed to meet processing and performance requirements. Typical additives include heat stabilizers, ultraviolet light stabilizers, and colorants. Many molders dry and blend their own colored materials and may add other additives to help the flow.

Precolored polyethylene powders save rotational molders the difficulty of dry blending pigments with natural-colored resin powder. Also, when compared to dry blending: higher pigment loading is possible with precolored polyethylene powders; there is greater lot-to-lot color consistency; and higher levels of inherent properties are retained with precolored powders.

Drying is required with some rotational molding powders (for example, polycarbonate and some nylons) that absorb moisture from the air, that is, they are hygroscopic. Moisture can affect the processing of rotational molding powders, as well as the mechanical properties of molded parts.

Rotational molding liquids, primarily vinyl plastisols, consist of a vinyl (homopolymer or copolymer) powder suspended in a plasticizing liquid. Generally, vinyl plastisol compounds are purchased from custom compounders rather than made by processors. The majority of large processors compound their own PVC.

A starting amount of powder required to rotationally mold a polyolefin part is determined by the formula:

\[ \text{Shot weight} = \text{mold cavity area (in.}^2\text{)} \times \text{nominal wall thickness of part} \times \text{density (lb/in.}^3\text{)} \times \text{multiply density (g/cc) by 0.0022 (g/lb) \times 0.43 (cc/in.}^3\text{)} \]

Adjustments to this amount, to account for part shrinkage during cooling, are then made through trial and error.
2. Using a dump box in the mold, the material for the second layer is dropped into the mold.

**CROSS-LINKED MOLDINGS**

Cross-linked rotational moldings can be made by using materials that contain a chemical cross-linking agent. Cross-linking improves impact strength, dimensional stability, creep resistance and environmental stress crack resistance (ESCR) (see “Secondary Finishing” in this chapter).

**INSERTS**

Inserts for mechanical fastening are molded in place during the rotational molding process. The inserts are placed in the mold cavity prior to dispensing the material into the mold. Reinforcement inserts, such as glass fiber-reinforced plastic rods, also can be added to rotational moldings.

**EQUIPMENT**

Rotational molding systems, including both the basic molding machines and the auxiliary equipment, are significantly improved.

**GRINDING**

Attrition mills are a common type of equipment used to make rotational molding powders. Pellets are pulverized between two serrated or otherwise simple rough disks, which have a close tolerance between them and rotate either in opposite directions or with one stationary disk. The type of serration, the clearance between the disks, and the speed of rotation vary according to the pellets used and the required particle size.

**MIXING**

High-intensity shear mixers blend dry powders, colorants and additives. Other types include vertical whirlwind mixers, paddle mixers, ribbon mixers, drum tumblers, and drum rollers.

**DECORATIONS**

Decorations can be directly molded into rotational moldings or applied later (see also “Secondary Finishing” in this chapter). By embedding a graphic into the surface of a rotational molding, the graphic becomes permanent and will not peel, and cannot scratch or rub off. Molded-in Graphics® eliminate surface pretreatment required with other decorating methods.

Molded-in Graphics are printed on paper carriers. The carrier, graphic side down, is placed on the mold surface. The back of the carrier is rubbed to ensure that the graphic fits tightly against the mold surface without air pockets. Then the carrier is peeled off, leaving the graphic on the mold surface. The mold is charged with the molding powder and the part is molded. During the molding cycle, the graphic (which is made of colored polyolefin-compatible powder) becomes embedded in the surface of the part and a thin layer of the molding material forms over the graphic.

**DRYING**

Desiccant dryers run at high temperatures, and hot air circulating ovens remove moisture from hygroscopic rotational molding powders. Generally, a thin layer of the material is spread on large pans placed in the dryer.

**MATERIAL LOADING**

Usually, material is loaded manually, although the process can be automated. Accurate weighing of the material charge and distribution prior to starting the molding cycle is important especially in large molds.

**MACHINE TYPES**

There are seven machine types used for rotational molding:

- Clamshell.
- Turret.
- Shuttle.
- Swing.
- Vertical wheel.
- Rock and roll.
- Open flame.

**CLAMSHELL MACHINES**

A clamshell machine (Fig. 10-1) is a single-station machine including an oven with hinges for the cover and front panel. The mold rotation arm can swing into and out of the open oven. The cover and front panel are closed during heating and are opened for part cooling, part removal, and reloading of the mold.

**TURRET MACHINES**

Also known as carousel machines (Fig. 10-2), turret machines have a center pivot with three to six arms. Each arm has a mold attached to its end. The arms index individually or simultaneously from station to station. Depending upon production requirements, these machines can have two cooling stations and/or two load/unload stations. Arms can handle loads (mold and material) up to 4,000 lb (1,814 kg).

**SHUTTLE MACHINES**

Shuttle machines (Fig. 10-3) move the mold along an oval or straight track from the load/unload station to the oven, then to the cooling station.

**SWING MACHINES**

A swing machine (Fig. 10-4) has one or more pivot units with a single arm that indexes from the load/unload station, to the oven, and then to the cooling station.

**VERTICAL WHEEL MACHINES**

Vertical wheel machines (Fig. 10-5) operate like a ferris wheel. Molds, mounted on cradles, are indexed simultaneously from sta-
CHAPTER 10
MACHINE TYPES

Fig. 10-1 Single-station machine with an oven (clamshell machine).

Fig. 10-2 Turret machine.

Fig. 10-3 Shuttle machine.

Fig. 10-4 Swing machine.
tion to station, with the load/unload station at the bottom of the wheel. Vertical wheel machines with up to six cradles can mold small- to medium-size parts. The cradles have maximum load limits of 300 lb (136 kg).

ROCK AND ROLL MACHINES

Rotational moldings with very long length to diameter ratios can be made on equipment called rock and roll machines (Fig. 10-6). The mold, mounted on a cradle, is rocked back and forth on a stationary, horizontal axis while it is rotated about a moving axis perpendicular to the rotating axis. On some machines, the oven may move. Canoes and kayaks are made with this type of machine.

OPEN-FLAME MACHINES

The oldest type of rotational molding equipment, open-flame machines, produce open-ended items such as pails and drums.

PROCESS FACTORS

SINTERING

A significant part of the rotational molding heating cycle is taken up by sintering or curing of the part while the mold is still in the oven. During sintering, air pockets trapped at the mold surface or within the material collapse.

Air pockets can affect surface appearance and cause internal voids that affect the part’s strength. Sintering time can be reduced by controlling the air inside the mold or by using additives that reduce the formation of air in the material.

After the sintering cycle, the rotational mold is cooled, usually by free air convection. However, forced air convection can significantly reduce cooling time. Quick quenching, such as by water spray, can further reduce the cooling cycle, but can increase the amorphous structure in crystalline polymers. Slow cooling, therefore, is generally preferred for crystalline polymers when resistance to warping and good low-temperature properties are needed. The cooling rate has little effect on the properties of amorphous polymers. Also, the cooling cycle is reduced by injecting cool air inside the rotational molding. This technique also improves dimensional stability.

Generally, parts removal is done manually. Release agents either periodically sprayed or wiped on mold surfaces permit easy part removal. Occasionally, an air ejection assist is used to lift a part from the inner mold surfaces.

MOLD ROTATION

Wall thickness distribution is determined by rotation ratio, that is, the number of primary rotations per minute to the number of secondary rotations. The rotation ratio is a function of part shape. A sphere or cube can be molded at a ratio of 4:1, but irregularly shaped parts can require ratios of 1:8 or 8:1. The optimum rotation ratio is determined by trial and error and molder experience.

Rotation speed varies with the melt flow properties of the material. A material with a low melt index (MI) tends to uniformly cover the mold when rotation speed is low. However, low-oven temperatures may be needed, thus making the molding cycle longer. Also, MI affects the material’s properties.

 Generally, ovens for rotational molding machines use forced hot air, heated by natural gas, liquid petroleum gas (LPG), oil, or electricity. Temperatures up to 900˚F (482˚C) are reached by some models.

Cooling units apply forced air and/or water sprays to the outside of the mold. Also, cooling air can be injected inside the part through a vent hole in the mold.

CONTROL SYSTEMS

Basic controls for rotational molding machines include heating controls/sensors, cooling controls/sensors, timers, sequence controls, rotation speed controls, and on/off buttons. Rotational molding machines can have microprocessor controls and programmable controllers. Mold cycle data can be quickly inputted, stored, retrieved, and activated. Cycle data can include cycle times, oven temperatures, major and minor axis speeds, rotation time, and cooling temperatures. Also, automatic troubleshooting is possible.

A major development is the ability to control the rotational molding process by measuring temperature inside the mold.
Standard rotational molding machines have a thermocouple in a corner of the oven to control process temperatures. Temperature measurements inside the mold allow more accurate determination of when the plastic first starts to stick to the mold, when all the material has adhered to the mold, when the material has sufficiently cured, when the plastic has solidified, and when the part can be removed from the mold.

Another development is the use of a hand-held infrared thermometer to measure mold and oven temperatures.

### TRIMMING
Generally, rotational moldings that have well-designed parting lines do not require trimming. However, with prolonged mold use, parting line flash may develop and require trimming. Also, molded-in holes may require some trimming.

### MOLDS
One key advantage of rotational molding compared to other plastics processing methods is the low cost of molds. Generally, molds consist of two pieces, although three or more piece molds may be used to allow for removal of a complicated part.

Major factors to consider in designing a rotational mold are heat transfer of the material, where parting lines are located, where to vent the part, how the mold is clamped, how the mold is mounted for rotation, and how many parts the mold will make.

Rotational molds are subjected to large thermal stresses during the process. In a relatively short period of time, they are heated to 600˚ F (316˚ C) and higher and then cooled down to about room temperature. Selection of a mold material must consider this thermal stress, as well as design, production, and economic factors.

### CAST ALUMINUM MOLDS
Cast aluminum molds are the most widely-used and are made quickly and relatively inexpensively. Aluminum has excellent thermal conductivity. Castings made from plaster foundry tooling can be made with surface texture, although high-gloss surfaces are not possible. Porosity is a concern for cast aluminum molds. As mold size gets larger, the problem of casting porosity becomes more difficult to overcome. Internal air pockets insulate heat and are stress risers.

### Sheet-metal Molds
This type of mold is for making large parts that have relatively simple contours. Sheet sheets 0.03-0.06 in. (0.76-1.5 mm) thick are formed and then welded together. The weld areas are then ground and polished. Parting lines are machine planed. A key advantage of sheet metal molds is uniform wall thickness and low cost compared to aluminum casting of a single mold.

### Electroformed Molds
Hard nickel or copper molds have good thermal conductivity and corrosion resistance, and they are nonporous. High-gloss surfaces and excellent surface texture is achieved. Electroformed molds exactly reproduce the details of the model from which they are made.

### Vapor Formed Molds
This type of mold is made by chemical vapor deposition of nickel which can be used to make rotational molds. Molds have excellent surface texture, very uniform thickness, and very good thermal conductivity.

### Design
Mold design for rotational molding relies upon molder experience. There are many “tricks of the trade,” which are learned from many years of working with different types of molding machines, mold materials, and molding materials.

A basic consideration in mold design is that one half of the mold cavity must be large enough to hold the resin volume needed for molding the part. For powders, the key property needed is the material’s apparent bulk density.

### CLAMPING
Clamps ensure that rotational molds do not leak at the parting line. Clamps must be easy and fast to operate. There are numerous types of clamp designs, but vise clamps, spring loaded clamps, toggle clamps, or nuts and bolts are generally used.

### Flanges
To securely clamp a mold closed, the mold has flanges located around the parting line. Flanges are mechanically fastened to the mold, welded to the mold, or included as part of a mold casting.

### INSERTS
Metal inserts increase or decrease wall thickness in a particular area of a molding. Wall thickness increases as the thermal conductivity of the insert material increases. High-heat conducting inserts can improve material flow in areas where good flow is difficult to achieve, such as deep ribs or pockets. Inserts can produce molded-in holes and generally have a nonstick coating, such as a fluoropolymer. Also, nonstick inserts are used for the cover of a drop box. These are called shielding.

### MOLD ARMS
Mold arms are designed to rotate the mold 360˚ horizontally (called the primary axis). On the end of the arm there is a spindle unit that rotates the mold 360˚ in a second direction, generally vertically to the arm. Molds can be rotated at various speeds and the primary and secondary rotation speeds can be different. Rotation speeds are low (15 rpm or less).

Mold arms are straight or offset (Fig. 10-7). The offset arms mount large, single cavity molds to maximize use of the molding machine’s capacity.

The arms of rotational molding machines can contain pipes for injecting air and/or a controlled atmosphere into the mold. Mold temperature sensors can also be run through the arms. Nylon requires a nitrogen atmosphere in the mold. Some equipment uses air-injection units that inject air inside a part to hold it against the mold surface and improve dimensional stability. Inert gas can be forced into a mold to purge the cavity and injected hot or cold air can reduce cycle time.

Mold spiders. Mold arms can hold multiple molds by using devices called spiders (Fig. 10-8). Spiders also can be double-mounted.

### MOUNTING
Frames are attached to the molds so that the molds can mount on the arm(s) of the rotational molding machine. Also, frames can serve as reinforcing members to prevent mold distortion. Mounting frames can have baffles to direct hot and cold air to deep recessed areas of molds.

Molds are mounted on the end of arms so that there is minimal shielding of any surface from the heat source and the cooling medium.
Mold parting line location is a key factor in mold design. It is located where:

- The line it produces on the part will be least visible.
- Where it allows easy part removal from the mold.
- Where it can be effectively clamped to prevent leakage.

Part shrinkage during cooling, particularly if there are internal wall surfaces, affects mold parting line location. Mold parting line surfaces are coated with nonstick materials to prevent polymer build-up which can cause leakage.

**VENTING**

Molds are vented to avoid pressure build-up during the heating cycle and to relieve mold vacuum during the cooling cycle. Vent tubes are made of a material that the molten polymer will not adhere to. The vent holes are placed in the mold where they will not become plugged during the rotational molding cycle. Since vent holes will leave holes in the rotational molding, their location is important both to the part's appearance and in preventing moisture from entering the part during the cooling cycle. Vent holes should have a diameter of 0.5 in. (13 mm) for each yd³ (0.8 m³) of volume in the part. Rotationally molded balls do not require vent holes because the spherical shape equalizes inside and outside pressure.

**DROP BOX**

To make multilayer rotational moldings, molds have drop boxes. After the first layer has been molded, the box is opened and the material for the next layer is dropped into the mold. The box is closed and the molding continues. The lid of the drop box has a nonstick surface.

**MOLD RELEASE AGENTS**

External release agents (release agents that are periodically sprayed or wiped on the mold surfaces) include waxes, soaps, silicone fluids/emulsions, and fluoropolymers. External release agents are low cost and easy to apply, but they tend to build up on mold surfaces and can cause warpage and other part problems (see “Additives” in this chapter).

As a result of the U.S. Clean Air Act of 1993, many rotational molders are switching to environmentally friendly, water-borne release agents from CFC- and solvent-borne release agents. The water-borne release agents require a mold surface temperature of about 140°F (60°C). If a part is removed from its mold at this temperature or above, the water will quickly evaporate. If the parts are removed at lower temperatures, the water-borne release agent has to be heated, which can be done using a hot air gun. With the initial application of a water-borne release agent, the water can be driven off by running the mold through a dry cycle.

Improved surface gloss and smoothness, as well as reduced manufacturing costs, are possible with rotational molds coated with a fluoropolymer. The fluoropolymer coating allows the polymer melt to flow more uniformly, which can significantly reduce pin holes in the surface of molded parts.

A fluoropolymer-coated mold eliminates the need for and expense of repeatedly spraying the mold with a mold release.
There are many thermoplastics that theoretically can be rotationally molded. However, only a few are used to make commercial products. Polyethylenes (low density, linear low density, high density, cross-link high density, and copolymers) are the most widely used materials, followed by vinyls, used less often. Typical property ranges for rotational molding materials are shown in Table 10-1.

### POLYETHYLENES

Key physical properties are melt index, molecular weight distribution (MWD), and density. As melt index increases, gloss improves, heat resistance decreases, breaking tensile strength decreases and low temperature impact decreases. Resins with a narrow MWD have better physical properties and processibility. As the density increases, the stiffness, heat-deflection temperature, warpage, and shrinkage will generally increase.

Typically, polyethylene powders are rotationally molded between 572–806˚ F (300–430˚ C). Molding cycles for small- to medium-size parts average about 10–15 minutes.

#### LLDPE

Linear low-density polyethylene (LLDPE) is the most widely used material for rotational molding. The density of LLDPE rotational molding grades ranges from 0.923–0.940 g/cc with a melt index (MI) of 3–7 g/10 min. LLDPE rotational-molding resins offer good stiffness and low-temperature impact strength, excellent environmental stress crack resistance (ESCR) and warp resistance.

#### LDPE

The density of low-density polyethylene (LDPE) rotational molding grades ranges from 0.915–0.920 g/cc with an MI of 10–25 g/10 min. LDPE rotational molding resins offer good impact strength, low shrinkage, good warp resistance and good flexibility.

#### HDPE

The density of high-density polyethylene (HDPE) rotational molding grades ranges from 0.942–0.950 g/cc with an MI of two to eight g/10 min. HDPE rotational molding resins offer high stiffness, impact strength, and excellent chemical resistance.

#### Copolymers

The density of ethylene vinyl acetate (EVA) copolymers for rotational molding ranges from 0.925–0.945 g/cc with an MI of 10–25 g/10 min. EVAs offer good low-temperature impact strength and flexibility.

#### Cross-Linked Polyethylene

The density of cross-linked polyethylenes (XLPE) for rotational molding ranges from 0.936–0.941 g/cc. Cross-linked polyethylenes offer excellent ESCR, very good low-temperature impact strength and good heat resistance. Recent research shows that cross-linked polyethylene rotational molding scrap can be recycled as a powder filler for rotational molding. At 350.6˚F (177˚ C), cross-linked polyethylene powders become tacky and will bond to other materials.

#### Recycled Polyethylene

Pressure from environmental groups, both government and private, is leading some rotational molders to incorporate post-consumer resins (PCR) into their products.

Most commercially available PCRs are made from high-density polyethylene (HDPE) blow molded containers. Thus, these HDPE PCRs have much lower melt indexes than the MI of typical...
rotational molding resins. Therefore, for rotational molding, an HDPE PCR is blended with a virgin resin. HDPE PCR content in blends can range from 10–25%. The blends can be made by either melt compounding or dry blending PCR/virgin blends.

How the PCR/virgin resin blend is prepared affects the inner surfaces of rotationally molded parts. Parts rotationally molded from dry blends can have very rough inner surfaces. Parts made from HDPE PCR/virgin resin extrusion blends exhibit smooth inner surfaces.

The color of parts rotationally molded from HDPE PCR/virgin resin blends will be influenced by the type of HDPE PCR in the blend. Since some HDPE PCR is green (PCR based on HDPE copolymers), rotational molding resins made with these resins have a green tint. Other HDPE PCR is gray with black specks. Thus, parts rotationally molded from blends made with some HDPE PCR have an off-white color.

Compared to the virgin LLDPE resin, the toughness of HDPE PCR/virgin resin blends is much less, decreasing as HDPE PCR content increases.

The environmental stress crack resistance (ESCR) of HDPE PCR/virgin resin blends is considerably lower than that of the virgin polyolefin resin.

The physical properties, including impact strength and ESCR, of rotational moldings made from HDPE PCR/virgin resin blends, as well as many other rotational molding resins, can be dramatically improved using electron beam cross-linking.

Adhesive polyethylene grades can form a liner on the inside of metal pipe (called rotolining) and form a tie-layer between two resins that are rotationally molded.

NYLON

Nylon, which is used in its pellet form rather than as a powder, offers good heat resistance, toughness, good wear and abrasion resistance, high strength and stiffness, and good chemical resistance. Nylon pellets may require drying immediately before they are rotationally molded. To prevent discoloration and to achieve optimum properties, inert gas (nitrogen or carbon dioxide) is injected into the mold. Nylon is rotationally molded at 550–700˚F (288–371˚C). Typically, a nylon part 0.125 in. (3.2 mm) nominal wall thickness has a molding cycle of 15–20 minutes.

A liquid nylon monomer can be rotationally molded. The liquid polymerizes during heating. For larger parts, optimum wall thickness and surface appearance can be achieved using a two-shot molding process.

POLYCARBONATE

Key benefits of polycarbonate rotational molding resins are high-heat resistance, good impact strength and clarity, and more dimensional stability than polyethylenes. Polycarbonate resins must be dried immediately before they are rotationally molded. Typically, polycarbonates are rotationally molded at 680–700˚F (360–375˚C) and cycle times range from 10–20 minutes. Part shrinkage in the mold is less than 1%; therefore, draft is needed for all walls.

POLYPROPYLENE

Polypropylene rotational molding resins offer higher heat resistance and stiffness than polyethylenes. Typically, polypropylenes are rotationally molded at 500–550˚F (260–288˚C) and cycle times range from 18–28 minutes.

VINYL

Both powder and liquid vinyl rotational molding resins are available. Vinyl plastisols are liquid rotational molding resins that offer a wide range of stiffness, from very soft (low durometer) to very rigid (high durometer).

Plasticizer level determines the properties of vinyl plastisols. Vinyl plastisols generally are rotationally molded at 450–480˚F (232–249˚C) and molding cycles are 5–10 minutes. Rotationally molded vinyl plastisol products are easily painted.

ADDITIVES

With the exception of colorants, rotational molders generally do not prepare their own compounds. Resins that contain the required additives are purchased from materials suppliers.

Colorants

Powdered colorants can be added to rotational molding resin powders and then dry blended. Precolored powders are available, as are precolored resins in pellet form, which are ground into powder.

Antistatic Agents

For some powders, antistatic agents can improve material flow during processing. Antistatic agents also reduce static buildup on the surface of molded parts.

Cross-linking Agents

Chemical cross-linking agents, most often a peroxide, can improve strength and ESCR.

Fillers

Fillers provide added stiffness, but their use can cause processing problems, including surface roughness and reduced melt flow and impact strength.

Flame Retardants

Flame retardants allow use of rotational molding materials for electrical applications covered by Underwriters Laboratories (UL) requirements.

Flow Modifiers

Complex mold designs use flow modifiers to improve polymer flow and to achieve complete and uniform filling of the mold.

Foaming Agent

When heated, rotational molding powders that contain a foaming agent generate a gas and, thus, foam the material.

Glass Fibers

Although they improve strength and stiffness, glass fibers can cause processing problems, including surface roughness and reduced melt flow.

Heat Stabilizers

Thermal degradation is prevented during processing by using heat stabilizers. Rotational molding materials contain higher levels of heat stabilizers than resins used by other plastic processing methods.

Impact Modifiers

Most notably for elastomers, impact modifiers increase impact strength, but their use can cause processing problems, including surface roughness and reduced melt flow.
Release Agents
Internal release agents, that is, release agents mixed with the resin, include both stearates (fatty esters) and fatty amides. Internal release agents can eliminate or reduce the need for external release agents, but they also can affect mechanical properties of the rotational molding material and cause discoloration.

UV Stabilizers
Materials such as polyolefins require UV stabilizers, such as hindered-amides-light stabilizers (HALS), to protect them from the effects of sunlight.

DESIGN GUIDELINES

The following design recommendations refer to polyethylene rotational molding.

ANGLES
The minimum recommended angle is 30˚.

CORNERS
Outside corners generally have thicker walls than the nominal wall thickness of a part and inside corners generally have thinner walls. The radius for outside corners should be no less than 0.060 in. (1.5 mm) and, ideally, they should be 0.250 in. (6.4 mm). The radius of inside corners should be no less than 0.125 in. (3.2 mm) and, ideally, they should be 0.500 in. (12.7 mm).

DRAFTS
An advantage of rotational molding is that parts often are made with no draft angles because when the part cools, it shrinks away from the cavity. However, if there are mold surfaces inside the part, such as the core of a doughnut shaped part, draft angles of one to two degrees are necessary.

FLATNESS
Typically, a flatness tolerance for rotationally molded parts is +0.020–0.050 in./in. (+0.020–0.050 cm/cm).

HOLES
Large holes are formed during rotational molding or are made by machining. Molded-in holes are achieved by using inserts to which the plastic melt does not adhere. Also, holes are made by rotationally molding two identical parts end-to-end and then cutting them apart.

INSERTS
If metallic inserts are heated, the molten polymer’s surface adhesion is increased. Inserts should have undercuts to increase holding strength. The shrinkage that occurs during part cooling provides good gripping strength; however, it is important to avoid stress cracking.

MULTIWALL PARTS
An adequate distance between parallel walls in double-wall parts is five times the nominal wall thickness.

RIBS/BOSSES
Stiffening ribs and bosses are not designed as solid elements; they must be hollow. Rib/boss depth is at least four times the nominal wall thickness and the width at least five times the nominal wall thickness. While rounded ribs/bosses are better for material flow, rectangular-shaped ribs/bosses provide more stiffness.

Kiss-off ribbing, where two closely spaced walls are attached to each other, is a unique capability of rotational molding. Kiss-off ribbing counters warpage in large flat surfaces and provides added stiffness.

TEXTURED SURFACES
Draft angles are necessary for textured surfaces on the inside surfaces of rotational moldings. The draft angle is 1˚ more than the draft angle for an untextured part.

THREADS
Inside and outside threads are possible with rotational molding, but coarse forms of acme or modified buttress type threads with a thick profile are used.

TOLERANCES
Because of the shrinkage that occurs during part cooling, close tolerances are not recommended for rotationally molded parts. Although tolerances of ±0.010 in./in. (±0.010 cm/cm) are possible using special cooling fixtures, ideal tolerances are ±0.020 in./in. (±0.020 cm/cm).

UNDERCUTS
Small external undercuts are possible with rotational moldings if the material is flexible enough to allow stripping of the part from the mold cavity. Internal undercuts are not recommended since the part shrinks onto the mold as it cools, making part extraction very difficult.

WALL THICKNESS
The basic nature of the rotational molding process produces uniform wall thickness. Depending on part size and shape, a wall thickness tolerance of ±20% is generally recommended. A lower tolerance may require special processing procedures and add to part cost. Nonuniform wall thicknesses are achieved by altering the mold temperature, using inserts, or mold shielding in areas where the variance is desired.
SECONDARY FINISHING

Secondary finishing procedures are determined by the type of rotational molding material rather than the process.

DECORATING/PAINTING

There are many techniques for decorating rotationally molded parts including painting, hot stamping, silk screening, and labeling. Surfaces of polyolefin parts that are decorated or painted are oxidized by flame treatment or electronic treatment to achieve optimum adhesion. Adhesion also is improved by using surface primers either alone or with oxidation.

U.S. federal legislation is causing rotational molders to use water-borne coatings for their products. The two-step coatings (base coat and top clear coat) are available in a wide range of colors. Both airless and/or conventional air spray equipment are used with the water-borne coatings. Air drying for five to 20 min at 175 to 250˚F (79–121˚C) is recommended to enhance gloss and shorten production cycles.

ELECTRON BEAM CROSS-LINKING

Secondary cross-linking involves exposing the molded parts to electron beams. With electron beam cross-linking (EBXL), the degree of cross-linking is controlled; therefore, the level of property improvements is controlled. With EBXL, reject parts are recycled before they are subjected to the EB treatment. Thus, scrap losses are reduced compared to chemical cross-linking.

Another benefit of EBXL is that, unlike chemical cross-linking agents, it does not affect the U.S. Federal Drug Administration (FDA) status of a rotational molding resin. The ability to make parts that have excellent ESCR and that can meet FDA requirements makes EBXL very attractive for molding food handling products.

An EBXL facility is cost prohibitive for most rotational molders. However, electron beam cross-linking equipment is available on a tolling basis.

FOAM FILLING

In a secondary operation, rigid polyurethane (PUR) foam is injected through small holes, into the hollow space between the walls of rotational moldings. The PUR foam system is injected as a liquid and after it has risen and set, the holes are sealed with caps made of the same material as the rotational molding. The foam core adds stiffness and structural strength. Further, for products such as boat hulls, the PUR foam provides permanent buoyancy if the polyolefin skin is punctured or cut.

MACHINING

Rotationally molded parts can be drilled, sawed, milled and routed. Machining conditions will vary according to the rotational molding material.

WELDING

Various types of welding techniques are used with rotational moldings, including hot-plate welding, electromagnetic/induction welding, spin welding, hot-gas welding, thermal welding, and extrusion welding.

Hot-plate Welding

Hot-plate welding consists of holding two surfaces against a hot-plate long enough to heat and soften the joint and then forcing the two pieces together until the joint has cooled. Joints must be flat.

Electromagnetic/Induction Welding

A magnetically active material and an oscillating electromagnetic field are used to produce a weld. The magnetically active material is applied to the joint and then briefly exposed to the electromagnetic field by a set of conductive coils through which alternating current runs. Fusion temperatures are reached rapidly. The magnetic material melts and flows, filling the joint, and transfers the heat by conduction to the abutting surfaces, fusing them together. Long joints are quickly welded and joints can be in more than one plane.

Spin Welding

Frictional heat caused by rapidly spinning one surface under pressure against another is used to melt the interface and cause the two surfaces to bond together.

Hot-gas Welding

Hot-gas welding consists of beveling the edges of two parts that are joined, bringing the two edges together to form a groove, and laying and pressing a hot bead of thermoplastic into the groove. While inexpensive, this technique produces welds with uneven strengths and typically low bond strengths.

Thermal Welding

Hot-melt adhesive guns are used to apply a molten bead between two surfaces that are joined.

Extrusion Welding

Extrusion welding is similar to hot gas welding except it uses a hot-melt applicator (extruder) to apply the molten bead of thermoplastic into the groove between two surfaces that are joined.

TROUBLESHOOTING

Solutions to rotational molding problems will vary from material to material. Following are some general guidelines.

BLOW HOLES AT PARTING LINE

- Mold parting lines not clean—clean and coat with mold release.
- Poor mold parting line—repair mold.
- Plugged vent—replace vent.

BLOW HOLES AROUND INSERTS

- Material not fully adhering to insert—change insert and/or location.
- Air leakage around the insert—stop the leakage.

BLOW HOLES IN OTHER AREAS OF PART

- Impurities on mold surface—clean mold surface.
CHAPTER 10

TROUBLESHOOTING

- Poor blending of fillers or reinforcement—change blending method and/or procedure.

BUBBLES ON SURFACE OR IN PART
- Incompatible mold release—change mold release.
- Poor mold parting line—eliminate pockets of entrapped air.
- Inadequate venting—relocate vent. Increase vent size.

DISCOLORATION OF PART
- Oxidation on mold surface—clean mold surface and check for moisture source.
- Sintering cycle too long—reduce oven heat and/or shorten cycle.
- Resin degradation—decrease oven temperature or heating cycle. Increase or change antioxidant. Change to more thermally stable pigment.

FLASHING AT PARTING LINE
- Internal mold pressure during heating cycle—check for vent clogging. Reduce the air pressure. Relocate the vent. Increase vent size.
- Insufficient clamp pressure—increase clamp pressure or type of clamp used.

INCOMPLETE MOLD FILL
- Poor mold design—increase space between walls and corner radii and change rib design. Consider using mold inserts.
- Improper mold rotation—change ratio and speeds.
- Cold spots in mold—check for shielded areas and mold wall thickness uniformity.
- Poor powder flow—change powder particle size and/or add flow modifier.

INCOMPLETE FUSING OF MATERIAL
- Low-oven temperature—increase oven temperature.
- Poor heat transfer—use thinner mold wall thickness and/or change mold material.
- Resin powder too coarse—use finer mesh powder.
- Moisture in mold—keep molds warm and dry before charging with powder.
- Moisture in resin—dry resin before molding.
- Melt index of resin too low—use resin with higher melt index.
- Improper mold rotation—change ratio and/or speed of rotation.

LOW-IMPACT STRENGTH
- Parts improperly sintered—increase or decrease oven temperature and heat cycle.
- Improper pigment loading—change type of pigment and/or reduce pigment loading.
- Parts improperly cooled—change cooling cycle.
- Insufficient fusion of resin (see “Incomplete Fusing of Material” in this section).

LOW-PART STIFFNESS
- Wall too thin—increase powder loading.
- Poor resin choice—change resin.
- Material underfused (see “Incomplete Fusing of Material” in this section).
- Poor design—change part design.

LONG-OVEN CYCLE
- Poor heat transfer rate—reduce mold wall thickness or change mold material.
- Poor heating—increase air velocity, check oven for leaks, check oven temperature sensor and recalibrate or replace.
- Resin powder too coarse—use finer mesh powder.

MOLD BULGING
- Gas build-up in mold—relocate vent or use multiple vents.

PART STICKS IN MOLD
- Insufficient mold release—apply mold release more often and/or change application method.
- Ineffective release agent—change type of release agent.
- Mold surface roughness—refinish mold surface.
- Build-up of degraded resin on mold surface—periodically clean mold surface.
- Part shrinking onto mold surfaces—increase vertical wall tapers.
- Material too stiff to release from mold undercuts—change material or reduce undercuts.
- Material shrinkage too low—use higher density resin.

PLATE-OUT
- Additives building up on mold surface—change additive.

POCK MARKS ON PART
- Improper heating cycle—reduce heat and/or cycle time.
- Improper mold release—change mold release.

UNEVEN COLORING
- Moisture in pigment or resin—dry color blend before processing.
- Static build-up—use resin that has an antistatic agent.
- Insufficient blending—change dry blending procedure or type of equipment used.

WALL THICKNESS UNEVEN
- Improper mold speed and rotation ratio—adjust speed and ratio.
- Uneven mold surface temperature—change wall thickness. Check for shielded areas. Use inserts with high heat transfer.
- Mold arm improperly balanced—rebalance arm.
- Fusion rate too fast—lengthen heat time and lower mold temperature.

WARPING OF PART
- Inadequate venting—increase vent size.
- Nonuniform part cooling—rotate mold during cooling cycle. Use less release agent. Reduce cooling rate during initial part of cooling cycle. Apply air pressure inside part during cooling. Increase cooling medium temperature.
- Uneven mold wall thickness—redesign mold.
- Parts of mold are shielded—change how mold is mounted to arm. Add baffles to direct heat to recessed or shielded areas.
- Part overcured—decrease oven temperature or heating cycle.
- Part underfused (see “Incomplete Fusing of Material” in this section).
- Powder contains moisture—dry powder or change drying procedure.
• Improper coloring—change pigment type and/or loading level.
• Vacuum in part during cooling—check vent for clogging. Increase vent size.

Table 10-2 shows the appearance of rotationally molded parts at different cures. The information may not relate to all resins.

**Table 10-2**

<table>
<thead>
<tr>
<th>State of Cure</th>
<th>Under</th>
<th>Slightly Under</th>
<th>Cured</th>
<th>Slightly Over</th>
<th>Over</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside surface color</td>
<td>Same as outside surface</td>
<td></td>
<td></td>
<td>Slightly yellow</td>
<td></td>
</tr>
<tr>
<td>Inside surface gloss</td>
<td>Dull</td>
<td></td>
<td>Shiny</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside surface appearance</td>
<td>Rough</td>
<td>Waxy</td>
<td>Smooth</td>
<td>Slightly sticky</td>
<td>Sticky</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>not sticky</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bubbles</td>
<td>Many</td>
<td>Few</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fill</td>
<td>Less than best to best</td>
<td>Best</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tear resistance</td>
<td>Less than minimum</td>
<td></td>
<td>Maximum</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**INDUSTRY ASSOCIATION**

The rotational molding industry is represented by the Association of Rotational Molders, 2000 Spring Rd., Suite 511, Oak Brook, IL 60521 (Telephone (708) 571-0611). ARM is the major source for distributing technical literature and educational material about rotational molding. In addition, ARM annually conducts a technical conference and an exhibition at which the latest developments in rotational molding are displayed.
CASTING

ACRONYMS

BMC Bulk molding compounds.
MEKP Methyl ethyl ketone peroxide.
MEK Methyl ethyl ketone.
NCO Nitrogen-carbon-oxygen.
PETG Polyethylene terephthalate glycol.
PMMA Polymethyl methacrylate.
PVA Polyvinyl alcohol.
PVC Polyvinyl chloride.
rpm Revolutions per minute.
RTV Room temperature vulcanized.
SMC Sheet molding compounds.

GLOSSARY

acrylics A class of polymers based on various forms of acrylic acid and its esters. One of the most important acrylics polymers is polymethyl methacrylate which is produced by polymerizing the methyl ester of methyl acrylic acid.
amine An organic derivative of ammonia in which the ammonia protons are formally substituted with organic groups.
b-stage Same as gelation.
blushing The formation of a whitish discoloration which appears on plastics articles that are highly stressed, or where water absorption (especially in glass reinforced polyesters) occurs. It appears most frequently in periods of high humidity.
casting The formation of a plastics material in a mold, with subsequent hardening or curing in only atmospheric pressure. The most common casting resins include polyesters, epoxies, and acrylics.
catalyst A substance that causes or accelerates a chemical reaction without being permanently affected by the reaction.
cross-link Applied to polymer molecules, the setting up of covalent chemical bonds between the molecular chains. When extensive, as in most thermosetting resins, cross-linking makes one infusible super-molecule of all the chains. Cross-linking can also be achieved by irradiation with high-energy electron beams or by means of chemical cross-linking agents such as organic peroxides.
cure, curing The hardening process by chemical action or to heat-set a resin. Curing is the process during which polymerization to insolubility takes place binding each of the elements. The term is generally used to refer to thermosetting resins and certain cast thermoplastics materials.
e-beam, electron beam Irradiation by beta or gamma rays which serves as a catalyst to certain resins of both classes without the addition of chemical substances.
ebidentment Encasement of an object in a given mass or sheath of plastics material. Embedments are usually decorative in nature and are always cast or molded in a transparent plastics material. Embedments can be medical, biological, or industrial as well as purely aesthetic. Electrical units thus treated are termed encapsulated; electrical or electronic units, if encapsulated in opaque plastics, are referred to as potting.
epoxy Generic name for a group of thermosetting resins that originally included products made by the condensation of bisphenol and epichlorohydrin, but which now are also made by other means. Uncured epoxy resins are characterized as having two or more epoxide groups (or oxirane groups) per molecule.
etejectic alloys Combinations of metals that are easily fused or will fuse at the lowest possible temperature. It is an alloy with a melting point lower than any other combination of the same components.
exotherm The quantity of heat generated during the course of chemical reactions that evolve heat. Polymerization reactions are usually exothermic reactions.
filler(s) Inert materials added to plastics for added bulk, shrinkage control, or modifying physical properties.
gel The initial jelly-like solid phase that develops during the formation of a resin from a liquid. In this form, the resin has very low strength and does not flow like a liquid. It is soft, flexible, and will rupture under its own weight unless externally supported.
gel coat In reinforced plastics, a thin outer layer of resin, sometimes combining pigments and/or fillers, that provides the structure with a surface gloss and/or finish. It also serves as a barrier to liquids and ultraviolet radiation. In thermosetting

The Contributor of this chapter is: Armand G. Winfield, Director, Training and Research Institute for Plastics, The University of New Mexico, Albuquerque, NM.
The Reviewers of this chapter are: David E. Thompson, PhD, Chair, Mechanical Engineering, The University of New Mexico; J. Shield Wallace, PhD, Senior Scientist, Professional Analysis, Inc., Albuquerque, NM.
molds, it is a strength-finish layer over which mold releases are applied prior to lay-up or spray-up of parts.
gelation The formation of a gel.
glitter A gilded or silvered crushed mica flake used to add sparkle to transparent plastics. Glitter also is made from finely diced Mylar™ which has been gold or silver vacuum-plated.
hydrocolloid A substance capable of forming a suspension or emulsion with a liquid (in this case, water), which will not settle out to a noticeable degree and will not readily diffuse through vegetable or animal membranes. Colloidal particles are usually of high-molecular weight, ranging in diameter from about 3.94 × 10^{-7} to 0.9 × 10^{-3} in. (9.9 × 10^{-5} to 5 × 10^{-3} cm).
hydroquinone (C_6H_4(OH)_2) A white crystalline organic compound derived from aniline, used in combination with many of its derivatives as an inhibitor in unsaturated polyesters, and in monomers such as vinyl acetate and methyl methacrylates. The hydroquinones are relatively colorless and require trace amounts of oxygen in the resin to be activated.
latex/synthetic latex A stable dispersion of a polymeric substance in an essentially aqueous medium. Latexes of interest to the plastics industry are those based mainly on styrene-butadiene copolymers, polystyrene and vinyl polymers, and copolymers. In the case noted in this chapter, the latex closely resembles rubber.
melted in an essentially aqueous medium. Latexes of interest to the plastics industry are those based mainly on styrene-butadiene copolymers, polystyrene and vinyl polymers, and copolymers. In the case noted in this chapter, the latex closely resembles rubber.
melamine Common name for melamine-formaldehyde, one of the amino plastics and compounds. It is an amino-type thermosetting resin made by the condensation of melamine (the amide of cyanuric acid) and formaldehyde. Alpha-cellulose filled melamines are widely used for dinnerware.
monomer A relatively simple chemical compound capable of reacting with like or unlike compounds to form polymers.
phenolics Resins produced by the condensation of a phenol with an aldehyde, particularly of phenol with formaldehyde.
poly(methyl methacrylate) (PMMA) A thermoplastic polymer produced by the polymerization of a methyl methacrylate monomer. It is used to make molding compounds for casting. It has exceptionally good optical properties and can be made in a wide range of transparent, translucent, and opaque colors. Clear, it can be used for embedding or for optical components.
polyester, unsaturated polyester A reactive plastic product formed by the esterification reaction between polyhydric alcohols and polybasic acids. This indicates a large class of materials known as polyester or alkyd resins. Polyesters in this chapter refer to unsaturated polyester base resin dissolved in a copolymerizable monomer.
polymerization A chemical reaction in which the molecules of a monomer are linked together to form high molecular weight molecules.
resin A solid or semisolid amorphous organic compound or mixture of such compounds with no definite melting point and no tendency to crystallize; a common name applied to most uncured thermosetting liquid materials. Most resins are polymers.
syntactic foam Foamed materials made without the use of foaming agents. In the case of the foams herein described, the air cells introduced into the resins are those made of glass or plastic micro-balloons. They are most commonly used with epoxy or polyester resins. They can be cast in molds, troweled onto a surface, or incorporated into laminates. After forming, the mass is cured with a catalyst and heat.
thermoplastics A family of plastics capable of being repeatedly softened by heat and hardened by cooling. These include such commonly known plastics materials as acrylics, cellulosics, vinyls, polyethylene, nylons, etc.
thermosets Same as thermosetting plastics.
thermosetting plastics A family of polymers that will undergo, or has undergone, a chemical reaction by the action of heat (generated by a catalyst), light, ultraviolet, irradiation, etc., which has resulted in chemical cross-linking of the system. Once this change has taken place, the plastics become infusible and insoluble. These plastics include polyesters, epoxies, phenolics, alkyls, melamines, ureas, silicones, and polyurethanes.
tripoli A light porous rock—white, gray, pink, red, or yellow in color—consisting of weathered chert and siliceous limestones. It is used to make polishing compounds and abrasives. For plastics, it is known as a hard, somewhat greasy dark brown compound available in 1-2 lb (0.45-0.9 kg) cake forms.
vacuum forming A method of sheet forming in which a thermoplastic sheet is first clamped into a frame, heated, then finally drawn into or over a mold by vacuum below and atmospheric pressure above the sheet.
water-white A low-viscosity, exceptionally clear and colorless unsaturated polyester, epoxy, or acrylic resin used in casting, embedding, or decorative laminating. Water-white can also refer to any clear, colorless organic material. It does not necessarily have to be a plastics.

## THE CASTING PROCESS

Casting is one form of conversion for plastics materials, both thermoplastics and thermosetting plastics or thermosets. It is a form of conversion that is probably among the least understood and least used techniques. Casting usually, but not always, refers to open mold, gravity flow processing, with or without heat and/or pressure. Although it appears simple and easy to accomplish, casting can be one of the most difficult, complex, and sophisticated types of molding. Each part cast is usually different from previous ones and each has its own inherent problems attendant to its specific size and mass. Casting can be as much an art as it is a science.

### WHAT CAN BE CAST

There are relatively few plastics materials that can be cast, the most frequently used are shown in Table 11-1:

<table>
<thead>
<tr>
<th>Material</th>
<th>Casting Materials</th>
<th>Year Introduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylics*</td>
<td></td>
<td>1936</td>
</tr>
<tr>
<td>Unsaturation polyester**</td>
<td></td>
<td>1942</td>
</tr>
<tr>
<td>Polystyrenes</td>
<td></td>
<td>1938</td>
</tr>
<tr>
<td>Epoxies**</td>
<td></td>
<td>1947</td>
</tr>
<tr>
<td>Silicones**</td>
<td></td>
<td>1943</td>
</tr>
<tr>
<td>Elastomeric polyurethanes**</td>
<td></td>
<td>1954</td>
</tr>
</tbody>
</table>

*Acrylics are a class of many different polymers based on various forms of acrylic acid and its esters. It is often used interchangeably with PMMA (polymethyl methacrylate).
**Thermosets.
These materials are usually converted by more traditional methods: acrylics or polymethyl methacrylates and polystyrenes can be injection molded, extruded, blow molded, thermoformed, rotationally molded, fluid-bed molded, calendared, coated, or fabricated. Thermosetting phenolics, silicones, and elastomeric polyurethanes can be compression or transfer molded. Unsaturated polyesters are converted by hand lay-up and by spray-up while the epoxies can be layed up or autoclaved with glass and/or carbon fibers to produce structural parts. Some silicones are room temperature vulcanized (RTV) to process while others cure from moisture in the atmosphere.

CASTING ACRYLICS

THE OLD METHOD
Casting acrylics in years past was a long and cumbersome process. Acrylics shrink 15% volumetrically and molds were a critical part of the process. In the initial Winfield process, acrylic monomers were filled with acrylic low-molecular-weight polymers (powders) until a white “dough” was produced. This was first laid as a thin layer in the bottom of the mold. Then the embedded item was laid on the viscous dough and covered with a top layer of the polymer-monomer mass. The mold was then closed. As the mass in the mold was curing and shrinking, springs in the mold expanded and held the mold closed with constant pressure during the heating/curing cycle. Curing was done in cauldrons of boiling water and could take two or more hours to cure depending upon the thickness of the part. The process was limited to thicknesses of less than 1 in. (2.5 cm) and in sizes not exceeding approximately 4 in. (10 cm) wide and 10 in. (25 cm) long.

ACRYLICS CASTING TODAY
Acrylics casting is done using either new or primitive techniques. Cast sheet, rod, and tubing are still done the old way: a methyl methacrylate monomer is usually inhibited with hydroquinone to prevent polymerization at ambient temperatures. The inhibitor must be removed to allow for necessary curing. Removal is accomplished by chemically trapping the inhibited monomer by pouring through an activated alumina column. After completion, the monomer can be polymerized by heat without pressure.

MAKING AN ACRYLIC SHEET
To make a sheet of transparent acrylic 4 ft × 8 ft × 0.25 in. in thickness (1.2 m × 2.5 m × 0.63 cm), two oversized pieces of tempered glass are used, each sheet being approximately 5 ft × 9 ft (1.5 m × 2.8 m).

Around three of the four edges, a bead of caulking or mastic is placed between the outer edge of the glass and the line marking the area of the cast sheet, allowing for both shrinkage of the acrylics and the uneven edge of the caulking (Fig. 11-1). Stops are placed appropriately which are 0.25 in. (0.64 cm) thick plus appropriate allowances in thickness to accommodate shrinking of the acrylics. This guarantees the thickness of the sheet and precludes the void being less than the desired thickness.

The caulking moves and forms an uneven edge around the periphery because of pressure from the weight of the tempered glass and resin. Because of this, the finished sheet is made oversized so the sheet can be trimmed to exact size.

When caulking and stops are in place, the second sheet is appropriately placed over the first one, locking the caulking and stops in place. Clamps are now placed around the edges every 3 or 4 in. (7.6 or 10 cm) to ensure tightness to the caulking and preclude leaking. The clamps must be covered at contact points on the glass to avoid fracturing the glass. The top edge (dotted line in Fig. 11-1) is left open so the monomer can be poured into it (Fig. 11-2) and air bubbles can escape.

Depending on the circumstances, this area is left open if the sheets are stored upright during curing; or, after air is evacuated, a mastic is forced down between the glass, sealing it so the sheet can be cured in the horizontal position; or the mastic is applied on all four sides and the monomer is poured in the horizontal position, after which an upper glass plate is brought down over the monomer. As pressure is applied, the trapped air is forced to the periphery where it is eventually removed by trimming after curing.

The filled sheets are placed in ovens where the temperature is set at approximately 220˚ F (104˚ C) and left to cure. Depending upon the thickness of the sheet (which may vary in thickness from 0.125-4 in. [0.3 to 10 cm]), the time in the ovens can vary from hours to days or several weeks in the thickest sections.

TUBES AND RODS
Tubes and rods are made by filling long glass or metal tubes. Appropriate cores produce tubes while rods are made without cores.

After the cure is completed and the cross-linking and cooling have taken place, the glass is removed and a pressure sensitive cover sheet is applied to both cast acrylics surfaces to avoid scratching or marking (acrylics will not stick to the glass or to
highly polished or plated metal surfaces, eliminating the use of mold releases). The sheet is then cut to the required size. Tubes and rods are not usually covered and must be treated with care.

Regardless of whether the embedment process continues to use the dough method, or whether unsupported, uninhibited monomers are used, autoclaving is the accepted mode of curing.

AUTOCLAVES

Autoclaves are large, heavy-walled, round, tubular metal chambers in which inert gases can be introduced with heat and pressure. When open molds are used with the acrylics, nitrogen is used as the inert gas to avoid air inhibition during the curing cycle. Appropriate temperatures of about 220°F (104°C) and pressures of 100-300 psi (689-2068 kPa) are generated to produce an even specimen cure from approximately ½ in. (1.9 cm) in thickness up to 5 or 6 in. (12.7 or 15 cm) or more. The open mold is commonplace in this type of casting and can be made of metal, glass, or plaster, but mold releases are required with the latter.

Artists are creating cast-acrylic sculptures up to 15 ft (4.6 m) or more in length and weighing several tons. This work is done in very large and expensive autoclaves. Size and weight are no longer restrictions to the process, which guarantees a crystal-clear piece regardless of size and having a light transmission of over 92%. Curing times, however, are dependent upon the mass, and as the mass increases, more time is required for curing.

Acrylics made in multiples, in large sheets, or masses containing a number of individual pieces, need separating following the curing and polishing process and after shaping to guarantee its unique look. Special oil-lubricated saws should be used to preclude gumming.

POLISHING

Acrylics polishing, as in the case of the water-white unsaturated polyesters, requires many individual steps:

1. For rough surfaces that need to be reduced, file or scrape with a single-edged razor, using the blade perpendicular to the surface.
2. Use wet or dry sanding sheets or sandpapers designed for use with metals or other extremely hard surfaces. Start with a 60 grit, the next successive grits to use are 100, 220, 360, 400, 560, and 600.
3. The part should feel very smooth to the touch.
4. Begin polishing with a series of buffing wheels at speeds considerably slower than those used for metals. Metal wheels usually run at speeds of 3,400 revolutions per minute (rpm); to prevent plastics burn, wheels must not exceed 1,750 rpm.
5. Rough buffing is next. Use a stitched muslin buff, which is a hard fibered cloth, and apply tripoli to cut the plastics surface.
6. Polishing is a series of very fine scratches on the surface of the part. The finer the scratch, the higher the polish or finish, as these tiny scratches reflect light in a continuous pattern. After the rough buffing, use a stitched flannel buff with a white compound for a final polish; often this polish is pink, indicating a small amount of jeweler’s rouge has been added to it. This polish will bring out the ultimate beauty of the part.
7. Finally, coat the polished surface with white carnauba wax and rub with a very soft cloth or facial tissue to produce the final high polish.

The number of steps can vary from a minimum of six up to nine or ten. If only an edge needs polishing, acrylics can be “flame polished.” This is done with an open torch applied to the edge's surface. It melts the rough segments of the saw-cut into a smooth flowing surface. As noted, these same steps should be followed (except for flame polishing) with the cast unsaturated polyesters, some epoxies, and cast polystyrenes.

POLYSTYRENE CASTINGS

Polystyrene can also be obtained as a monomer which is inhibited with 4-tert-butyl-catechol. Like the acrylic monomers, this can be removed by pouring through an activated alumina column. The inhibitor can also be removed by careful distillation.

Polystyrene is less expensive than the acrylics and has almost the same inherent transparency characteristics as acrylics, with three prime exceptions: polystyrenes are not good outdoor materials which precludes their use in glazing and fenestration. It is also brittle and fractures more easily than the acrylics. Finally, polystyrenes do not have that unique phenomena called edge lighting or even the high percentage of optical clarity as acrylics. Styrenes can be used for optical fibers; the phenomenon applied to this plastics is noted as wave guiding. For these reasons, polystyrenes have never become popular casting or embedding resins. Moreover, they can exhibit some milkiness in their appearance when compared to the acrylics and will also yellow from exposure to ultraviolet rays.
POLYESTER CASTINGS

The most popular, inexpensive, and easy to use of the casting materials is unsaturated polyesters or polyester resins. They are considered a thermosetting plastics and are used as a two-part system (resin and catalyst) that when combined, goes through a gel or b-stage, into its exotherm and full cure stage, and finally cools to ambient temperature.

Water-white resins that are almost as clear as acrylics can be purchased today as well as “mass cast” resins which can be poured in very heavy sections without cracking. Although these new resins still exhibit slight color casts toward blue, red, pink, or yellow (if examined in very strong light), they are still superior to anything produced in the past. However, typical of unsaturated polyesters, they have a tendency to darken with age and exposure to strong light, in spite of masking and ultraviolet inhibitors.

CATALYSTS

Unsaturated polyesters are cured or cross-linked by the addition of a wide range of percentages of catalysts which include methyl ethyl ketone peroxide (MEKP), the most popular and easy to use; benzoyl peroxide, a high-temperature catalyst used with sheet molding compounds (SMC) and bulk molding compounds (BMC); hydrogen peroxide, used when a long b-stage is required and eventually cured by postheating; and cumene hydroperoxide, which can be used as a substitute for most of the others.

The catalyst starts the cross-linking or curing process, then evaporates out of the resin without becoming a part of the compound except in cases where catalysts contain metal and are not volatile. Electron beam (e-beam) curing, a by-product of atomic radiation, is in its infancy and precludes the use of the catalyst entirely.

CATALYSTS AND HEAT

In any catalytic reaction, there are several important factors that must be considered, especially in the casting field.

Any such reaction causes heat, and as the amount of catalyst is increased, heat increases from the exothermic reaction in the resin mass. Thus, to make a successful casting, as the mass is increased, the percentage of catalyst is decreased. Likewise, a thin-walled casting or a smaller mass requires a greater percentage of the catalyst. In all cases, the percentage of catalyst range, by weight, is from 0.2-2.0% or more. The ambient temperatures also play a similar role: the hotter the ambient temperature, the lower the catalyst percentage and vice versa.

Where the resin mass is large, another technique can be used to reduce potential resin cracking: flexible polyester resins can be added up to approximately 15-20% by weight, though often as little as 5-10% will suffice. Modifying the resin is another way to reduce cracking.

In general, castings, and especially polyester castings, require much experimentation for success.

CALCULATE THE WEIGHT

When venturing into castings, be sure to first calculate the weight of the casting. Mass can be deceiving: unsaturated polyesters have a specific gravity of 1.21 to 1.23. A gallon (3.8 L) weighs approximately 8.5 lb (3.8 kg), a cubic inch (16 cm³) about 1.25 ounces (0.04 kg), and a cubic foot weighs 78 lb (35.3 kg). A casting 4 in. × 6 in. × 4 in. weighs 5.06 lb (2.3 kg); a casting 4 in. × 6 in. × 12 in. weighs 22.75 lb (10 kg) and a casting 12 in. × 24 in. × 36 in. weighs 819 lb (372 kg).

CATALYZATION CONSIDERATIONS

Several important factors must be considered when catalyzing large masses of resins:

- Catalysts can be reduced from the normal, rule-of-thumb amount of 2% by weight to as low as 0.01%. The very low amounts of catalyst, however, retard the curing process and much more curing time must be allowed. Postcuring is also recommended after a total cure has taken place.
- On some very large pieces in areas where seam lines are not an issue structurally or aesthetically, casting can be done in sections and joined with catalyzed resin.
- On very large castings, what has been termed as drop cataly- sis can be used. In this process, the catalyst is added to the mass in drops, below the 0.01%. Sometimes only a single drop is used. Curing will be very slow—days, weeks, even months—but no cracks will occur.
- On large castings, and even on critical smaller ones, external cooling techniques can be used to retard the exothermic reaction. Such techniques include refrigerating the casting, cooling the mold by flowing cold water around it, or floating the mold in water. After gelation, an open molded part can be totally submerged in cold mineral oil or in cold water. Ice packs can also be used around the molded part.

Mineral Oil for Air Inhibition and Lube

Clear, water-white medical grade mineral oil is a good cover on open mold polyester castings or on any resin that is air inhibited during curing. The mineral oil has low viscosity, is essentially transparent, and is not compatible with the resin so it will not become a part of the casting. Also, as the polyester shrinks, the thin oil will run down between the part and the mold wall, making it easier to remove from the mold when the part has cured.

When breakaway-glass molds are used, especially those with globe shapes and small pouring apertures, an oil cover (which will eventually flow on all surfaces) makes it considerably easier and safer to remove as the glass mold is broken.

Air Entrapment

Air entrapment is another concern in casting. To counter the problem in small castings, the resin can be heated prior to catalysis and pouring. The heating makes the resin less viscous and will allow any entrapped air to rise to the surface. If the resin is viscous and a low amount of catalyst is added, the air will have time to rise to the surface before gelation takes place. Sometimes it is better to degas the resin in a vacuum chamber prior to pouring. While this does not remove all of the air from the resin, it does remove a substantial amount. When bubbles come to the surface of a resin, they will break spontaneously or can be broken with a wooden tongue paddle or a toothpick. Also, in embedment work, air can easily get trapped in or around the embedded part and spoil it. With a hollow or porous embedded part, presoak the part in thin oil will run down between the part and the mold wall, making it easier to remove from the mold when the part has cured.

In embedding biological specimens, an effective procedure for embedding biological specimens is to freeze-dry the specimen, then allow catalyzed resins to soak.
and cure it. The piece can then be embedded without fear of entrapped air ruining it.

**Color**

Another phenomenon of large castings to be alert to is that of inherent color. The polyester resins are darker in basic coloring than the acrylics. Thus, as the casting increases in thickness, so too will the darkness of the color. In reverse, the thinner the casting, the more clear the polyester will appear.

There are ways to mask color, cleavage lines, even odor, in polyester castings. One way is to use a colored background over which the embedment is placed and cast a clear cover over it. In castings without embedments, tint the resin throughout.

**Odor**

Odor can be masked by the addition of a very small amount of an essential oil (±0.02%). Such oils are made for use in toiletries, cosmetics, and perfumes and are very concentrated scents. Some companies cater to the plastics industry and can provide oils in many scents, including pine, fruit flavors, or even leather.

**POLYESTER CASTING CASE STUDY**

Casting a religious sculpture as the model for a series of large angels is an example of the steps required in casting polyester. Each angel was to be 8 ft (2.5 m) tall with one suspended above another, two high. Two such pairs were to surround a church/chapel doorway. The castings were to simulate Murano (Venetian) glass with their inherent internal colors and gold flecking. Following completion of the necessary engineering and detailed drawings of the armatures (Fig. 11-3), a smaller prototype of one angel was made prior to casting the larger 8 ft (2.5 m) sculptures. The artist sculpted the figure and work began.

**Making the Molds and Casting**

Two molds were made. The first was taken directly from the sculpted figure but eliminated the head, hands, and feet. Only the torso with its flying robes was used. Later, similar molds were made for hands, feet, and head. A second mold was made of the torso but 1.5 in. (3.8 cm) smaller in all directions. The second, smaller mold was used to cast the core of the casting. This was done by taking acrylics molding pellets, which were translucent white, and mixing them with gold glitter and catalyzed polyester resin. The resin was used as a mastic to hold the pellets and glitter in a homogeneous conglomerate of translucent white and gold flecks. This was a reduced version of the full-scale angel and was carefully cast. Next, this cast piece was suspended in the two-piece mold of the entire torso with its flowing robes, and a resin was prepared for the outer layer. The polyester was accentuated with yellow transparent dyes to resemble the Murano glass. The resin also contained more gold glitter suspended throughout. This was then poured in the mold around the white/gold core so that it filled the void between the core and the mold surface.

The hands, feet, and head were cast with water-white resin, dyed similar to the other coating resin but with no inner core, making them appear almost crystalline when compared to the body sections. When the torso casting was completed, it was removed from the mold, cleaned and polished. The head, hands, and feet were attached to the torso using catalyzed resins.

**Finished Prototype**

The finished prototype was 4 ft (10 cm) in height and weighed 75 lb (34 kg). No internal bubbles were evident nor were any cracks or air bubbles. It was estimated that the 8 ft (2.5 m) angels would weigh at least 300 lb (136 kg) each, or a total of at least 600 lb (272 kg) per pair, plus the weight of the steel armatures holding them in position.

**Results**

This casting became a landmark piece in the development of large polyesters clear castings. Careful catalyzation made its success possible.

**EMBEDMENT/CASTING CASE STUDY**

In all of the casting techniques covered so far, the discussions have involved clear (water-white) unsupported, unfilled resins. Illustrating this process is a very large embedment/casting weighing more than 2,000 lb (907 kg) with a Christmas tree embedded in it.

**Design and Prototype**

An artist designed a hexagon column 60 in. (152 cm) tall and 26 in. (66 cm) from point-to-point of the hexagon cross-section. The embedded tree was a plain pine without lights or decorations and suspended dead center in the column.

The first step was to make prototypes. The prototypes served two purposes: first, to determine what would happen to the pine
when embedded without previous drying, since water that was entrapped in the needles might become a problem which could cause internal cracking. Secondly, the prototypes could be used to check cleavage patterns, since the column would have to be poured in sections.

At the time, there were really few, true water-white polyesters and the clearest one found had a slight bluish cast to it. A small metal mold was made about 18 in. (45.7 cm) tall and approximately 9 in. (22.9 cm) from point-to-point of the hexagon. Filled with polyester resin, the casting would weigh 45 lb (20 kg). Tree sections of appropriate size were obtained and dipped in catalyzed polyester resins to avoid needle loss and lock in moisture.

Testing the Method
The first test began with casting in layers from the base of the column upward, each layer being approximately 1 in. (2.54 cm) thick with the tree standing in the center. This casting was successful: no cracking, but the cleavage lines were very pronounced (Fig. 11-4).

The second test consisted of casting the tree in the column in one operation, but the exothermic reaction, even with substantially reduced catalysis, caused cracks in and around the tree.

The third prototype was poured against the sides of the hexagon with each flat of the six-sided configuration considered as one pouring of resin. After gelation, the hexagon would be rotated and the next flat poured. This system of pouring would continue until the casting was completed (Fig. 11-5). When the embedment stood upright, the cleavage lines were perpendicular and gave the appearance of a prism. This method was chosen for the full-scale tree embedment (Fig. 11-6).

Final Casting
The full-scale mold was made of 1 in. (2.54 cm) plywood faced with melamine formaldehyde sheeting, commonly known as Formica® or Micarta®. This would provide a hard, smooth surface and would be considerably less expensive to build than a metal mold this size. It was made oversized to accommodate the volumetric shrinkage of 6% in the unsaturated polyester resin, or a linear shrinkage of approximately 2% or about 0.25 in. per ft (2 cm/m). Allowances also had to be made in length to allow for trim, since the pouring ends would be irregular.

Determining Pour Size
A special set of horizontal rolls was constructed to accommodate the part’s weight of well over a ton. The rolls also rotated the part one-sixth its diameter for every pour. The pour size was determined to be safe at 25 lb (11 kg) in the beginning and later reduced as the pours got closer to the center. About 25 lb (11 kg) of resin spread over approximately 5 ft² (68 cm²) would be thin enough to prevent exothermic cracking. The thickness of the pours started at about 0.5 in. (1.3 cm) and built up toward the center to about 1–1.25 in. (2.5–3 cm). The embedment process required 132 pours and continued day and night without a break.

The first several rotations provided a clear shell of approximately 1 in. (2.5 cm) in thickness, which retracted from the mold. To see activity inside the column during the pouring/embedding process, the mold was removed. Due to shrinkage, the sides were not totally flat and some voids were present on the surfaces. These were filled with resins and each side was sanded flat and polished for transparency. At this point, the shell measured 26 in. (66 cm) from point-to-point. The calculations were correct. The column length was 5 ft 6 in. (168 cm).

Preparing the Tree
A symmetrical pine tree of proper size was first sprayed with a catalyzed resin to lock the needles in place and seal moisture from escaping as was done on the prototypes. After curing, it was again sprayed with catalyzed resin and this time the wet tree was pulled by the trunk into the hollow column, centered, and allowed to cure in its original position.

Warp-free Casting
To guarantee a warp-free casting, the pours had to be continuous. As each pour gelled, the column was turned on the rolls and the next pour was made. Before each pour, however, new end dams on either end were necessary and were usually made of wood or glass held in place with mastic or duct tape. After seven days of continuous pouring, due to time constraints it was necessary that the process be shortened from the two-hour pouring intervals, even though cracking would occur. By the morning of the ninth day, the column was almost completed, with internal cracks visible in the innermost pours. At this point, one end was cut flat and sanded and polished, then the column was hoisted upright and the center pour was made. Finally, the top was cut and sanded flat.

Fig. 11-4 Upright section of first prototype showing horizontal cleavage lines.

Fig. 11-5 Pouring configuration of third prototype showing cleavage line pattern. This is cross-section looking down from top.
Stresses and Shrinkage
Whatever stresses and shrinkages occurred in these pours were kept to a minimum due to the use of a 1% ratio of catalyst to resin. As each layer gelled, the exothermic heat generated was maintained inside the column and aided in the gelation of the successive pours. The column would have been crack-free if the original pouring schedule had been followed.

Unpredicted Results
An unforeseen phenomenon occurred as the water-white polyester resin thickened: it became darker. By the time the 26 in. (66 cm) diameter was achieved, little light penetrated to the center. The bluish cast seemed to predominate. When flood lights were focused through the column from a location beneath it, the 2,070 lb (939 kg) column had a reddish glow which afforded an interesting contrast to the green of the tree inside.

Large Casting of Polyester Today
Large bulks of polyester in big castings are still difficult to do and many precautions have to be taken. Today, with the introduction of the ultra-large autoclaves, the tree could be embedded in the clear acrylics with their 92% light transmission qualities.

CORPORATE LOGO CASE STUDY
Another interesting project involved casting sets of six optically clear, tinted crystals that would form two corporate logos. The crystals, all the same size and shape, were pyramidal, but flattened to a height of approximately 5 in. (12.7 cm). They were to be 15 in. (38 cm) in length and 6 in. (15 cm) in width. They had a faint orange/tan tint and were optically clear so copy could be read through them.

Molds and Casting
Molds were made oversize to accommodate shrinkages and plated with shiny decorator chrome to obviate the use of mold releases. Because of the small number made, only one mold cavity was constructed and the crystals were poured one at a time. The mass was cooled during the curing cycle to eliminate cracking, voids, or other imperfections that might normally take place. Time was also needed to allow internal bubbles to rise to the surface and not stay entrapped in the cured mass.

Cooling
The cooling was accomplished by floating the filled mold pyramid point down in a tank of water which was cooled as the exotherm increased. By reducing the catalyst and by cooling the exterior, an almost perfect, bubble-free casting resulted. To ensure a total cure which would not allow for any future distortion, the crystals were postcured for one to two hours in hot air ovens set at 160˚ F (71˚ C).

Final Finish
The mold was open during gelation because of the volumetric and linear shrinkages. This resulted in the upper open surface of the resin being cured in a rippled pattern. It was sanded flat in one pass to guarantee optical perfection. A smaller belt than the one ultimately used would have caused a ripple on the sanded surface as it was moved over the edge of the belt. To prevent this occurrence, a giant sander was used with a platen size of 15.5 in. (39 cm) wide and 26 in. (66 cm) high. Using a 15 in. (38 cm) belt, the crystals were cut without ripple or blemish, then carefully polished and waxed.

SYNTHETIC STONE
Another form of filled polyester casting is that of “cultured” or synthetic stone: marble and granites.

There are basically three types of cultured stones: marble, granite and terrazzo. All are made virtually the same way but the final finesses and sophistication can vary from product to product.

Cultured stones are usually cast quite thick: 0.75–1 in. (1.9–2.5 cm). This robustness prevents breaking of thinner sections, which are not reinforced or held together by external means. A mold is made to the top of the part, including walls up to the thickness of the part. Such molds can be made of Formica or Micarta with plywood backing or of chrome-plated steel or aluminum. Counters, sinks and vanity tops, etc., can be made flat with appropriate aperatures, or with coves for backboards or splash protectors. More sophisticated molds can be made for circular walled tables and mitered cube tables.

PRODUCTION STEPS
Steps for making cultured stone are:

1. Incorporate an appropriate mold release on the mold. Hard white carnauba wax or sprayed polyvinyl alcohol (PVA) is a good choice.
2. Spray on a 0.01–0.03 in. (2.5–7.5 mm) clear gel coat over the mold’s surface, 20 mils (5 mm) being an average thickness.
3. Use a large electric bowl-type mixer such as a dough or pizza machine with a 40–50 quart (38–47 L) bucket (preferably stainless steel) and place an appropriate amount of uncatalyzed and unsaturated polyester in the bucket.
4. Add a fine white marble dust (CaCO₃) to create a mix of 85% filler (marble dust) and 15% resin. Although white
when placed in the mixer, the marble dust will change to gray when mixed with the resin. If a white marble is required in the finished product, add titanium dioxide (TiO₂) powder and blend in the mix. If a verde antique is desired, instead of TiO₂, add inorganic pigments of dark green and black. The same process is used if other basic background colors are wanted. Appropriate inorganic pigments are added to the basic mix.

5. Add the catalyst and the graining. First, add 2% methyl ethyl ketone peroxide (MEKP) by weight based on resin weight only. Mix thoroughly before adding graining. This may take several minutes depending on the size of the mass. Graining can be done with pigments (paste type) alone or with pigments mixed with a small amount of the catalyzed resin from the pot. Next, carefully add the color to the mass in the pot and turn the paddle very slowly two or three turns, just enough to spread the pigments into long lines. Do not mix it into the mass.

6. Place the gel-coated mold on a large floor-type vibrating table and carefully pour the appropriate amount into the mold. To achieve the graining, the pot should be poured from end to end of the mold in a series of pours until the mold is filled. The vibrator should be running as pouring takes place. Never pour the pot in the center or around the edges. If this is done, the graining patterns will be very strange and not like real marble.

Vibration

Vibration has several functions: It controls the graining and graining patterns. Second, it compacts the filler particles against the gel-coat surface layer. Finally, it brings any entrapped air and/or excess resin to the surface. The pour should bring the cast part in the mold, pry carefully to prevent marring. Where surface tension holds the part in the mold, it should easily separate from the mold. Where surface tension holds the part in the mold, pry carefully to prevent marring.

Warping

To avoid warping in large parts (occurs after the gel has taken place), the part is placed on a large flat surface. Along the exposed surface, heavy weights such as concrete blocks are placed appropriately on the part during the curing and cooling. If postcuring is required on the part during the curing and cooling. If postcuring is needed, a walk-in oven can be used to heat the part for one to two hours at 160–180° F (71–82° C). During such postcuring, heavy weights should also be used during the oven time and until cooling is complete.

Gel Coat

The clear gel coat on the surface guarantees a continuous smooth surface which can be polished if surface marring or scratching occurs. This coating also provides additional protection against household cleaners and other chemicals. For outdoor usage, the gel coat provides a barrier against differential weathering. The highly filled mass precludes “blushing” or white spots from water absorption often seen on the surfaces of glass fiber-reinforced polyester panels used in various outdoor applications.

GRANITES

Cultured or synthetic granites are made in a manner similar to the marble, but utilize sands of various colors and granule sizes and stone chips in place of the marble dusts. Often, ores, clays, and other earth or mineral products and by-products are used. Combinations of these products can also help make beautiful and interesting stone products. When these materials are mixed into the resin in the same proportions, smaller particles fill the voids made by larger ones, thus producing real conglomerates. Graining is usually not done in these mixes. Colors can be added by inorganic pigments. Also, in some cases, the gel coat can be eliminated if the texture of the stone surface is more important than the smooth surface coating.

When the product has been catalyzed, poured into the mold(s), and vibrated, bubbles will rise to the surface as will more of the unfilled resin. This latter phenomenon is caused as the particles compact themselves to the bottom of the mold.

In either of these systems, unusual and beautiful effects can result. It is possible to imitate almost any type of marble or granite. With the marbles, sophisticated graining can be produced by combining pots of graining materials in a number of colors, five being perhaps the maximum. Sophisticated granites are those using such chips as ground opal waste, iridescent colors found in rare ores, or in ground seashells. Strange but interesting effects can be produced by varying the graining colors and combinations even though they do not appear in nature.

Configurations

In both cultured marble and granite work, molds of many configurations can be used to cast these materials into three-dimensional sculptures, bas-reliefs, and configured architectural details. Both of these materials increase the weight of the unsaturated polyesters from about 1.25 ounces per in³ (78 g/cm³) or about 8.44 lb per ft³ (40.5 kg/m³) × 0.75 in. (1.9 cm) thick to approximately 9.5 lb (4.5 kg). At 1 in. (2.5 cm) in thickness, the weight per board foot (0.3 m) (12 in. × 12 in. × 1 in. [30 cm × 30 cm × 2.5 cm]) increases from 11.25 lb (5 kg) to about 12–13 lb (5.4–5.9 kg).

Support. Thin sections, if unsupported, have a tendency to crack and/or break. This can be remedied with the addition of glass fiber reinforcements or by curing with or cementing to understructures such as end grained balsa wood or rigid high-density foams.

The terrazzo type of synthetic stone incorporates thin, flat slices of natural stone placed against the gel coat, backed with a fine stone matrix. Even if the gel coat wears away through abrasion, the flat stone slices prevent such abrasive action. The terrazzo products can be used as flooring, interior and exterior wall panelling, fireplace facia, etc.
EMBEDMENT AND CULTURED MARBLE

A variation on both the embedment and on cultured marble was developed for making very large table tops (6–10 ft [1.8–3 m] in diameter) with embedded beach scenes and sand, shells, seaweed, and other nautical flotsam. In the beginning, because of the shrinkage factors of the polyesters around the embedded objects, and because of the large mass in which exothermic reaction was severe, cracking occurred. To alleviate this, a system of pouring was developed. The polyester was pooled in the center of the table casting, then a continuous pour was made around the periphery, leaving an open space between it and the center puddle. Next, the catalyzed resin was poured between the two cured areas. This process was repeated several times, building up mass until close to the desired thickness. At this stage, the entire table top was covered with a single layer. This technique allows large table top casting up to 1 in. (2.5 cm) thick or more with no cracking.

ADDING FILLERS TO POLYESTER

Polyester with other fillers such as wood, nut flours, sawdust, wood chips, and the like, in association with micro-balloons, can be formulated to simulate wood products and be cast into furniture parts, decorative moldings, picture frames, architectural details, sculpture, etc. With care, these parts can be made to match the specific gravity of wood and can likewise be nailed, screwed, drilled, sanded, filed, painted, or stained.

REINFORCED POLYESTER

Another architectural material, reinforced polyester, comes in large sheets up to 5 ft × 10 ft × 1.5 in. (1.5 m × 3 m × 3.8 cm) thicknesses and can be cast in one piece, as well as into objects of art or decoration such as bowls, bookends, statuary, lamp bases, ashtrays, cigarette lighters, hardware handles and knobs, push plates, architectural columns, details, curtain walls, etc.

The product was transparent to translucent, but sometimes opaque, in a myriad of colors or color combinations. The appearance of the sheets was one with thousands of tiny connected cracks running through it which gave it a crackled look and helped to scatter light as it passed through. The internal and external reflected light provided interesting and unusual aesthetics. Although it looked weak, as though it might break easily, in reality, it was very strong. Discreetly held together by hidden glass fibers, it met the physical requirements established by architects who used it in such applications as curtain walls and building facia, even in tub/shower enclosures. Balls made of this material up to 3 and 4 in. (7.6 and 10 cm) in diameter did not break apart when dropped on concrete from heights of several stories.

EPOXY CASTINGS

Some, but relatively few, epoxies have been made that approach a water-white clarity. Most epoxies tend to be yellow to brown in basic resin color. Epoxies have both advantages and disadvantages over the polyesters. Both are two-part liquid systems and both are thermosts with marked shrinkage factors. The epoxies, however, have a volumetric shrinkage of 2% and a linear shrinkage of approximately 0.2%. These shrinkage properties avoid the ripple effect on the surface as the epoxy goes through its b-stage or gelation and cure. Epoxies are usually stronger and more dimensionally stable but are also more tenacious. Care must be exercised with mold releases or they will stick to mold surfaces, often beyond the ability to save a casting. The minimal shrinkage also implies the need for greater mold draft angles. Epoxies are better as a filled material or one where the yellow color is not a detriment.

FEATURES

Epoxies have good dielectric strength, are resistant to most chemicals and moisture, and have very low coefficients of expansion. They are used almost 100% in the electric and electronic encapsulation/potting field. Because of their dimensional stability, they can be used with or without fiber reinforcements and fillers, as quality control devices, and jigs and fixtures throughout industry. Reinforced epoxy using glass or carbon fibers is used almost exclusively in composites for everything such as drop hammer dies, aircraft components, and space vehicles.

TYPES

There are several types of epoxies: aliphatic, modified, liquid aromatic, and solid. The aliphatics are the heaviest averaging over 10 lb (4.5 kg) per gal, while the others are in the 9.5-9.9 lb/gal (4.3-4.5 kg) range.

DILUENT EFFECTS

While polyesters are usually diluted or extended with a styrene monomer, the epoxy diluents are usually reactive monoeopoxides made by the reaction of epichlorohydrin with such monohydroxyl compounds as allyl alcohol, butyl alcohol, and phenol to produce allyl glycidyl ether and other ether structures. When added in small amounts to the epoxy resin, these reactive diluents reduce viscosity without impairing the physical properties in the cured resin.

CROSS-LINKING

Epoxies can be cross-linked/cured by tertiary amines such as piperidine dimethylaminopropylamine, diethylaminepropylamine, tris (dimethylaminomethyl) phenol, which are used in relatively small amounts, four to six parts per hundred of resin.

HARDENERS

Reactive hardeners can be used from a secondary amine which, in turn, can affiliate with another epoxide, the product of such reaction being secondary alcohols. Hardening agents for the epoxides are boron trifluoride and aliphatic amines. They tend to shorten the curing, allow resins to react at ambient temperatures, but increase the exotherm during curing.

EPOXY CASE STUDY

Epoxies were used to produce dimensionally stable large transparent sheets of plastics for interior decoration (Fig. 11-7). Epoxies were selected for this task because they are warp-free, have good indoor-outdoor properties, are strong, withstand abuse, and could handle wear and tear. Weighing 2.2 lb/ft^2 (180 gm/cm^2) at 0.375 in. (0.95 cm) thick, they were designated to be yellow-orange in color with gold “glitter” embedded and textured surfaces but with no visible reinforcements. This eliminates the need of glass fibers or other forms of internal reinforcements. They
There are basically two types of polyurethanes that cure as foam castings when poured into a mold. Typical castings are made with elastomeric polyurethanes and liquid, one- or two-part systems where curing is dependent upon the moisture in the air. Since foams are usually treated as a separate class of plastics, a short discussion of them will follow the phenolics.

**TYPES**

Polyurethanes comprise a large group of thermoplastics and thermosets. Because of the tremendous variety of intermediates, they may be:

- Soft elastomers, very hard solids, or anything in between.
- Fibers for clothing or “rubbers” for shoes or tires.
- Protective coating media or thermal insulation for cushions or mattresses.

Eventually became the most popular free-standing, clear, embedded, unsupported epoxy panels.

The total area of each panel was 756 in.² (2615 cm²) or about 5.25 ft² (2.6 m²). The exterior shapes and internal cutouts were molded in each panel which ultimately weighed 11.65 lb (5 kg). At this time, a stoichiometric balance within the resin had to be developed to minimize the exotherm and slow the cure rate.

**Blending**

In blending the amine catalysts avoid reducing the amount of catalyst, as in the case with polyesters, since the epoxy formulations are critical. Blending occurs by the percentage replacement of the catalyst by a relative percentage of another catalyst in the same proportion. The total amount of catalyst is constant. When more than one catalyst is used, the proportions are altered to equal the whole. Variations in the resin blend can be 60-40, 30-70, etc.

Another casting material of consequence is a two-part thermosetting clear silicone. This material has limited but very important uses in the casting field.

**CHARACTERISTICS**

The clear two-part silicones are practically the only casting resins that are both transparent and resilient. Although some polyester can be modified to almost identical elasticity, the addition of a flexible polyester to a water-white resin makes it yellowish in appearance and affects certain inherent physical characteristics. Some castable silicones are FDA-approved for making candy molds and for medical applications.

**USES**

Because of their resiliency and good dielectric properties, silicones can be used as shock absorbers in certain critical embedments or in potting. This is very important where implanted circuitry is used in human and/or animal bodies, especially where such bodies are subject to harsh treatment such as bumping, falling, running, jumping, etc. The silicone, however, should be limited to the covering of very fragile electronic parts and then the entire product or part should be totally coated or encapsulated in a potting resin or, for implant use, with an encapsulating resin that has been FDA-approved for such usage.

In some experimental electronics work, either for electronic instrumentation or for body implants where it is necessary to see the inner workings of the circuitry or the implant, the total encapsulation can be done with the clear silicones but unusual care must be taken as the clear silicones are a frangible material with a tendency to tear or develop a foam-like structure.

There are basically two types of polyurethanes that cure as foam castings when poured into a mold. Typical castings are made with elastomeric polyurethanes and liquid, one- or two-part systems where curing is dependent upon the moisture in the air. Since foams are usually treated as a separate class of plastics, a short discussion of them will follow the phenolics.

**TYPES**

Polyurethanes comprise a large group of thermoplastics and thermosets. Because of the tremendous variety of intermediates, they may be:

- Soft elastomers, very hard solids, or anything in between.
- Fibers for clothing or “rubbers” for shoes or tires.
- Protective coating media or thermal insulation for cushions or mattresses.

With the polyesters and/or the epoxies, they are among the most versatile of the present-day polymers.

Basic types of polyurethanes include the following, based on ASTM classifications:

- Type I: urethane-modified alkyd coatings;
- Type II: one-package moisture-cured urethane;
- Type III: one-package, blocked urethane;
- Type IV: two-package urethane, one package contains the isocyanate adduct or prepolymer and the second, a small amount of highly reactive diamine compound plus other ingredients to promote flow;
- Type V: a two-package urethane in which the first package is the diisocyanate prepolymer and the second is a polyol.

Types IV and V are quite similar and often grouped together. These are not all of the urethanes, by far, but are the best known in the coating field.
CHAPTER 11

POLYURETHANES

The nitrogen-carbon-oxygen (NCO) percentage (the reactive isocyanate) in these urethanes reacts with amino hydroxy or acid groups to set up cross-linking. The higher the NCO percentage, the faster the reaction, and the higher the cross-link density and physical and mechanical properties of the compound.

CURING
The group that links amine curing to the proto-catalytic reaction is:

\[
R_1 - N - C - N - R_2
\]

\[
H \quad H
\]

(moisture in the air supports the curing).

APPLICATIONS
There are many types of polyurethanes for multiple uses. They find applications in clear coatings, in paints, or as elastomeric, even foamed, materials. However, castable polyurethanes require tightly controlled laboratory procedures and equipment that may not always be available to the user. The same is true for the foams.

Two-part clear coating kits can be purchased off-the-shelf in hobby shops or plastics supply houses as can two-part foamed urethane kits. Clear coatings are castable and easy to use over wood artifacts, such as boat decks and on a plethora of other materials and products. Foams can also be used for many things, from the protection of very fragile items to model making to the making of foam parts, furniture details, architectural pieces, etc.

Like other reactive products, however, good housekeeping must be exercised when using these materials, and especially very good air circulation and ventilation.

PHENOLICS

The final class of materials to be discussed is phenolics. These are considered the workhorse of the plastics industry.

Available as a compression/transfer molding compound, phenolics can also be made as a liquid and as such used as a cement, a foamable solid, and a castable material.

True phenolic casting resins are syrupy in nature. They are solidified in a suitable casting mold by the addition of a chemically active hardener or by subjecting them to carefully controlled heating periods, depending upon the size/mass, from two hours to more than 10 days. Such curing can be done in a closed vessel, by autoclaving with heat, or in standard baking ovens of various sizes where the product can be made least expensively and with little or no restrictions on size or bulk.

COLD MOLDING
Another variation on phenolics casting is what is referred to as cold molding. In this molding process, the liquid syrupy resin is filled with material such as paper, cotton, mica, felt, asbestos, or soft glass and uses no heat in the process. After the compound is mixed to a doughy mass, it is placed in a closed mold, similar to a compression mold. The mold is then closed and pressure from 2,000–4,000 psi (13.7–27.5 MPa) is exerted. The compound binds from pressure within the mold. After removal from the mold, the part is postcured in an oven at ±450˚ F (±232˚ C) for 72 hours to totally fuse it into a heterogeneous mass. Products such as buttons, knobs, electricals, and circuit boards can be made, as well as rods, sheets, and blocks.

CASTING MOLDS

Casting mold technology is focused on molds, mold releases, and covers. A general guide when working with heat and/or pressure is to use mold materials that are heat resistant and strong.

- For self-curing materials, use molds that have inherent good release properties or externally applied releases.
- Plastic parts in general should have good draft angles (2-5˚) and radii, instead of sharp corners.

MOLD MATERIALS
Molds are made of many materials or material combinations.

Steel
For casting, hard or soft metals can be used. Steel can be used as a plate or as a tooled mold. Chrome-plated steel does not need a release for work with polyesters or acrylics. Steel molds can be hard chrome plated, but the surface is not so smooth and often a mold release is a good addition/precaution. Steel can be used unplated but care must be taken to protect against rusting; also, mold releases are required. Mold releases such as light silicone oil, mineral oil, white carnauba wax, sprayed on PVA (polyvinyl alcohol), and other spray-on mold releases containing Teflon™ are excellent. If waxes or oils are used, apply, then wipe off, and polish several times before the resin is poured.

Brass
Brass is a soft metal and easy to tool. It is also easy to chrome plate and can be used like steel, but caution must be exercised to avoid bending or marring the soft metal surfaces. Mold releases are the same as for steel.

Aluminum
Cast aluminum is another metal mold material that is less costly than tooled steel, yet can be cast into mold configurations. Its big drawback, however, is that it is very porous and unless excellent mold releases are used, parts will stick to the surface.

Mold release. Probably the best permanent mold release for cast aluminum molds is Teflon™. It eliminates the sticking of practically all of the castable resins with the exception of epoxies, for which a mold release such as a silicone must also be used. Teflon coatings are sprayed on the porous aluminum surfaces, then heated to between 650–850˚ F (343–454˚ C), depending on formulation. They form a mechanical bond to the porous surface, and with care, can last for hundreds or thousands of castings.
Electroformed Metal Molds

Electroformed metal molds can save a considerable amount of money over conventional pantographic mold cutting. A part with many configurations can be electroplated, then backed up with a hard metal such as beryllium. When removed from the part, this detailed mold is cast into a block so it can be handled and will lie flat and level during curing in the casting process. If possible, the interior of this mold should also be chrome plated.

Glass

Glass molds are easy to make for parts without curves. Glass is easily cut with hand cutters, and sheets can be held together with a wide variety of materials such as masking tape, duct tape, caulking compounds, waxes, modelling clay, etc. All joints should be tight and covered with mastic to prevent leakage of the resin, especially if a liquid system is used. Glass itself is an excellent mold release although it is easier to handle if a mold release such as carnauba wax, light oil, or spray-on release is first applied.

Types. There are several types of glass that can be used. For embedding or casting in small molds, window glass works well; usually 0.125 in. (3 mm) or slightly less in thickness is sufficient. For large parts, plate glass is preferable and usually 0.25–0.5 in. (6–12 mm) thick but can still be cut and snapped with hand tools. Clamps should be applied to plate glass with soft rubber or cloth pads over metal contact points.

For parts with substantial heat buildup during curing or with very large flat sheet castings, tempered glass is strongly recommended because it has good flexural strength. This glass, however, cannot be cut after tempering. If it is cut or even scratched, it will explode, breaking up into thousands of tiny pieces. Use mold releases with this glass and put pads on the clamps before applying.

Shaped glass. Glass cast into shapes (such as bottles) can also be used. To keep resins from sticking to the glass, a small amount of clear, lightweight mineral oil poured over the resin in the pouring spout will work. As the resin cures and shrinks, the oil will run down between the glass and the resin making it much easier to break off.

Glass tubes. Glass tubes are great for casting rods and are available in different diameters from either glass or chemical supply companies. Interiors should have a mold release applied as extra precaution against sticking. Large diameter tubes are quite costly. If a tube is to be cast, it is better to use flexible plastics as the core. A polyethylene tube can be slipped over a wooden dowel if the flexible plastics core is not compatible with the resin used. Since the plastic casting will shrink, it will pull away from the glass tube but lock tightly around the core. If the material is flexible, it can be pulled out. If it is a plastics tube over a wooden core (dowel), it is advisable to knock the dowel through. It will slide along the inside of the polyethylene tube. When the dowel is removed, the tension is removed from the tube and it can be pulled through the new open channel.

Wood

Wood is easily handled and can be cut and tooled into whatever configuration is required and should be fine grained hardwood where possible. After shaping, it should be sanded smooth, filled with an appropriate paint filler, lightly sanded then painted with a hard surface paint, sanded again, then waxed and buffed. For hard surface paint, an epoxide or polyurethane-based paint can be used. Mold releases should always be used with wood molds. These typically include hard carnauba wax or PVA spray-on film. The PVA makes a water-soluble film, which, after casting, can be removed from the mold and/or part by washing with a cloth soaked in warm water. Depending upon which basic mold material is used, the PVA film in most cases can be pulled off in a continuous sheet or even steam off, if appropriate.

Melamine Formaldehyde

This material is known under the trade name Formica or Micarta. It is a smooth-surfaced, often colored or decorated thermoset available in thin sheets (approximately 0.03 in. (1 mm)) and cemented to heavy plywood or particle board using industrial pressure-sensitive adhesive or an epoxy cement. After the composite board is cemented in place, it is cut into molds or mold parts. Clamps, bolts, screws, or nails are used to hold mold parts together. (See section on cultured or synthetic stones.)

Plaster

Hard plasters can be molded over a pattern and then used as the casting mold. Soft plasters such as wall/ceiling plaster or plaster of paris are not recommended. Although called hard plasters, all of these plaster materials are relatively soft and should be used with care and discretion, especially with clamping or when prying apart. Mold releases are required. In large applications, pipe or burlap mesh or glass reinforcements should be used within the plaster for added strength.

Paper and Cardboard

For small molds, especially where a single shot or single prototype is involved, paper, cardboard, or even very thin balsa wood are used singly or in combinations. Walls are held together and to a base by mastic or caulking compounds or by pressure-sensitive tapes such as Scotch™, masking, or duct. Wax or plaster backings can be added to keep walls from sagging or buckling when the resins are poured in. Mold releases are used with this method.

Wax

Two types of waxes—dental and pattern—are good for mold-making.

Dental waxes are hard, thin sheets of pink-colored waxes about 4 × 8 in. (10 × 20 cm) each with release or slip sheets between each layer. The waxes are available at dental supply houses in most large cities. Easy to handle, they can be cut with scissors or razors. They can be bent into a number of curves, sharp corners, and complex shapes with or without the addition of external heat. They can also be attached to base surfaces with masking or duct tapes or by carefully melting an edge.

Pattern waxes are another choice and available from pattern supply companies. They are available in a wide variety of thicknesses, sizes, and colors. Easy to handle, equally easy to hold together by tape, they can be manipulated into molds rapidly and efficiently and used without mold releases. In applications where heat is involved, exothermic reactions must be minimized to avoid losing the casting prior to gelation.

Low-fusing Eutectic Alloys

Although these really fall under metal technology, they are a totally separate type of mold and for this reason are placed in a
CASTING MOLDS

Positive Mold Making

A technique unique to castings is that of making a positive of the part to be cast in a hard aluminum alloy or in steel and mount it on a long handled tool. This tool (Fig. 11-8) is used as follows:

1. Keep a pot of an appropriate eutectic alloy in the molten state adjacent to the tool.
2. Dip the head only in the alloy then lift it out.

The alloy will stick to the aluminum/steel configuration or mandrel. If tooled with the correct draft angles, the eutectic alloy part can be removed from the mandrel using a gloved hand.

After using the alloy as a mold, it can be remelted and used repeatedly. Any resin contamination on the alloy is burned off as it enters the molten bath, and burnings or other contaminants are removed from the metal molten surface with an appropriate scoop.

Eutectic alloys can also be used as removable cores in certain types of castings.

Vacuum-formed Molds

Where a series of similar castings are needed, especially those with low reliefs, vacuum-formed molds can be made which are good for one or at best a few castings. This type of mold is often called a “throwaway mold” (like glass shapes or eutectic alloy molds). Normally, mold releases are not necessary because the molding material is not compatible with the resin from which the mold is made, and therefore won’t stick. With polyesters, for example, the best materials for making vacuum-formed molds are the cellulose acetates, polyethylene, polypropylene and polyvinyl chlorides (PVC). Polyethylene terephthalate glycol (PETG), a thermoplastic polyester, is an FDA-approved material. Cast polyester will adhere to this material and becomes an integral part of the casting if the surface detail is not critical.

Acrylics are normally too expensive if used only for relief shapes and are used for embedding in autoclaves. Unless there is a very special reason, epoxies are not used in this type of casting procedure.

Vacuum-formed molds can be used, too, to cast other materials such as plasters, cookie dough sculptures, candy (chocolates and hard candies in FDA-approved PETG), and hobby parts.

Plastic Sheets

Where castings are flat, or where cores are needed to cast tubes, a selection of nonstick plastic sheets or tubes can be used as molds. Polysters will not stick to glass, polished metal plate, decorator chrome-plated surfaces, Mylar (a polyester film), cellulose acetate, polyethylene, polypropylene, or polyvinyl chloride. It will stick to PETG and acrylics. Acrylics will not stick to glass, polished or plated metals, or to Mylar. Epoxies will tend to stick to most anything and careful mold releasing is critical.

RTV Silastics

One of the most versatile, well used and well known of the molding compounds, room temperature curing (RTV) silastics, are superb mold materials that are relatively easy to use, making the use of other molding compounds such as synthetic latices, polysulfides, and gelatin compounds unnecessary.

When mixed at ambient temperatures, usually 10% catalyst by weight to 100 parts of resin, these materials take a full 24 hours to cure. During this period, entrapped air can escape by rising to the surface without the aid of vacuum equipment, making a bubble-free part (mold).

But silastics do have drawbacks. They cannot come in contact with some materials such as oil-based modelling clays and most polyurethanes. Silastics are soft and need jacketing to maintain the shape of cast parts. Such jackets can be wood, metal, or hard plastic. With wood or metal, the jacket is placed before the RTV is poured around the model or pattern. With hard plasters, they are added as the mold is made and over a cast RTV when the casting has solidified/cured over the pattern. When two halves are needed for a multiple part mold that is closed, the halves are made individually while the pattern is still encased within.

Hydrocolloids

When a part was extremely fragile such as a living organism, museum artifact, extremely delicate specimen, etc., a system was devised for casting such specimens without possible damage to them.

For example, in the casting of a human hand, the following steps were performed:

1. The hand would be placed on a table.
2. A hydrocolloid is activated by the addition of a measured amount of slightly warmed water and once mixed, pot life is very short. It must be immediately poured over the specimen and it will set in a matter of one to two minutes, but it is very soft.
3. A plaster jacket must be immediately poured over the hydrocolloid and left to harden.
4. The jacket is carefully removed as is the hydrocolloid from the specimen. It is very weak, frangible, and tears if extreme care is not exercised. The hydrocolloid is still very wet.
Foams are castable, but are usually treated as a separate category when working with plastics materials. While several companies supply two-part kits to produce certain foam-in-place materials, only syntactic foams are discussed here.

In general, if two-part kits are available, closed molds are used that are thick enough or have substantial jacketing to withstand the pressures created by the expanding foams. Molds must also have very good mold releases. With syntactic foams, however, these precautions are not required. A syntactic foam is a mechanical foam made through the introduction of micro-balloons. These tiny microscopic-sized balloons made of glass, melamine, or phenolics will, when mixed into a resin, provide the air in the mix that is present in a foam created with foaming agents. The micro-balloons feel like a fine powder. The glass and melamine balloons are white while the phenolics balloons are dark brown.

As more micro-balloons are mixed into an appropriate resin, the part becomes lighter in color. When catalyzing, however, the catalyst must be measured to the initial resin weight, not the weight of the entire mix.

Using this technique, parts can float; cultured marble is made lighter without changing its graining or outward appearance. With

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**Synthetic Latex**

Another standard mold material is synthetic latex. It is a water-ammonia based rubber that dries as the liquids evaporate, leaving a continuous rubber surface. It can be applied to the part by brush or spatula. Each layer dries according to the ambient temperature and with heat the drying rate is increased. From a milky white color, it dries naturally to a tan/beige. When enough layers are built up over a pattern, a plaster jacket is poured over it to guarantee shape in the casting. Lattices are good for plaster castings but many casting resins have a bad effect on the latex. Some will make it gummy; others will stick to it. When used, it should be carefully released from the mold. It will make one or two good casts or serve as an intermediate plaster casting, as in the case of the hydrocolloids, until a more permanent mold is made.

**Reinforced Polyester**

A final mold material, reinforced polyester, utilizes the same basic technology as those molds made for glass polyester lay-up/spray-up molds for boat hulls, architectural panels and details, domes and radomes, aircraft components, and other large parts.

In Figure 11-9, an oversized model or pattern is appropriately made to allow for mold and part shrinkages and mold release. It is then set on a flat or shape contoured to the bottom of the pattern (+). If it is a multiple part mold, thin metal divider(s) are placed at the cleavage points (**). If a tooling gel coat (usually red or black) and painted on the pattern if there is no other way to do it. A safe thickness for this layer is 0.02–0.03 in. (5–7.6 mm).

When this coat has gelled by a polyester glass fiber hand lay-up or by machine, a polyester chopped-fiber spray-up is applied to build up a mold thickness compatible with the size of the part. Often, end-cut balsa wood is applied to a thin lay-up or spray-up, then additional glass and resin is applied, locking in the balsa wood stiffeners. In some applications, too, metal pipes are built into the mold as glass resin is applied. These pipes serve two functions: as stiffeners and handles for moving heavy molds or to maintain an upright position during the actual molding of the part(s).

After the mold is made and cured, it is removed from the pattern. If it is a multiple piece mold, after the dividers are removed, the flanges of these mold parts are drilled and bolted together. Seams are sealed against resin leakage.

Molds of this type require mold release coatings during use. Either hard carnauba wax applied and buffed four or five times or sprayed PVA is recommended for this purpose. Without such mold releases, polyester or epoxy parts will stick to the mold surface.

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**FOAMS**

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As more micro-balloons are mixed into an appropriate resin, the part becomes lighter in color. When catalyzing, however, the catalyst must be measured to the initial resin weight, not the weight of the entire mix.

Using this technique, parts can float; cultured marble is made lighter without changing its graining or outward appearance. With
heavy masses of thermosets, where clarity is not an issue, weight is reduced, thus reducing the exothermic heat in the mass.

The resins most used with micro-balloons are the polyesters and the epoxies, although they can be used with other casting materials discussed in this chapter.

References

1. The author* invented the first mass-producible embedding process with acrylics in 1945. It became the precursor to electronic, biologic, medical, and art embedments in the United States.
2. Project was an angel prototype for the Archdiocese of St. Louis, MO, 1956: Bernard MacMahon, Architect; Hillis Arnold, Sculptor; Author*, Plastics Consultant; project by Hanley Plastics Company Division of Wallace Pencil Company, St. Louis, MO.
3. Christmas Tree Embedment for R.H. Macy & Co., New York City, 1968: Milton Glazer, Artist/Designer; Author*, Plastics Consultant; project was joint effort by Armand G. Winfield Inc. and LaBarge Industries Ltd., West Babylon, NY.
4. Logos for Bristol-Meyers, New York City, mid-1970s. Produced by author*.
5. The author* was a pioneer in the development of cultured stones in the early 1960s—and specifically developed granites and multipot graining techniques as well as light-weight products in these technologies.
7. Invented in France by Jean-Pierre Fisholle, 1958, under Trade Name Crystopal. The process was brought to the United States by the author* in 1962 where it was reduced to American manufacturing practices in Hazardville, CT, for Crystopal, Ltd.
9. Author* developed Hydrocolloidal castings for Department of Anthropology, Washington University, St. Louis, MO, 1948.

Bibliography

Archives/Records of Hanley Plastics Company, Division of Wallace Pencil Company (St. Louis, Missouri, 1955-1957).
Swanson, Robert S., Plastics Technology (McKnight & McKnight Publishing Company, 1965).

*Armand G. Winfield
INTRODUCTION

During the past 40–50 years, foamed polymers have found increasing importance in the world marketplace due to the unique characteristics and properties they provide when compared to solid plastics. While most thermosets and thermoplastics can be made in a foamed or cellular structure under certain conditions, the materials known as polyurethanes have become predominant for many applications in this field. Through the proper selection of the starting materials, foamed polyurethanes can range in characteristics from extremely soft, resilient cushioning products to very tough and rigid structural members. As varied as the products are, so too are the machines and processes used to produce them. This chapter gives an overview of the many types of equipment and production processes that are used for specific products. Certain other systems, such as polyureas, are also processed with the same equipment as polyurethanes.

The word polyurethane is somewhat misleading since, unlike most plastics, the final product is not made by polymerizing a monomer. Instead, the products contain a number of polyurethane groups in a complex structure that is controlled by the choice of starting materials and the production conditions. Commercial products are manufactured by the reactions of two liquids: isocyanate (NCO) compounds and polyol (polyoxyalkylene) components, in the presence of catalysts and processing aids.

Basic isocyanate chemistry has been available for more than 100 years, but it was not used commercially until the mid-1930s. Nearly simultaneously, the DuPont Co. in the United States and I.G. Farben in Germany began their developments. DuPont directed its efforts toward films and adhesives, while I.G. Farben concentrated on products to circumvent nylon patents. Dr. Otto Bayer of Bayer AG (part of I.G. Farben at the time) is considered to be the “father” of the urethane industry, and work in the Bayer labs led to commercial polyurethane products as well as to the machinery used to make them. During World War II, German polyurethane developments centered on products to replace scarce materials. The major products were rigid foams and cast elastomers. Following the war, the technology was exploited by the United States, and rapid advances were made in the development of products and processes. Commercially important cushioning products were achieved by the end of the 1950s. While polyurethanes serve a worldwide market, the development centers in both chemistry and machinery have remained in Western Europe and the United States.

BASIC CHEMISTRY

The basic chemistry of flexible polyurethane foams is not difficult to grasp. It is the reaction of an alcohol or OH group with an isocyanate or NCO group. The alcohol is normally polyfunctional, ranging from 2–8 OH groups, which are referred to as polyols. As the number of OH groups increases, the foam structure becomes more rigid. Polyols are classified as polyether or polyester, based on the starter (initiator) materials used in their manufacture. The initiator is reacted with propylene oxide, ethylene oxide, or a combination of the two. The choice of which initiator and oxide to use depends on the foam characteristics desired. A variety of polyols are available to tailor the foam characteristics. The usual isocyanates for foam are toluene diisocyanate (TDI) and diphenylmethane diisocyanate (MDI). Various forms are available, again tailored to specific applications. The foaming operation is complex because three basic reactions are occurring concurrently and at different rates. These reactions are chain extension, gas formation, and cross-linking.

CHAIN EXTENSION

The primary reaction is that of the isocyanate group of the alcohol to give a urethane linkage:

\[ R^1{-}N\equiv C=O+R{-}OH \longrightarrow R^1{-}N\equiv C-O{-}R \]  
\[ \text{Isocyanate} \quad \text{Alcohol} \quad \text{Urethane} \]

The urethane further reacts with additional isocyanate to yield an allophanate:

\[ R^1{-}N\equiv C=O+R^2{-}N\equiv C-O{-}R \longrightarrow R-O-C-N-R^1 \]  
\[ \text{Isocyanate} \quad \text{Urethane} \quad \text{Allophanate} \]

The primary catalysts used for this reaction are organotin compounds; however, in very reactive systems, no catalyst may be required.
FOAM PRODUCTION METHODS

There are two basic methods for commercial foam production: spray and pour. The spray method is generally limited to rigid foams, while the pour method is used for all types of foams. The pour method is further subdivided into the categories of open pour, froth, and closed pour.

OPEN POUR
In this method, the mixed foam reactants are dispersed either continuously or in timed shots into open cavities, where the reaction takes place. Except for very fast systems (such as high-density foamed elastomers), all flexible and rigid foams can be made by this technique. The cavity may be left open or closed after the pour. If the cavity is substantially open, the resulting material is called slab stock foam. When the cavity is closed, the foam is termed molded. Little rigid foam is made today using the slab method due to overall production inefficiencies.

Molds may be individual, such as those used for automotive seats, or continuous, for products such as rigid foam laminate board. Many specialized machines were developed over the years for molding applications.

FROTH
In a specialized version of the open pour technique, highly catalyzed systems are used or an auxiliary blowing agent is added to produce a stable froth as the reacting mixture exits the mix head. In rigid insulation foams, this results in low pressure generation and good mold flow. The highly catalyzed flexible foams are used where the foam is poured into fabric. This is difficult to do with conventional foams due to fabric bleed through. Stable flexible froth, using specialized formulations and equipment, is also used to back carpets for pile bonding and cushioning. Machines used to disperse rigid froth foam, such as the Auto-Froth® units supplied by BASF Corp., consist of pressurized component tanks, hose systems, and static mixer units. In addition to having pour capabilities, these units can be used with a spray gun. The spray foam in this case, however, is not of the same quality as that produced from a standard spray foam system.

CLOSED POUR
In this method, the foam reactants are introduced into a closed mold, and as the foam expands, it completely fills the mold. The mold is closed either for part design considerations or because the foam reaction is too fast to permit closing the mold after the foam reactants are dispensed. For many applications, the foam mixture is simply poured through a hole that is plugged after the shot. With faster chemical systems or for specific design considerations, the mix head is either fixed directly to the mold or it is held against the mold until a pour gate is closed.
As a first consideration, foam equipment is classified as either low- or high-pressure, depending on the pressure of the chemicals as they enter the mix chamber or head. Typical low pressures are 50–200 psi (345–1379 kPa), and high pressures are considered as 1000–3500 psi (6.9–24.1 MPa).

Some machines, particularly those used for slab foam production, are hybrid types that use low-pressure pumps on some streams and high pressure on others. The type of machine chosen depends on the foam type, versatility required, foam volume, and employee skills. High-pressure machines require greater technical skills for both operators and maintenance personnel.

Independent of the technique used, several common elements are needed for effective foam production:

- Raw material supply.
- Metering units.
- Mix heads.
- Temperature control system.
- Process control system.

**RAW MATERIAL SUPPLY**

Raw material supply includes the delivery containers from the chemical suppliers, in-house storage tanks, blending tanks, and the supply or day tanks for the foam machine. In some cases, a given container may serve two or more purposes.

Supplier delivery is from rail cars, tank trucks, rubber bags in trailers, tote bins, or drums. When the delivery is made in large bulk containers, the materials are normally transferred to in-house bulk storage tanks. Handling of the bulk components depends on the chemical requirements, such as the need to maintain temperature or agitation. Isocyanates are stored in moisture-free conditions to prevent undesirable reactions. Some isocyanates also require heating to prevent solidification.

For high-output slab stock machines, materials are normally delivered directly from bulk storage to the metering pumps. With other machines, the materials are delivered to intermediate conditioning tanks or day tanks at the foam machine for better maintenance of temperature and material conditioning. The specifics of the day tanks vary with the machine manufacturer and include single- and double-walled tanks with or without internal temperature control coils or plates, insulation, agitators, and means for recirculation. The tanks may also be pressurized or nonpressurized.

Construction materials depend on the characteristics of the component, but the tanks are typically carbon steel with inner coatings of phenolic or epoxy if the component is corrosive. Stainless steel tanks are required for specific applications. Automatic fill systems are generally used to ensure proper component conditioning.

**METERING UNITS**

Metering units may be high- or low-pressure units. Independent of these classifications, the units must deliver and maintain a high degree of accuracy, usually within ±1%. Low-pressure machines are available to handle as many individual components as necessary to meet the formulation requirements, while high-pressure units are typically limited to two or three components, unless special provisions are made. Output capabilities range from a few ounces or milliliters per second for applications such as pour-in-place gaskets, to 1000 lb/min (454 kg/min) or more for large molded parts or slab stock production. With machines that are used for periodic shots, recirculation capabilities ensure proper material conditioning and exact material delivery during the shot. With continuous pour machines, recirculation capability may be a needless expense.

**Low-pressure Machines**

Low-pressure machines normally use high-precision gear pumps. Specially designed pumps are required if abrasive fillers are used in the foam formulation. To eliminate problems that exist with seal leakage and environmental controls, isocyanate pumps are supplied with magnetic drive coupling systems. Various pump drives include direct drive units with DC or variable-frequency AC motors, gear motors, chain drives with replaceable sprockets for output adjustment, gear trains, and power pulley drives. High-output machines may be configured as hybrid machines (with high- and low-pressure pumps) for better accuracy in metering the specific components. On slab stock machines, there is the capability for many streams, but all of the streams may not be active concurrently. They are installed to permit quick formulation changes to reduce change time and eliminate waste. With shot machines, the trend is to minimize the number of streams and thereby eliminate problems that occur with on/off operations.

**High-pressure Machines**

High-pressure machines are frequently called reaction injection molding, reaction impingement mixing (RIM), or high-pressure impingement mixing (HPIM) machines. This terminology, developed during the early 1970s, refers to systems where the component mixing occurs through impingement of the component streams at high pressure without using mechanical stirrers. Another term, liquid injection mixing (LIM), was used for urethanes; however, the term was later trademarked by General Electric for liquid silicone rubber systems. While they are most frequently considered shot machines, RIM machines are also used for continuous pour applications such as laminated rigid foam panel production. There are two types of high-pressure metering: pumps and cylinders.

Metering pump systems. This type of pump uses high-precision axial, radial, or in-line piston pumps capable of delivering the pressures required. These are modified versions of pumps that were originally designed for hydraulic oil or fuel service. Because of the close tolerances and construction materials, these pumps are not used with particulate materials that are abrasive, such as glass or mineral fibers. Very high viscosity materials are also not handled successfully, since the pumps have virtually no suction capability and clearances are very small. The nominal maximum viscosity limit of these pumps is 2000 centipoise (cP) at operating temperature. Through the use of booster pumps, higher viscosities are handled. The metering pumps are either fixed or adjustable output types. Various drive systems are used, and output can be varied manually through DC or variable-frequency AC motors, or with servo systems. Figure 12-1 is a schematic of a high-pressure machine shown with double-wall day tanks for temperature control.

Cylinder metering units. Designated reinforced RIM (RRIM) machines use lance- or plunger-type cylinders that are capable of handling abrasives and high-viscosity materials. With a lance cylinder, shown in Fig. 12-2, the moving lance does not contact the inside surface of the cylinder; it only contacts the labyrinth seals so that pressure is developed. The material is displaced, and the cylinder does not empty completely after each lance stroke. Cylinders may be driven independently or with hydraulic slave cylinders.
A schematic of a lance cylinder-type machine is shown in Fig. 12-3. To reduce the capital cost, a machine may have only a single cylinder to meter the abrasive component while a metering pump handles the nonabrasive component.

Although operating pressures for cylinder machines are generally on the same order as metering pumps, special units can deliver impingement pressures up to 15,000 psi (103 MPa) for difficult-to-mix systems. While cylinder units are usually made to accommodate a fixed shot capability, special units, such as tandem cylinders that are carefully controlled to have overlapping strokes and precise operation of switching valves, are made to permit continuous output. Gusmer-Admiral also offers a continuous cylinder metering unit, the CDC pumping system. This double-acting cylinder system, shown in Fig. 12-4, is not a lance cylinder due to the internal piston seal requirement. Other true cylinder metering units are used for special purposes, such as color addition or very low output, where it is difficult to achieve the desired accuracy with a rotating or reciprocating pump. Piston seal wear considerations limit these pumping units to nonabrasive service.

Spray foam machines are also cylinder-metering units. They are normally driven pneumatically, and the stroke of each cylinder is locked to ensure a constant ratio of materials. Ratios are varied by changing cylinders. Spray units usually have external-mix, self-cleaning, hand-held guns, and the impingement pressures can reach 3500 psi (24 MPa). Valving arrangements are used to ensure essentially continuous flow with these machines. Most spray machines do not have recirculation capability, and components may be warmed by heat-traced hoses to ensure uniform fast reaction of the spray foam; this provides the desired laydown for a smooth surface. A typical pneumatically operated spray unit is shown in Fig. 12-5. Linden provides a hydraulically powered unit for spray or pour that eliminates problems that can occur if the compressed air supply pressure is inconsistent.

**MIX HEADS**

Mix heads are classified in two ways: recirculating or nonrecirculating, and low-pressure or high-pressure. In a recirculating head, the components are recirculated from the day tanks through ports in the mix head and back to the tank. The recirculating type with proper temperature control is essential for good operation when foam dispensing is intermittent. While recirculating, back pressure is controlled at the mix head. Spool valves or ports open when the shot is called for. Some continuous pour mix heads also provide some recirculation; however, most are nonrecirculating. With nonrecirculating heads, pumps are started or valving is opened in a sequence that ensures start-up is smooth and losses are minimized. On start-up, the minor streams (catalysts, surfactants, and liquid additives) are turned on first, followed by the polyol and then the isocyanate.

**Low-pressure Mixing**

Low-pressure machine mix heads are chambers with rotating impellers that are driven by hydraulic or electric motors. Drive speeds are usually variable from 2000 to 6000 rpm. The impellers may be a low- or high-shear design, depending on the mixing efficiency required. Low-pressure mixers can give excellent mixing and are designed for a wide range of output, including very low output. Essentially all of the mixing is done by the mechanical action. The mixer imparts high shear energy due to the close tolerances between the mixing element and the mixer barrel. Rotational speed and/or...
back pressure on the mix chamber is varied to alter the foam cell structure and mixing efficiency. One design of a high-shear mixer is shown in Fig. 12-6.

Hybrid machines require less efficient mechanical mixers, since some mixing is achieved by impingement of the streams even though the impingement efficiency is low. The mixing element is simpler than the high-shear type and is usually a pin or “Christmas tree” type, as shown in Fig. 12-6.

Low-pressure mix heads, with the exception of the hybrid machine types, have valving arrangements for the components that ensure simultaneous opening to minimize a condition known as lead-lag. With lead-lag, a component enters the mix chamber out of sequence with the other(s), resulting in the wrong ratio of components and defects in the foam product. The valving arrangements include individual component cone or ball valves that are opened by a single operator and spool valves that are coupled to an opening/closing cylinder. Depending on the manufacturer, low-pressure mix heads may have two to six component streams. Elastogran Polyurethane GmbH developed a low-pressure mix head with up to seven ports that can be opened hydraulically in any combination. This offers the possibility of formulation changes between shots. With all low-pressure heads, separate valving is provided for solvent flushing and air purge to evaporate any solvent residue.

A disadvantage of low-pressure mix heads is the need to purge and flush the head periodically, sometimes after each shot. This is because cured foam residues can build up on both the stirrer and mixer barrel. This build-up can diminish mixing quality, causing...
Fig. 12-4 CDC pumping system.
the mixer to overheat or jam. After the component streams are stopped, the head is first blown out with a blast of air. The chamber is then flushed with an appropriate solvent followed by another air blast to dry the head. Methylene chloride is a common solvent, but cost and environmental concerns have led to a search for alternative solvents. Several proprietary agents are available. Hot-water flushing systems were introduced in the 1980s and work satisfactorily for some applications. The flush water may be reused after decanting to remove foam solids. Low-pressure mix heads typically are partially disassembled each day following operations for thorough cleaning.

The use of particulate fillers to modify foam properties presents a number of problems in processing. These include the strong tendency of fillers to settle and cake; oil absorption of some fillers, which increases viscosity and mixing difficulty; metering pump wear; and filler agglomeration. Edge-Sweets (PTI) Co. has developed and patented a low-pressure mix head system, designated FFH, which overcomes these problems by metering dry fillers into the mix chamber. Up to four different dry fillers are metered into an auger screw that is mounted concentrically to the mix chamber. The fillers are then flushed with an appropriate solvent followed by another air blast to dry the head. Methylene chloride is a common solvent, but cost and environmental concerns have led to a search for alternative solvents. Several proprietary agents are available. Hot-water flushing systems were introduced in the 1980s and work satisfactorily for some applications. The flush water may be reused after decanting to remove foam solids. Low-pressure mix heads typically are partially disassembled each day following operations for thorough cleaning.

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High-pressure Mixing

Although used since the early days of the industry, high-pressure impingement mixing has become increasingly popular since the mid-1970s. The reasons are threefold. First, they can handle very fast reacting systems. Second, flush solvent is eliminated. Finally, the high-pressure machines are less complicated and require less overall maintenance than low-pressure machines. The high pressure in the mix head is dissipated in mixing and heat energy. The discharge pressure from the mix head is the back pressure created by the material flow through the restriction of the discharge nozzle outlet. The heads are opened and closed hydraulically, and no mechanical stirrers are required. For effective mixing, the mix head chamber diameter is matched to the desired machine output. If the output is too low for the diameter, the mix quality is poor. If the output is too high, splashing is a problem when making open pours.

As the interest in high pressure grew, the machine manufacturers were particularly aggressive in patenting head designs, and in many cases, aggressively protected those patent rights. This has led to many commercialized concepts. Another reason for developing new mix head designs was to improve the mixing efficiency at high pressure to approach the quality of the best low-pressure mixers. A schematic of one early type of high-pressure head (cross-licensed between Elastogran Polyurethane GmbH and Krauss Maffei) is shown schematically in Fig. 12-8. This head features recirculation grooves that are cut into the single moving part, the control and clean-out piston. The component streams enter the head directly opposite from each other for direct impingement. When the head is closed, the components are pumped through the recirculation grooves under the same conditions they see when the mix head is open. The impingement pressure is controlled by fixed orifices or needle nozzles that are mounted in the mix head body. The control piston opens very rapidly as the head is shifted from the recirculation state to the mixing state; this is on the order of a few microseconds. Speed is essential to prevent operational problems, because the component streams are shut off momentarily during the switch. The mix head is sealed between the reacting components when closed by the close tolerance of the parts and a self-renewing polyurethane seal. As the patents for the recirculation grooves expired, this simple concept was adopted by other manufacturers in a variety of head designs.

The majority of high-pressure machines are equipped with two-component mix heads. While heads are available with more component streams, these designs usually support specific requirements. For example, Cannon introduced its TRIO mix head with components entering at 120˚ angles to each other. This arrangement improves mixing, particularly with very fast reacting chemical systems. Four-component mix heads are also available for specific applications.

While the straight head design shown in Fig. 12-8 is satisfactory for many applications, special head designs are available to reduce splashing and/or improve mix quality. The most popular of these is the L-head design, shown in Fig. 12-9. This design features both mixing (or transverse) and cleanout pistons. Heads of this type include the Cannon FPL, Elastogran SMA, Gusmer-Admiral RIM X, Krauss-Maffei UL, and Linden Industries MHL. The heads vary in mix chamber length, impingement nozzle arrangements, and other details to avoid patent infringement. Another Elastogran variant is the B-head design, which has three-component injection and actuated pins below the mix zone to smooth the flow. The major component is normally split into two opposing streams and the minor component enters roughly perpendicular to the opposed streams. The B-head schematic is shown in Fig. 12-10, and the operating principle is shown in Fig. 12-11.

Hennecke Machinery has taken two other approaches to improved mixing. These are the MQ and MX mix heads, shown in
Fig. 12-7 FFH mix head system.
CHAPTER 12

FOAM EQUIPMENT

Fig. 12-8 Principle of recirculating high-pressure mix head.

Mold
Dispense

Recirculate

Component A

Component B

Hydraulic oil

Hydraulic oil
Fig. 12-9 Operating principle of L-type mix head.
All of these designs provide improved mixing compared to the straight mix head shown in Fig. 12-8. Special heads were also developed for adding color to the reacting mixture. This application is particularly directed to integral skin or high-density microcellular foams, which require very uniform color. Cannon has the CCS color system, which directs the liquid color pigment through a hole bored through the cleanout piston. Another successful approach for color addition is done with a third stream added to the basic L-head configuration.

With some chemical systems, particularly high-density microcellular and integral skin foams, aftermixers are used in closed mold pours. These mixers are channels cut into the mold that do little actual mixing. They create back pressure on the mix head, which increases its efficiency.

**TEMPERATURE CONTROL**

Since polyurethane foaming involves chemical reactions, good temperature control is essential for maintaining foam production consistency. Particularly demanding are the requirements for high-pressure machines due to the heat generated by recirculating under high pressure. It is common to see a temperature increase of 10–15°F (6–8°C) in a single pass of the material through the mix head. One way to avoid heat build-up is to have automatic switching for low-pressure recirculation when there is sufficient time between foam shots. Most machine systems are equipped for heating and cooling to cope with a range of ambient conditions. Production systems typically achieve temperature control within ±2°F (±1°C).

The machine day tanks are part of the temperature control system if they are fitted with jackets, external coils, or internal coils. Heating is done by electrical units immersed in the component tank or fitted to the component line at an appropriate location. A more common heating method is to recirculate hot water that is generated in a separate unit. Cooling water is supplied from a chiller unit or other local supply (water mains or wells) if the temperature is maintained at 60°F (16°C) or less. Using sensors located in the component streams, the temperature is controlled by either cycling between the hot and cold water sources or by using tempered water. When heat exchangers are used, the location is a matter of design philosophy.

With all types of machines, separate temperature control loops with dedicated lines and recirculation pumps are used. Some high-pressure machines use a recirculating system that also provides low-pressure feed to the inlets of the high-pressure metering pumps. The simplest system for high-pressure systems uses the metering pumps as recirculating pumps, with the heat exchangers placed in the return lines to the day tank. Plate heat exchangers have become increasingly popular due to their efficiency, low pressure drop, and ease of cleaning compared to tube-and-shell heat exchangers.

**PROCESS CONTROL SYSTEMS**

Systems range from basic relay logic systems, which turn equipment on and off in response to manual actuation and mechanical timers, to highly sophisticated computer-monitored electronic systems. Statistical process control data are generated by various means including high-pressure flowmeters, pressure transducers, and rapid-response temperature sensors. Flowmeter systems can provide flow control by using variable-speed drives for metering pumps or by servo adjustment of pump output. Programmable systems frequently feature CRT displays for easy access to control and process parameters.

The costs for modern process controls can exceed that for the mechanical components of the machinery. In addition to controlling the foam machinery, the systems can also control any conveying systems, temperature systems, mix head traversers, and molds for complete system integration.
1. Closed and recirculation position

2. Recirculation with mixing pins in mix position

3. Foaming position

Fig. 12-11 Operating principle of Elastogran B-type mix head.
Fig. 12-12 Operating principle of Hennecke MQ mix head.
Fig. 12-13 Operating principle of Hennecke MX mix head.
There are three main types of foam machines: slab stock, block foam, and molded foam.

**SLAB STOCK FOAM MACHINES**

Slab stock foam machines produce large continuous slabs or blocks of foam, which are later fabricated for use in final products. Fabricated parts include furniture cushions, mattress cores, carpet underlay, packaging, clothing innerliners, recreational vehicle seating, vehicle interior trim pads, and aircraft seating.

A conveying system is an integral part of a basic slab stock foam machine, and most lines are supplied as a single unit. The conveying system is a powered slat conveyer that is capable of varying the speed and angle from horizontal. The conveyer also has moving side walls that match the speed of the slat conveyer. The side walls are moved to adjust the width of the foam block buns. Bun width changes are made during production; this width must increase if such changes are made. Many variations of slab foam machinery exist. Machinery suppliers have attempted to make the buns more rectangular to reduce trim losses when the foam is fabricated. At least 10% more prime foam is obtainable from a rectangular block compared to a conventional crowned block.

To describe a crowned block, Fig. 12-14 shows the profile of a rising foam bun. The components are poured onto an angled conveyer to permit higher buns than are possible on a flat conveyer. As the foam mixture leaves the mix head, it is clear or slightly cloudy (as long as the polyol is clear and contains no fillers). The mix head or a dispensing hose is traversed across the conveyer to distribute the material as evenly as possible. The conveyer and side support walls are lined with treated paper or plastic film that moves at the same speed as the conveyer. As soon as the reaction becomes visible, the material is said to be creaming; the cream line is the distance from the mix head to the start of creaming.

As the foam begins to rise, there is frictional drag on the foam from the side wall paper/film. As a result, the foam at the side walls does not rise as much as that in the center of the bun, thereby giving a crowned shape. Generally the higher the bun, the higher the crown. Careful control of the traversing action can reduce the crowning. The foam reaches its maximum height, at which time “health bubbles” appear; these indicate that the cell walls are rupturing and the gas generated (which causes the foam to rise) is being released. A slight amount of sigh back occurs shortly thereafter; this may slightly reduce the crown. A bun’s cross-section shows where the trim loss occurs, as indicated in Fig. 12-16. Obviously, a flatter bun reduces the trim loss.

Conventional slab stock machines have output capabilities approaching 1100 lb/min (499 kg/min) and conveyer speeds up to 33 ft/min (10 m/min). Conveyer lengths and widths vary depending on the intended use of the foam but are generally 50-200 ft (15-61 m) long and 6-8 ft (1.8-2.4 m) wide. Bun height is controlled by the angle of the conveyer and the output of the machine. Therefore, good coordination is required between conveyer speed, conveyer angle, metering output, and the chemistry to maintain consistent production. Conventional conveyer lines (and the conversion of those lines to make flat-top buns) require the most floor space of any flexible slab stock foam line.

Several mechanical methods are used to make buns that are more rectangular. The machinery is often referred to as flat-top equipment. Numerous patents were issued for these methods. Royalties are frequently required when these special machines are used. Even with royalty payments considered, flat-topping normally results in lower-cost foam production.

The earliest flat-top methods were modifications to the conventional conveyer system. A schematic of a conventional system is shown in Fig. 12-16. Side wall paper is not shown in this figure. Figure 12-17 shows the Draka/Petzetakis modification. In this version, an additional side wall film is used. The film is lifted at a rate equal to the rise rate of the foam. Frictional drag is minimized to give a relatively flat-topped bun. This system is difficult to control and is labor intensive, since additional operators are required to handle the film.

Another modification of a conventional machine to give a flat-top bun is the Planiblock, Hennecke, or Econo Foam process.
Although the concept of these processes is the same, their details differ. The Planiblock and Hennecke systems were designed to retrofit existing lines, while the Econo Foam system was a complete line system. These systems use a top release paper to help spread the foam uniformly across the conveyer. The rise is restrained by special slats or pressure plates to give the flat-top surface. The top paper is automatically perforated to allow the foam to gas off, and the foam is essentially continuously molded. A schematic of the Planiblock system is shown in Fig. 12-18.

The most popular current flat-top equipment is the Maxfoam approach, developed by Unifoam Company and shown in Fig. 12-19. This approach requires completely new equipment. In this case, the components are dispensed through a fixed mix head at the bottom of a trough located at the end of a conveyer. The rising foam overflows the trough onto an insulated fall plate. The fall plate angle and the conveyer speed are adjusted to keep the top surface flat. In essence, the foam “rises” down. The original equipment had capability for only one width at a time. To get varying widths, the trough was exchanged. Newer versions, called Varimax, can change the width easily and quickly. The output of a Maxfoam line is lower.
than that of a conventional line; outputs range from 440–880 lb/min (200–400 kg/min), and conveyor speeds are 13–26 ft/min (4–8 m/min). Bun heights are normally 40–50 in. (1–1.3 m).

All of the conveying systems described previously are designed for high-capacity production of slab foams. The basic layout of the line requires a large floor area. A machine was developed to reduce floor space requirements while providing accurately shaped round or rectangular buns. This is the Vertifoam® machine, developed by Hyman PLC and Crain Industries, now licensed by Vertifoam International, Ltd., which produces foam vertically instead of horizontally. The metering unit capacity is low compared to that of horizontal machines: 200 lb/min (91 kg/min). Maximum block dimensions are 7 × 7 ft (2.1 × 2.1 m), and the block is cut to 4.5-ft (1.4-m) lengths at the end of the foaming conveyor. Block dimensions can be varied quickly, and round blocks up to 5.5 ft (1.7 m) in diameter are possible. The machine is shown in Fig. 12-20.

Round blocks are also made on other machines with special conveyer configurations and are desirable to reduce scrap losses when foams are peeled from a bun in the same manner as trees are peeled for plywood. Peeling is used to make wide, continuous sheets for applications such as carpet underlay.

With the elimination of CFCs as auxiliary blowing agents, formulation adjustments were necessary to make various foam grades. Some of the chemical modifications consist of low-boiling-point hydrofluorocarbons (HFCs) and normal gases, such as carbon dioxide and cyclopentane. These materials present unique metering requirements for successful use. The products are used by adding them batchwise to a proper mix tank. This requires higher-pressure-
rated tanks than those normally used. Cyclopentane adds the complication of being a flammable and potentially explosive product.

Machinery manufacturers have responded to the challenge by introducing in-line blending equipment. These units include the Cellomat™ system from Hennecke and the EasyFroth™ system from Cannon. Cannon has gone one step further, introducing a complete slab foam production line, the CarDio® system, as shown in Fig. 12-21. Liquid carbon dioxide is blended into the polyol and fed to a multicomponent low-pressure mixer. The mixed materials exiting the mix head are a rapidly expanding froth. To control this froth, a special laydown device stabilizes the froth and provides a smooth laydown with the foam pre-expanded to about 30% of its full height. Conveyer speeds are generally slower and output is lower than those for Maxfoam machines, but the pre-expansion gives a fully cured foam quicker. A typical output of 90–130 lb/min (41–59 kg/min) and a conveyer speed of 3.3 ft/min (1 m/min) is used to produce full-size blocks. The CarDio system can be retrofitted to existing conventional or Maxfoam slab stock machines.

Since the carbon dioxide that is generated in the water-isocyanate reaction is the primary blowing agent in flexible foams, increasing the water level is a means of replacing CFCs or methylene chloride if the objective is only to adjust density. Unfortunately, other foam properties are also affected (some adversely). While other formulation changes can overcome physical property changes, higher water levels give higher exothermic heat, which can lead to foam scorching (discoloration) or autoignition. To overcome this problem, rapid cooling systems were developed and patented for slab stock foams; these systems eliminate the need for auxiliary blowing agents. Two commercial systems are Enviro-Cure®, developed by Crain Industries, and RapidCure®, developed by General Foam. Both of these systems can be retrofitted to existing conveying systems. They use cooling chambers to pull cool air through the foam to reduce its temperature. A short delay between foaming and cooling is desirable to get the proper foam cure. Depending on the particular foam machine operation, the foam block may require trimming, or barrier films may be applied to ensure that the cool air flows completely through the foam. The RapidCure system additionally has a carbon absorption tower to prevent volatile material emissions to the atmosphere.

For many years, foam formulations were modified to maintain the density of the foams as the production plant altitude varied. At higher altitudes, the foam has a lower density for a given formulation. Taking this into account, Foamex patented the variable-pressure foaming (VPF) slab stock process, which can produce a wide range of densities using water as the only source of blowing agent. This is done by adjusting the ambient pressure around the foam as it reacts and rises.

**BLOCK FOAM MACHINES**

Preparation of foams in large discrete blocks was done for many years, primarily in lesser-developed countries. Machinery developed for this purpose is shown in Fig. 12-22. The foam is supplied to the day tanks as two components: a polyol blended with water and catalysts and an isocyanate. These components are fed automatically to the tanks. The cycle starts with the polyol component in the mix tank with both weigh tanks filled. The mixer is started, and the drain valve for the isocyanate tank is opened. After a predetermined mix time, the hinged bottom of the mix tank opens, dropping the mixed foam reactants into the mold box. The bottom then closes, and the next polyol component charge is fed to the mix tank to act
as a diluent to the residual foam and to nearly eliminate foam build-up in the mix tank. The mold box, which is on wheels, is moved away from the machine. An end flap is raised and a floating lid is placed on the top to achieve the desired rectangular configuration for maximum foam utilization.

This equipment, commonly known as the “Golden Bucket”, presents several processing difficulties. The components require careful formulation to avoid foaming problems with the partial prepolymer that is left in the mix tank at the end of each cycle. If mix tank cleaning is required, the component in the tank is often scrapped. As the foam mixture is dumped from the mix tank, it splashes and traps air, frequently leading to foam defects. It is difficult to make low-density foams with this equipment.

The discrete block foaming system was updated by developing and patenting the Controlled Environment Foaming (CEF) system by Foam One. In principle, it is similar to the VPF system previously described, where the foam is made under reduced-pressure conditions. This process can eliminate an auxiliary blowing agent in preparing low-density foams. Foams are made in any cross-section desired for final fabrication. The foam components are introduced into a closed mold. By ensuring full mold fill under vacuum conditions, the foam yield is maximized, and larger blocks are possible than with the older block foam method. An additional advantage of the CEF system is that the foam is virtually skin free. A schematic of the CEF system (less the proprietary mixing equipment) is shown in Fig. 12-23.

MOLDED FOAM MACHINES

Molded foam techniques are used when the final product cannot be made by fabrication from slab foam because of design, cost, or chemical reaction constraints. Molded products include items such as automotive cushions with molded-in frames or support wires, automotive instrument panels, automotive exterior body parts, refrigerators, building doors, and metal-faced construction panels.

Metering units for molded foam are either high- or low-pressure units with the output sized to most effectively produce the required part. There are several types of conveying systems available for molded foams such as rotary tables, hanging conveyers, drag chain conveyers, shuttle systems, and laminating lines. The type of conveyer chosen depends on factors such as the number of parts required per unit time, foam cure rate, pour technique, and part complexity, which may require multiple operations or mold manipulation.

With the conveying system, some type of mix head support is required to manipulate the head over the mold. This can range from a manually operated boom to an automatic multiple-axis robot. Molds are poured while either open or closed.

FOAM CONFIGURATION

The flexible molded foam industry grew with three basic technologies: cold cure, hot cure, and high resiliency. Cold-cure foams are processed at ambient temperatures. Molds may be temperature
Hot-cure molded foams require conveying systems with high-temperature oven capabilities. The typical conveyer configuration is a “racetrack” design, with a drag chain conveyer. Molds are mounted in carriers that ride on parallel drive chains. Mold opening and closing is usually done by using curved rails. When high-resiliency foams were introduced, production was started on existing lines. Modifications were made to increase line speeds and to reduce oven requirements. Few changes were required to the metering equipment. Racetrack lines are continuous movement lines, but it is difficult to provide special movement of individual molds. A schematic of racetrack lines is shown in Fig. 12-24. Racetrack lines are most frequently used when large volumes of identical parts are required over extended periods of time. All mold temperature control on these lines is done by hot-air recirculation. As technology advanced, the cure temperature for high-resiliency foams decreased, and the ovens on older lines often served only to conserve foam exothermic heat for cure enhancement. Mold carriers are switched on these lines by using forklifts or overhead cranes.

A variant of the drag chain conveyer system is the hanging conveyer. In this design, the molds are mounted in carriers suspended from an overhead conveyer chain. Provisions are made for mold temperature control by mounting hot-water heater units in the mold carriers. A single mold heater may serve several molds. Power to the heaters is supplied through slip rails. Because the mold carriers are precisely positioned, overhead conveying systems offer the possibility for more mold actuation, such as for clamping airbags and for automatic opening and closing devices. Mold carriers are changed by guide rails that are switched onto the overhead system.

Drag chain conveyers are also made with a single drive chain, with wheeled carts riding on a steel track. Various mold sizes can be mounted on the carts to provide production flexibility. As with the overhead chain type, power is supplied to the mold carriers for temperature control or mold actuation.

Rotary table or carousel systems are used for many molded foam applications, both flexible and rigid, and the lines may be custom built for specific part applications. The usual construction for heavy molds features the table supported by a central bearing point, with the outer edge supported by heavy-duty nonpneumatic wheels. The table is electrically or hydraulically actuated by a caterpillar drive that engages drive dogs on the outer edge of the table, a drive chain around the circumference, or pneumatic tires driving along the outer vertical edge. Light-duty tables are supported by only the central bearing; they are driven by the same means as the heavy tables or by cam follower systems.

The tables are usually indexed between stations. Indexing provides more working time for operators and simplifies the pour patterns and mix head carriers. While mold carriers can be changed automatically without interrupting production, cost considerations generally require that the molds are changed by forklift or overhead cranes during break periods. Rotary tables are more versatile than the racetrack systems, since it is easy to install a variety of molds on the table and achieve proper control. Molds are frequently temperature controlled with tempered water systems, and provisions for vacuum are easily made when molding parts into plastic or special fabric covers. A heavy-duty rotary table system is shown in Fig. 12-25.

Many molded foam applications are best met by using stationary molds. These applications include a variety of parts, such as automotive trim parts and instrument panels, automotive exterior body panels, residential entrance doors, specialized seating products, and refrigerated display cases. Multiple molds are serviced by using manually operated booms or by robots. Another approach is to use ring line systems. This system has multiple mix heads that are supplied from a single metering unit. The mix heads are operated in any sequence; however, only one head may pour at a given time. While the mix heads are most likely fixed to the molds, the system is adaptable to boom or traverser operation. The number of heads possible is determined by the line length and foam reaction time requirements, with a typical maximum of 12 heads. Figure 12-26 shows the concept.

![Fig. 12-24 Molded foam lines—racetrack configuration.](image-url)
Fig. 12-25 Molded foam line—rotary table configuration.
Foam molds for cushion production are usually cast aluminum; however, some small-scale operations have used epoxy or glass fiber-reinforced polyester or epoxy molds. Molds for integral skin and microcellular foams used for automotive exterior parts are nickel-plated aluminum or steel since grain, texturing, or Class-A paintable surfaces are important for the applications. Automotive instrument panel and door trim molds are typically cast or machined aluminum or epoxy-surfaced cast aluminum. The epoxy surfaces on the aluminum facilitate tuning molds for better fit. Metal molds are often made with cast-in temperature control coils for optimum efficiency. Machined metal tools are gun drilled for water temperature control. Some molds for small parts, such as those for shoe soles, are electrically heated. Molds are either self-contained (all means of actuation are part of a single unit) or they are mounted in mold carriers. Mold carriers range from simple clamping frames to heavy hydraulic presses, depending on the total system requirements.

**MOLD CARRIERS**

Simple clamping frames are used on the drag chain and hanging conveyor systems. The back edge of the frame is hinged, and the front edge is equipped with some type of toggle clamp. Opening and closing of the mold carrier is a function of the conveying system. The molds are adjusted in the frames to achieve the proper sealing at the parting line. Small molds used on stationary systems also use this concept, since they are easily manipulated manually.

The simple mold carriers can be upgrading to carriers with hydraulic or pneumatic actuation for opening, closing, and locking, and all are controlled by programmable logic controllers (PLC).

These carriers are also provided with inflatable air cushions to move the cavity or lid of the mold after the frame is clamped to ensure full metal-to-metal contact across the entire parting line. This eliminates frequently adjusting clamps during prolonged production or when molds are changed. The air cushions provide self-adjustment.

As molds get larger or the foaming pressure increases, the previously discussed mold carriers may not be suitable. Mold carriers that have their origins in presses used for woodworking, plastic compression molding, and injection molding have been developed for foam handling. Both pneumatically operated (Fig. 12-27) and hydraulically operated (Fig. 12-28) mold carriers are available. These carriers are used in producing door panels, steering wheels, computer housings, and automotive body panels and fascias.

**FIXTURING**

Four-post presses used for mold spotting or compression molding are also used in foam-part production for products such as residential doors or refrigeration units. Part fixtures with metal or plastic faces and other fittings are placed in the press. When the press is closed, the foam is injected into the cavities through pour holes in the part.

For hot-molded flexible foams, the lids generally “float” under restrained conditions, with the lid lifting from the foam rise and then settling as sigh back occurs. Vents are drilled in the lid in appropriate areas to eliminate trapped air. Venting is also placed around the parting or flash line, where the cavity and lid meet.

High-resiliency foam molds are of higher quality than hot-cure molds. They are of heavier construction and have very tight flash
Fig. 12-27 Pneumatically operated mold carrier.
Fig. 12-28 Hydraulically operated mold carrier.
lines; the lid is not permitted to lift during the foam rise, because this can lead to foam collapse problems. Some molds are fitted with extruded silicone rubber seals to ensure sealing. Venting is also more carefully controlled with high-resiliency foams.

MOLD TEMPERATURE

The initial mold temperature is critical. With hot-molded foams, the optimum is about 100˚ F (38˚ C). Much lower temperatures give a soft foam layer, a densified layer, and then the desired foam in the core. As the temperature is increased, the densified layer becomes thinner and closer to the surface. When the mold gets too hot, the skin that forms is loose and flaky, creating a poor appearance, or areas of very closed cell foam can exist. High-resiliency foams can be poured into cold molds with few problems other than higher density and longer cure, since there is usually no skin and none of the densification that occurs with hot foam. If the mold gets too high with high-resiliency foam, outer surface defects and collapse become a problem.

Instrument panels can show a range of problems if the mold temperature is not correct. These panels are a composite of an outer skin (ABS, vinyl, or polyolefin), semiflexible foam, and an insert or retainer (plastic, metal, or wood fiber). If the mold temperature is low, the foam density increases, and the part does not completely fill out. If the mold temperature is too high, premature foam gel can occur, resulting in collapse or voiding. Gas pressure may also increase to the point that when the part is demolded, the skin is blown away from the foam. Shrinkage may also be a problem.

CRUSHING

Cushion foams usually have a large number of closed cells on demold. This requires crushing the foam after demolding, since the foam otherwise shrinks. Crushing is done by passing the foam through crushing rolls or by putting it into a vacuum chamber, where it is cycled through atmospheric pressure and a vacuum. Special techniques are available for high-resiliency foams to eliminate the need for crushing. Among these is the patented timed-pressure release (TPR) method, in which the foam mold is opened and then reclamped during the closed mold cure cycle. The same principle is also used in instrument panel production to prevent “gassing,” or blowing away of the cover on demolding.

Rigid foam molds for some applications are essentially the same as the molds used for flexible foams. Wood simulation parts are made with silicone rubber mold liners so that the exact surface replication is achieved. For molded products such as refrigerators, hot-water heaters, and doors, the outer metal or plastic shell of the product acts as the mold; however, supporting fixtures or jigs are required to prevent part distortion. These supporting structures take the place of mold carriers; they are integrated into shuttle or transfer line conveying systems or used in stationary systems specifically designed for the product.

MOLD RELEASES

Mold releases are used to facilitate demolding of foam parts where the foam contacts the mold surface. Various combinations of natural and synthetic waxes are used to obtain the best results. For high-resiliency foams, some mold releases add dimethylsilicone fluids to cause cell breakdown at the foam surface, providing greater breathability. Mold releases are characterized as water-based or solvent-based, depending on the carrier. Water-based mold releases are more difficult to use with high-resiliency foams, because the molds are too cold to evaporate the water in a short time. Alcohol in the release assists evaporation. For cushion foams, the mold release does not require removal from the part before it is used. Other parts may require removal of the release because of postoperation requirements. In some cases, solvent or soap washing is required. Some products, such as steering wheels and wood simulation, use in-mold coatings that act as the mold release and form the base or top color for the finished part.

Depending on the character of the in-mold coating, a light film of a conventional mold release is sprayed on the mold first. Excess mold release can build up on molds. Because part sticking can then result, operators may incorrectly add more release. The mold release can act as a thermal barrier, and trapped solvent can cause defects. To reduce this problem for integral skin and high-density microcellular foams where surface appearance is critical, internal mold releases were developed. These releases are generally proprietary and covered by patents. The basic approach is to use a material such as zinc stearate as the internal release. Even with an internal mold release, a periodic light coat of a standard mold release is usually necessary to ensure good part release. Mold release is minimized if the part is to be painted.

RIGID FOAM LAMINATE BOARD LINES

While a number of urethane foam products are manufactured in essentially their final form, few products match the complexity of production sophistication for faced rigid foam panels used in building wall, roof, and cold storage unit construction. These lines incorporate flexible or rigid facing layers, with rigid insulating foam continuously and automatically starting with rolls or sheets of facing material and the urethane raw materials, and ending with cut-to-length banded panels ready for shipment. A complete production line is shown in Fig. 12-29. Such a line can produce panels in the ranges shown in Table 12-1.

The largest conveyer of this type for steel-faced panels has a maximum output rate of 65 ft/min (20 m/min).

Because of the foaming pressure of the rigid foam, the conveyer is sturdy built to support the flat panels. Furthermore, the slat conveyer is properly guided to eliminate the pitch of the slat as it reverses direction at the end of the conveyer. This pitch, unless controlled, results in a polygon effect, which marks the face of the panel. Likewise, the upper and lower slat conveyers are absolutely speed-synchronized to prevent damage to the facings, particularly to painted finishes. Replaceable seal chains run at the edges of the conveyer slats to retain the reacting foam and give the desired edge profile of the finished panel.

PRODUCTION CYCLE

The production cycle takes the following steps:

1. The flexible facing material is fed to the roll forming machine to give the desired face appearance. If the face material is not flexible, the sheets are fed into the interface conveyer by a vacuum lifter. Roll forming dies can be changed in 30–60 minutes to meet varying requirements.
CHAPTER 12

RIGID FOAM LAMINATE BOARD LINES

Infeed and profiling
1   Coil unwinding station
3   Rollforming machine
2   Vacuum lifter

Metering and coating
4   Coating gantry
6   High pressure metering machine
5   Tank farm

The double belt
7   Double slat conveyer
9   Sealing chain structure
8   Upper and lower slat chain band

Cutting and cooling
10  Cross cutter (circular saw)
12  Cooling conveyer
11  Cross cutter (band saw)

Stacking and storing
13  Stacking system
14  Rack stacker

Controlling
15  Main control panel
16  Control

Fig. 12-29 Double-belt rigid panel production line.
As produced, many foamed polyurethanes are not immediately useful as an end product. Various fabrication methods were developed for specific types of foam, and some of these are discussed in the following sections.

TRIMMING, SLITTING AND CUTTING

A variety of equipment is available for cutting and fabricating slab stock foams into the sizes and shapes required for finished products. Cutting blades for flexible foams are kerfless to avoid ripping the foam and producing fine dust. Some types of cutting equipment are:

**Bandknife Slitters**

These slitters are positioned at any angle; however, the common orientation is horizontal or vertical. Some saws are equipped with automatic sharpeners. In some operations, buns up to 200 ft (61 m) long are slit by fixed-position horizontal slitters and reversible belt conveyers running at up to 200 ft/min (61 m/min). The foam is cut into thin roll stock that is used for lamination. The loose roll from the cutting operation may be placed in another machine for diameter compression and wrapping for shipment. Smaller slitter versions are used with automatic or manual tables for cutting small bun sections. The table surfaces are movable.

**Baumer Slitters**

These special slitters use bun lengths of about 400 ft (122 m). The ends of two 200 ft (61 m) buns are glued together to form an over-and-under loop that conforms to the conveyer. The slitter cuts from the inside of the loop. The slitter blade is automatically indexed down to maintain foam thickness. Roll stock is the final product.

**Carousel Slitters**

Short bun sections are placed on a special rotary table that is equipped with a vacuum to hold the buns in place. The table indexes the foam through a horizontal slitter blade to cut the foam to the desired thickness. The carousel and slitter are programmed to give the desired thick-cut slab foams, which are used for products such as furniture cushions or mattresses.

**Profile Cutters**

These cutters are a modification of the bandknife slitters using tables. The tables are fitted with dies and compression devices. The foam is compressed as it passes the slitter blade. When the foam recovers, it has the desired shape, such as dimpled foam used for packaging, mattress pads, pillows, and balls. The concept is shown in Fig. 12-30. Modern versions of these cutters use computer-controlled circular knife blades that can cut extremely complicated configurations.

**Die Cutters**

These cutters are used to cut thin sheets of foam (roll stock) to the desired contour for applications such as automotive trim covers or panels. Sharp die steel bands are fixed in plywood bases. The bases are mounted on a stamping press, which may be pneumatic or

---

**TABLE 12-1**

**Rigid Panel Sizes**

<table>
<thead>
<tr>
<th>Cut panel length</th>
<th>7–80 ft (2–24 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finished panel width</td>
<td>15–50 in. (381–1270 mm)</td>
</tr>
<tr>
<td>Finished panel thickness</td>
<td>1.5–8.0 in. (38–203 mm)</td>
</tr>
</tbody>
</table>

---

2. The facings are preheated to ensure proper adhesion of the foam to the face. Heated air in a closed-loop system is used, since infrared heating is ineffective with bare metal surfaces.

3. Rigid foam is dispersed using high-pressure metering equipment. The mix head, mounted on a continuously variable-speed traversing mechanism, is a special unit with a fan nozzle that disperses the foam uniformly across the lower facing material. Since the mix head does not have the self-cleaning ability of a standard high-pressure head, foam build-up in the head can occur. To avoid production interruptions, two mix heads are mounted on the traversing mechanism, and foam component flow can be switched between heads. The fouled head is automatically decoupled from the traverser for cleaning.

4. The conveyer is temperature controlled by heated air that passes through the upper and lower chords of the conveyer.

5. Upon exiting the double-belt conveyer, the foam panel enters the cutoff section. Circular or band saw arrangements are possible. Panels are cut in approximately 10 seconds with a tolerance of ±0.04 in. (±1 mm). For roof panels, which require an end-to-end overlap, saws are arranged to automatically cut the overlap section.

6. With panels over 4 in. (101 mm) thick, cooling is required, and a cooling conveyer is used.

7. If the panels are used for cold storage units, they are additionally milled to form a tight-fitting, tongue-and-groove shape.

8. At the end of the line, the panels exit on automatic stacking conveyers and are transferred to banding and wrapping machines as required.

The entire production line is maintained by a central control system that is equipped with monitors. Each section can, however, be operated independently for set-up and maintenance. Full process documentation is maintained by integration of a compatible industrial computer.
hydraulic, to cut the foam sheet. When used with special foams designed for flame lamination, the die-cutting operation features electrically heated platens/cutters to combine the operations of die cutting with the shaping of a flat foam piece and edge sealing in a single operation. Lamination of the foam to a cover can also be integrated into the operation using appropriate adhesives.

Routers
High-speed special rotary blades are used to cut grooves in thin sheet foam for the same applications as given for die cutters. Routers are used where it is not practical to fabricate the foam by other means.

Log Peelers
Where there is a requirement to have the foam slit wider than a standard bun width, log peelers are used to cut circular buns in the same fashion as plywood is cut from wooden logs.

Hot-wire Cutters
Foam is also cut by electrically heated wires. Such systems have limited commercial application because of slow cutting speed, problems with foam melting or discoloration, and high maintenance. If small foam blocks are required, however, hot-wire cutting can provide very accurately cut blocks.

LAMINATION
Lamination is used to bond foam to fabrics or other cover and substrate materials for use in automotive trim covers, headliners, sound-deadening pads, trunk liners, seating, and similar products. At one time, many automotive seat cushions were made using laminated parts; the cushions were referred to as “skived” seats, and the process is still used today to make aircraft and recreational vehicle seats. Two important factors in lamination are the choice of adhesive and the process used. Adhesive choice is based on economics and application requirements. Independent of the adhesive and process, urethane foam that is laminated to most fabrics requires good web tension and alignment control.

ADHESIVE TYPES
Solvent-based Rubber or Urethane Systems
Solvent-based systems are among the highest quality adhesives. The solvents chosen are generally volatile organic solvents, which are evaporated by various means. Since many of the solvents are flammable, excess air is used to dilute the vapors so that they do not sustain combustion or explode in dryer chambers. The solvent vapors must be eliminated from atmospheric discharge, through use of a vapor incinerator, carbon absorption, or more modern equipment that condenses the solvent for recovery and reuse. Carbon absorption has the disadvantage of the carbon pellets requiring periodic regeneration or replacement. If regeneration is done, the vapors are recovered or incinerated. Incineration is costly unless the heat is recovered for plant heating or other process requirements.

Latex Adhesives
These adhesives are water based but frequently contain other compounds, such as ammonia, that require special handling of the vapors from the dryer. Higher heat is required for latex adhesives than for the solvent types.

Hot-melt Systems
These systems use a variety of conventional hot-melt glues, thermoplastic films, and powdered adhesives. Powders have been used in laminating fabrics for garments since about 1965. Polyesters are the most frequently used powders. These polyesters are also supplied in films or meltblown webs or in molten forms. The most common polyesters are crystaline terephthalate copolymers. These types have melting points of 210–270˚ F (99–132˚ C) and crystallize from the melt in 1–10 minutes, depending on the grade. Adhesive crystallinity is important in fabric lamination to withstand laundering or dry cleaning. Viscosities cover a wide range, and the choice depends on the equipment used for lamination. If the viscosity is too low, the adhesive will flow into the cellular structure, and poor bonds result. Other solid thermoplastic adhesives that are widely used include polyamide, EVA, thermoplastic urethane. Adhesives are also made with the copolymers of polyamide, EVA, and thermoplastic urethane.

Powder
Powder is applied by dry powder spray units. The powder is applied to one of the substrates, which then passes under heaters to melt the adhesive. The second substrate is then applied, and the composite passes through nip rolls before it is taken up on a winder. Powder application has an advantage over molten hot melts in that adhesive build-up in melt trays and doctor blades is eliminated. A schematic of a dry powder system is shown in Fig. 12-31.
Thermoplastic Urethane Films

Thermoplastic urethane films and thermoformable slab foams can be combined in equipment to both laminate and form the composite, providing a product such as insulation or sound-deadening panels for automotive applications. The thermoformable foam is made in slabs and cut to feed into the transport conveyer of the laminating machine. It is heated in a hot-air oven; it then moves into the forming section, and at the same time, the thermoplastic urethane film is unrolled onto the sheet and cut to the proper length. The composite is then fed to the forming press, where the heated foam is cooled to set it to shape and fuse the film to the foam. The thermoplastic film serves as the show and protective surface. A process line for this operation is shown in Fig. 12-32.

Flame Bonding

Flame bonding is melting a foam surface with an open flame to produce a bond with a fabric. The foam is melted by a 2000° F (1093° C) flame before contacting the fabric. This process, used for many years, was originally based on specially formulated flame-laminatable foams. Polyester-based foams were preferred from a processing standpoint; however, they created problems in use because of degradation in warm, humid environments. The original polyether-based foams did not usually provide the desired bond strength. With the advent of the newer polyether polyols, a standard grade of flexible polyether-based foam can now be successfully laminated. To overcome problems with vapors from flaming the foam, most makers of flame-laminating equipment have incorporated scrubbers into their machines.

Composite Products

Composite products containing plastic films (such as PVC or ABS), nonporous fabrics, rigid plastics, metal shapes, or fiberboard are made using the natural adhesive characteristics of the urethane foam during the foaming process. Mixed liquid foam components are injected or poured between the substrates, and the products are formed in suitable molds. Common applications of this approach are automotive instrument panels, head restraints, and door panels. The structural RIM (SRIM) process also uses the adhesive characteristics of the urethane foam to bond materials such as nonwoven or woven glass fiber into rigid shapes that are used for door panel substrates, sunroof covers, spare tire covers, and bumper beams. In some cases, a plastic film is combined in a composite in the same operation. The glass fiber mat is placed in a mold, the urethane foam is dispensed on the mat, and the mold lid is closed. The rigidity of the product is controlled by the type and amount of glass, as well as by the foam formulation used.

DIELECTRIC SEALING

High frequency is used to seal or emboss suitable substrates. This is commonly used for PVC, polyester, and nylon fabrics or films. Special formulations for flexible foams make them sealable; however, even standard foams can be used in dielectrically sealed products if the foam thickness is small.

Radio frequency power is directed to the composite, and the seal is made by the heat-sealing die or electrode that is firmly pressed against the substrate. Time, energy input, and pressure are adjusted to obtain a satisfactory bond.

Embossing is used to simulate stitching or other decorative patterns on the sealing film by using suitably engraved brass dies.

CARPET UNDERLAY

Carpet underlay has become a major market for urethane foams, where it has replaced sponge rubber or jute fiber pads. Urethane underlay has greater durability and is a more uniform product.

PRIME FOAM

Underlay is produced from virgin foam slab stock that is cut to the desired thickness. The highest-quality foams used for this application are made from grafted polyols, which incorporate styrene and/or acrylic triol polymer into the matrix. The slit foam is laminated to a suitable film that permits easy installation of the carpet. Without the film, the nonspill characteristics of the foam make it difficult to stretch the carpet and avoid distortion of the underlay. Special laminating films made from ethylene-acrylic acid copolymers, ethylene-vinyl acetate copolymer, polyethylene, or terpolymers are used to face the underlay. The film is applied using a machine that heats and applies it under carefully controlled pressure. The use of film avoids using liquid adhesives, which are more difficult to apply.

BONDED FOAM

Rebond foam underlay is made from urethane scrap and/or slab foam made especially for this purpose. While the most desirable scrap is from slab production, molded foam scrap is used if it does not contain excessive tough skin or mold release residue, which would interfere with bonding. Scrap may be a preconsumer or postconsumer product. Bonded foam underlay is characterized by high density, high load bearing capability, and relatively low strength compared to prime foam. The high load bearing capability makes bonded foam a preferred product for commercial carpet underlay applications. Bonded foam is also used for other products such as automotive headrests, cushioning inserts for firmness and lateral stability, and energy absorption inserts in snowmobile seats.

To make bonded foam, the scrap is first ground into particles using a shredder. A low free-NCO prepolymer is sprayed onto the particles in a blender/tumbler. If the adhesive is properly applied, the foam particles are not sticky to the touch. The mixture is poured into large block molds or processed continuously on special purpose conveyers. Curing is done by heat, water-catalyst blends, or steam, all under varying degrees of pressure that depend on the density required. The blocks are round or rectangular, depending on the final fabrication process.

Direct Backing

Direct backing of carpet requires that the foam applied to the carpet does not penetrate the carpet facing. Bleed-through gives an unacceptable product. The viscosity of the foaming materials is kept high, and the carpet must have the proper backing.

In one process developed and patented by Textile Rubber and Chemical Co., the foam components are poured on a continuous Teflon®-coated fiberglass belt that has been sprayed with an acrylic release film. The reacting foam components are spread with an air doctor blade to obtain a uniform thickness. The reverse side of the heated carpet is then brought into contact with the
Fig. 12-32 Lamination line for thermoformable foam.
foam. After passing over heated platens while still on the continuous belt to cure the foam, the carpet is placed onto a finish roll.

Frothing techniques for urethanes that are similar to those for latex and PVC are also used. Foam expansion is largely accomplished by frothing, using a mix head as shown in Fig. 12-33. The froth is applied to the carpet by either knife coating to a release paper, with the carpet positioned on top, or by direct knife coating, as shown in Fig. 12-34. Union Carbide and Dow patented variations of this process. Dow licenses the process to use its Enhancer foam technology.

Spray foam technology was developed and patented by ICI in the 1950s. A traversing spray distributes a very fast reacting flexible foam system directly on the back of untreated carpet. The foam is formulated to give partial penetration of the foaming mixture into the carpet to bond the tuft to the primary backing. After partial curing under heat lamps, the carpet passes over a heated embossing roll to compact the foam skin surface for improved durability.

A significant amount of direct-backed carpet is made as molded products for the automotive industry. Large complex parts are made in this manner, and molding provides the opportunity to vary the foam thickness as required to fit the car. In many cases, the carpet is preformed prior to backing. In addition to providing cushioning, carpet backing serves as a sound insulator.
FOAM TYPES

RETICULATED FOAM

Reticulated foam has an extremely open cell structure. These foams are used for applications such as filters, sound absorbing pads, and speaker covers. Over the years, numerous patented processes were developed. Among these are:

- Immersion of the foam in an aqueous solution of an alkaline hydroxide, a water soluble glycol, and an aliphatic alcohol. U.S. 3,423,337.
- As above but replacing the aliphatic alcohol with a monocyclic aromatic alcohol. U.S. 3,423,338.
- Rupturing the cells with a water jet. U.S. 3,862,282.
- Contact with orthotoluidine. U.S. 3,753,756.
- Sealing the foam and combustible mixture in a chamber and igniting the combustible mixture. U.S. 3,175,025.
- Passing a heated stream of gas through the foam to melt the cell walls. U.S. 3,475,525.

Numerous formulation variations were also patented for the application. The preferred methods are those that do not use solvents or water due to the extra processing required to dry the foam after treatment. Perhaps the most common industrial processes are the light pulse and combustion methods.

RECYCLING FOAM

There is pressure on the plastics industry to increase recycling. In 1990, the Polyurethanes Division of the Society of the Plastics Industry established the Polyurethane Recycle and Recovery Council (PURRC) to address the issue of polyurethane product waste disposal. The goal was to reduce the amount of polyurethane that was landfilled by 25% by 1995. Similar activities were established in other parts of the world, particularly in Europe, where recycling is far ahead of that in the United States.

Rebond Foam

Flexible urethane foams are recycled in many ways. The resulting product is rebond or bonded foam. There is a market for this product, and the demand has outpaced the industry’s ability to supply it. Many tons of foam scrap are imported to the United States every year to cover the shortage of scrap for rebond. Scrap from both slab and molded foams is used. Rebound foams are characterized by relatively high densities and low strength properties, but the most important property for most applications is its high load-bearing capability. Carpet underlay is a major market, and many specifications are written for the product. Federal specifications have limited the extenders that are used for bonding adhesives, and the amount of polyester scrap that is combined with the polyether has limited the extenders that are used for bonding adhesives, and the amount of polyester scrap that is combined with the polyether.

A major effort is under way to recover foams from automotive seating. New seat assembly techniques and construction make it easier to recover this foam. Data show that 97% of the foam from pour-in-place seats can be recovered; it takes approximately eight minutes to disassemble a front seat. Ninety-two percent of the foam from cut-and-sew seats is recoverable, and it takes approximately 13 minutes to disassemble this type of front seat.

Recovered scrap foam is worth $500–$1000 per metric ton.

Filler Usage

Another potential application for the scrap from seats or from high-density foamed elastomers is the EcoStream process developed by Woodbridge. The foam is finely ground and used as a filler in new seats. One need for this technique is to find a more economical way to grind the foam; cryogenic grinding is currently used. The Illinois Institute of Technology has developed a process for solid-state shear extrusion (SSSE), which appears promising.

Ground scrap from reject or recovered high-density foamed elastomers used in bumper covers or other automotive body panels is also usable as a filler in making new similar parts. When used in this way, new machinery techniques were developed to overcome swelling of the filler when it was in contact with one of the reactive components. The problem was overcome by providing third-component metering on RIM machinery. As with the EcoStream process, the scrap is finely ground. Larger scrap particles are compression molded to make nonshock automotive parts.

Automotive Shredder Residue

There are foams in the automobile that are difficult to recover. They include the foam in instrument panels, door panels, headliners, and sun visors. In all likelihood, these foams would end up as part of the automotive shredder residue (ASR) that is left from the final breakdown of a scrapped car. ASR, or fluff, remains after as much metal as possible is removed. It is a mixture of rubber, various plastics, textiles, rust, and fluids with an average density of 25 lb/ft³ (40.5 kg/m³). It is a poor fuel because it contains an average ash content of nearly 58%. The National Research Council of Canada reported in 1994 that there are several reasonable solutions to the ASR disposal problem:

- While there was concern that hazardous materials would leach from the ASR if it was landfilled, this was not a problem. In fact, the ASR absorbs hazardous materials from other products in the landfill. ASR also performs better than dirt as a day cover for landfills; it settles less and is not easily washed away.
- ASR can be used in particleboard when combined with other recycled plastics. The resultant board is stronger than wood particleboard.
- Tertiary recovery processes, such as pyrolysis, can recover oil, gas, and carbon black.

A more selective ground scrap containing semiflexible foam with textiles and other plastic scrap is made into composite sheets. The scrap is mixed with polymeric isocyanate and then pressed into shape and cured with steam and heat. The product is suitable for glove box liners, package trays, and similar applications. Rigid foam scrap and panel trimmings, including bits of metal, are processed in the same way as the semiflexible foam previously mentioned. The resultant product is a very strong and durable board stock that is used for building walls and floors. Gymnasium floors made from this board function very well.
CHAPTER 12

FOAM TYPES

Chemical Recycling
There are a variety of chemical means for recovering foams. Some were commercialized to make polyols that are used for rigid foams or as part of a system for sound-deadening viscoelastic foams. In 1992, the PURRC presented a summary of the possibilities for chemical recycling of polyurethanes. This is shown in Table 12-2.

The use of urethanes as a fuel was also evaluated, and the PURRC has development projects underway to determine the best course of developing this fuel.

<table>
<thead>
<tr>
<th>TABLE 12-2</th>
<th>Chemical Recycling of Polyurethanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>Patents</td>
</tr>
<tr>
<td>Hydrolysis</td>
<td>41</td>
</tr>
<tr>
<td>Glycolysis</td>
<td>57</td>
</tr>
<tr>
<td>Aminolysis</td>
<td>10</td>
</tr>
<tr>
<td>Partial chemical thermal</td>
<td>5</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>8</td>
</tr>
<tr>
<td>ISO hydrolysis</td>
<td>24</td>
</tr>
<tr>
<td>Thermal processing</td>
<td>5</td>
</tr>
<tr>
<td>Polyester hydrolysis</td>
<td>0</td>
</tr>
<tr>
<td>Other recycle</td>
<td>46</td>
</tr>
<tr>
<td>CFC recovery</td>
<td>3</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>11</td>
</tr>
</tbody>
</table>

TROUBLESHOOTING FOR CONVENTIONAL SLAB STOCK FOAM

Many problems are encountered in producing slab stock polyurethane foams. The machines often have 10 or more independent metering streams and chemical costs alone exceeding $1000 per minute of operation. For this reason, it is important to quickly identify and resolve production problems.

The following list is designed to assist the operator of a conventional slab stock machine in solving these problems.

Within any defect, there may be several causes. These causes and the suggested remedies may at times appear contradictory. This occurs because of the multiple factors, chemical and mechanical, that affect foam preparation and are often interrelated. Using these suggestions may, however, eliminate some of the trial and error in stabilizing line operations. The problems and solutions are most specific to conventional foams and production lines; however, some are related to high-resiliency foam and flat-top machine problems.

Before discussing problems and solutions, a brief description of the slab formation is given to assist in understanding the problem areas. Figure 12-35 shows the profile of a rising foam bun. Conventional foams are poured on an angled conveyer to permit pouring a higher bun than is possible on a flat conveyer. As the foam reactants are discharged from the mix head, they are deposited on the conveyer (a). The mix head traverses perpendicularly to the conveyer direction. Traverse speed is adjusted to give a uniform final bun height. The reactants are clear or only slightly cloudy in the laydown area when conventional polyols are used. Polymer polyols result in an opaque laydown. As the foaming reaction becomes visible (b), the material creams; the cream line is the distance from the laydown to the start of creaming. A gradual rise occurs throughout the foam-blowing reaction (c). When the foaming mass reaches its maximum height (d), “health bubbles,” the release of blowing gases breaking through the top skin surface, appear. In e, a slight amount of settling or “sigh back” normally occurs.

Tables 12-3, 12-4, and 12-5 describe defects, causes, and possible remedies for producing slab stock foam.

Fig. 12-35 Profile of a rising foam bun.
<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
</table>
| A. Creeping cream line | Cream line moves toward the laydown | 1. Rapid foam reaction  
2. Machine output, conveyer speed or conveyer angle imbalance | 1. a. Reduce blowing catalyst level  
b. Lower component temperatures  
c. Reduce air injection to mix head  
d. Increase mix head back pressure  
2. a. Decrease metering unit output  
b. Increase conveyer speed  
c. Increase conveyer angle |
| B. Undercutting     | Liquid reactants from the materials reacting in b (see Fig. 12-35). This can cause streaks, splits, or densification lines | 1. Slow reaction initiation  
2. Machine output, conveyer speed, or conveyer angle imbalance | 1. a. Increase amine catalyst  
b. Increase component temperatures  
c. Increase air injection to the mix head  
d. Decrease mix head back pressure  
2. a. Decrease metering unit output  
b. Increase conveyer speed  
c. Decrease conveyer angle |
| C. Boiling          | Foam not rising, with severe bubbling on the surface | 1. Gas generation too fast  
2. Silicone surfactant level too low or inactive  
3. Metering problems | 1. a. Decrease amine catalyst  
b. Reduce component temperatures  
2. a. Increase surfactant level  
b. Check surfactant efficiency by hand mix  
3. Check component stream outputs for proper amount and consistent flow |
| D. Streaks          | Adjacent areas of different cell structure | 1. Result of undercutting  
2. Improper head traverser speed  
3. Traverse width too high, giving streaks near edge  
4. Mixer speed too low  
5. Leaking lines or head connections dripping material into rising foam  
6. Cold components causing poor mix  
7. Splashing during laydown  
8. Air leaks through mixer seal | 1. See B above  
2. Adjust as necessary  
3. Narrow traverse width  
4. Increase mixer speed  
5. Eliminate leaks  
6. Increase component temperatures  
7. a. Increase nozzle diameter  
b. Increase nozzle length  
c. Decrease metering output  
d. Install diffuser screen  
8. Replace seal |

(continued)
<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Streaks (continued)</td>
<td>Adjacent areas of different cell structure</td>
<td>9. Overheating of mixer 10. Improper incorporation of additives</td>
<td>9. Replace or lubricate mixer seal 10. a. Check additive compatibility b. Increase mixer stream c. If appropriate, increase pressure on additive stream</td>
</tr>
<tr>
<td>F. Smoking</td>
<td>Visible vapors rising from the foam, generally with a strong isocyanate odor</td>
<td>1. Isocyanate level too high 2. Metering inaccuracies</td>
<td>1. Reduce isocyanate level 2. Check component output for quantity and fluctuations</td>
</tr>
<tr>
<td>G. Moon craters, pimples</td>
<td>Pock marks or pits on the top surface of the cured foam</td>
<td>1. Excessive air entrapment during laydown, ( a ) (see Fig. 12-35) 2. Inadequate dissolved gases in the major components 3. Excessive gas entrapment in polyol or isocyanate from unloading operations</td>
<td>1. a. Eliminate air leakage into mix head b. Reduce output c. Increase mixer nozzle diameter d. Increase nozzle distance to conveyer e. Install diffuser screen 2. a. Increase day tank pressures b. Increase nucleation air 3. Allow gas to escape before using the component</td>
</tr>
<tr>
<td>H. Splits</td>
<td>Horizontal or vertical separations within the foam, sometimes breaking through the skin</td>
<td>1. Gel rate exceeds gas generation during the later stages of rise 2. Excessive movement of foam during the later stages of rise 3. Gas generation exceeds gel rate</td>
<td>1. Restore proper catalyst balance 2. Reduce conveyer vibration or erratic movement 3. Restore proper catalyst balance</td>
</tr>
</tbody>
</table>
### TABLE 12-3—(continued)

<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>J.</td>
<td>Tacky skin</td>
<td>1. Low catalyst levels 2. Low ambient temperature 6. Foam residue dropping into foam</td>
<td>1. Increase catalyst levels 2. a. Heat bun surface b. Spray bun surface with mist of water containing amine catalyst</td>
</tr>
<tr>
<td>K.</td>
<td>Crumbly or flaky skin</td>
<td>1. Excess isocyanate 2. Insufficient mixing</td>
<td>1. a. Decrease isocyanate level 2. a. Increase mixer speed</td>
</tr>
<tr>
<td>L.</td>
<td>Thick or heavy skin</td>
<td>1. Low catalyst levels 2. Low ambient temperature</td>
<td>1. Increase catalyst levels 2. a. Warm conveyer b. Heat bun top surface</td>
</tr>
<tr>
<td>M.</td>
<td>Gummy bottom, bottom cavitation</td>
<td>1. Tin catalyst too high 2. Conveyer too hot</td>
<td>1. Lower tin catalyst level 2. Cool conveyer</td>
</tr>
</tbody>
</table>

(continued)
### TABLE 12-3—(continued)
Troubleshooting for Conventional Slab Stock Foam

<table>
<thead>
<tr>
<th>Defect Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>N. Closed cells, glassy cells, shiners, windows, and mirrors</td>
<td>1. Gel rate too high</td>
<td>1. Reduce tin catalyst level</td>
</tr>
<tr>
<td></td>
<td>2. Incorrect mixer speed</td>
<td>2. Increase mixer speed and/or decrease hold-up time in mixer</td>
</tr>
<tr>
<td></td>
<td>3. Insufficient air nucleation</td>
<td>a. Increase air injection to mixer</td>
</tr>
<tr>
<td></td>
<td>4. Mix head pressure too high</td>
<td>b. Increase day tank pad pressure</td>
</tr>
<tr>
<td></td>
<td>5. Component temperatures too high</td>
<td>4. Decrease mix chamber pressure by reducing output or increasing the outlet nozzle diameter</td>
</tr>
<tr>
<td></td>
<td>6. TDI isomer ratio change</td>
<td>5. Reduce temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O. Shrinkage</td>
<td>1. Excessive closed cells</td>
<td>1. See N above</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. Scorching, discoloration</td>
<td>1. High water and/or high index formulation</td>
<td>1. Reduce water and/or isocyanate</td>
</tr>
<tr>
<td>Yellow to brown discoloration of foam bun core; in extreme cases, this can lead</td>
<td>2. Bun stacking in storage too close</td>
<td>2. Provide adequate free air space in storage</td>
</tr>
<tr>
<td>to bun autoignition</td>
<td>3. Color change from heat effect on additives, particularly flame retardants</td>
<td>3. Determine effect of heat on additives; choose alternatives as appropriate</td>
</tr>
<tr>
<td></td>
<td>4. Formation of “black nylon” in graft (polymer) polyol formulations</td>
<td>4. Reduce water level</td>
</tr>
<tr>
<td></td>
<td>5. Inadequate stabilizer in polyol</td>
<td>5. Contact polyol supplier for higher-stabilized product</td>
</tr>
<tr>
<td></td>
<td>6. Delayed exotherm</td>
<td>6. Increase amine catalyst</td>
</tr>
<tr>
<td></td>
<td>7. Foam excessively open celled for water level used</td>
<td>7. Increase tin catalyst</td>
</tr>
<tr>
<td></td>
<td>8. Component contamination</td>
<td>8. Check for presence of soluble iron salts</td>
</tr>
</tbody>
</table>

### TABLE 12-4
Troubleshooting for Flexible Molded Foams

The following table lists common problems encountered in producing molded foam parts such as seat cushions or head restraints. The causes and remedies are specified for both low-pressure (LP) and high-pressure (HP) impingement mixing machines. While defects and suggested remedies are given as individual items, in practice multiple defects and/or causes may be present, complicating troubleshooting efforts. In considering the causes for specific defects, some causes may be contradictory. The guide below can, however, eliminate some trial and error in solving line problems.

(continued)
### TABLE 12-4—(continued)
Troubleshooting for Flexible Molded Foams

<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Splits</strong></td>
<td>Tears in the foam that are generally parallel to the surface</td>
<td>1. Gel rate exceeds gas generation rate</td>
<td>1. Adjust catalyst levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Excessive movement of foam during latter stage of rise</td>
<td>2. a. Change pour pattern b. Reduce shot weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Lid movement during critical stage of gel</td>
<td>3. a. Close lid before gel point b. Avoid lid movement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Excessive mold pressure</td>
<td>4. a. Reduce shot weight b. Increase venting c. Use floating lid (hot-cure foam only)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Gas generation rate exceeds gel rate</td>
<td>5. Adjust catalyst levels</td>
</tr>
<tr>
<td><strong>B. Collapse</strong></td>
<td>Foam cell structure is destroyed and high-density residue is left</td>
<td>1. Gas generation rate too fast</td>
<td>1. Adjust catalyst levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Loss of catalyst activity</td>
<td>2. Check catalyst activity and replace if necessary</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Surfactant deficiency</td>
<td>3. a. Check to ensure that proper type is used for application b. Check activity and replace if necessary c. Increase level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Pressure relief collapse (high-resiliency foam)</td>
<td>4. a. Clean vents b. Increase number of vents c. Reduce vent size</td>
</tr>
<tr>
<td><strong>C. Foam shrinkage with closed cells (“shiny” or “glassy” cells)</strong></td>
<td>Foam surface is dimpled soon after demolding, or foam distorts upon cooling, as dimensions are reduced by condensation of gases in closed cells</td>
<td>1. Incorrect mixer speed (LP)</td>
<td>1. a. Increase mixer speed b. Reduce hold-up time in mixer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Impingement pressure too high (HP)</td>
<td>2. Reduce impingement pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Gel rate too high</td>
<td>3. a. Reduce gel catalyst b. Reduce component temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Mold too hot</td>
<td>4. a. Reduce mold temperature b. Ensure uniform mold temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Excess air in components</td>
<td>5. a. Reduce padding pressure on day tank b. Reduce mix air (LP)</td>
</tr>
<tr>
<td><strong>D. Coarse cells</strong></td>
<td>Large cell structure with harsh foam feel</td>
<td>1. Incorrect mixer speed (LP)</td>
<td>1. a. Increase mixer speed b. Reduce hold-up time in mixer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Insufficient dissolved air in components</td>
<td>2. a. Increase day tank padding pressure b. Increase mix air (LP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Insufficient shear in mix chamber (LP)</td>
<td>3. a. Increase hold-up time b. Increase back pressure c. Reduce mixer clearance</td>
</tr>
</tbody>
</table>
### TABLE 12-4—(continued) Troubleshooting for Flexible Molded Foams

<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
</table>
| D. Coarse cells (continued)                | Large cell structure with harsh foam feel                                    | 4. Surfactant deficiency                                               | 4. a. Check surfactant activity  
|                                             |                                                                             |                                                                     | b. Increase tin catalyst (hot-cure foam)                                        |
| E. Visible pour pattern                    | Laydown pattern of foam visible on foam surface and possibly causing ridges | 1. Splashing, erratic laydown                                          | 1. a. Decrease distance between end of mix  
|                                             |                                                                             |                                                                     | b. Decrease throughput of machine  
|                                             |                                                                             |                                                                     | c. Increase outlet nozzle diameter (LP)                                          |
|                                             |                                                                             |                                                                     | 2. Dirty mold                                                                   | 2. Clean mold to remove excess mold release and foam build-up  
| F. Blow holes                              | Large holes in foam from escaping gas                                       | 1. Air trapped during pour                                             | 1. See E1                                                                       |
|                                             |                                                                             |                                                                     | 2. Gelation too fast                                                            | 2. Adjust catalyst levels                                                       |
|                                             |                                                                             |                                                                     | 3. Component temperature too high                                              | 3. Reduce component temperatures                                                |
| G. Loose skin (hot-cure foam)              | Adhesion of thin foam skin is too low, causing it to separate from the foam | 1. Mold temperature low                                               | 1. Increase mold temperature                                                   |
|                                             |                                                                             |                                                                     | 2. Amine catalyst level low                                                     | 2. a. Increase amine catalyst  
|                                             |                                                                             |                                                                     | b. Increase isocyanate index                                                     |
|                                             |                                                                             |                                                                     | 3. Dirty mold                                                                   | 3. Clean mold                                                                   |
|                                             |                                                                             |                                                                     | 4. Underfill                                                                   | 4. Increase shot weight                                                          |
|                                             |                                                                             |                                                                     | 5. Lid movement during rise                                                     | 5. Limit lid movement by clamps or alignment pins  
|                                             |                                                                             |                                                                     | 6. Foam undercutting                                                            | 6. a. Increase machine output  
|                                             |                                                                             |                                                                     |                                                                          | b. Change pour pattern                                                          |
| H. Flaky skin (hot-cure foam)              | Crumbly surface or friable skin causes surface to rub off easily            | 1. Excess isocyanate                                                  | 1. a. Check calibration  
|                                             |                                                                             |                                                                     | b. Reduce isocyanate index                                                      |
|                                             |                                                                             |                                                                     | 2. Insufficient mixing                                                          | 2. a. Increase mixer speed  
|                                             |                                                                             |                                                                     | b. Decrease mixer clearance                                                     |
|                                             |                                                                             |                                                                     | 3. Dirty mold                                                                   | 3. Increase hold-up                                                             |
| I. Thick skin (hot-cure foam)              | Heavy, elastomeric skin surface                                             | 1. Mold temperature low                                               | 1. Increase mold temperature                                                   |
|                                             |                                                                             |                                                                     | 2. Surfactant level low                                                         | 2. a. Increase surfactant level  
|                                             |                                                                             |                                                                     | b. Use more efficient surfactant                                                 |
|                                             |                                                                             |                                                                     | 3. Dirty mold                                                                   | 3. Clean mold                                                                   |
| J. Tight skin (high-resiliency foam)       | Skin surface has a low porosity, giving a pneumatic feel                   | 1. Mold release                                                      | 1. Switch to mold release with a cell opener added  
|                                             |                                                                             |                                                                     | 2. a. Reduce surfactant level                                                    |
|                                             |                                                                             |                                                                     | b. Use less efficient surfactant                                                 |
|                                             |                                                                             |                                                                     | 2. Surfactant level high                                                        | c. Adjust catalyst levels                                                       |

(continued)
### TABLE 12-4—(continued)

**Troubleshooting for Flexible Molded Foams**

<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>K. Hard flash</td>
<td>Material vented from mold is very hard and difficult to trim</td>
<td>1. Overfill</td>
<td>1. Reduce shot time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Slow gel rate</td>
<td>2. Adjust catalysts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Excess mold pressure</td>
<td>3. a. Reduce shot time</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b. Change vent locations</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>c. Change vent size</td>
</tr>
<tr>
<td>A. Air trap void</td>
<td>Smooth and shiny bubbles that are near the surface of the foam</td>
<td>1. Flow restricted in the mold causing trapped air pockets</td>
<td>1. Revise flow pattern by regating or removing obstructions to flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Air entrained in foam reactants</td>
<td>2. a. Reduce day tank agitator speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b. Reduce day tank padding pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>c. Maintain day tank at upper limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Air drawn in through gate</td>
<td>3. Seal gate area outside edge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Underfill</td>
<td>4. See D below</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Machine output too high, causing splashing or sputtering in mold</td>
<td>5. Reduce machine output</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6. Improper or blocked vents</td>
<td>6. Check vent location, clean blocked vents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7. Improper mold orientation, with natural high spot too low</td>
<td>7. Reorient mold</td>
</tr>
</tbody>
</table>

### TABLE 12-5

**Troubleshooting for Composites Such As Instrument and Door Panels**

The following table lists common problems encountered in producing composite foam parts such as those having a plastic or metallic insert/substrate and a formed plastic film skin. The causes and remedies are specified for high-pressure impingement mixing machines; however, the suggestions given may apply to low-pressure machine operations. While defects and suggested remedies are given as individual items, in practice, multiple defects and/or causes may be present, complicating troubleshooting efforts.

<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Air trap void</td>
<td>Smooth and shiny bubbles that are near the surface of the foam</td>
<td>1. Mix ratio incorrect</td>
<td>1. Recalibrate machine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Mix head opening slowly</td>
<td>2. Check hydraulic system, particularly accumulator pressure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Improper mix</td>
<td>3. Check and adjust impingement pressures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Fouled component nozzle</td>
<td>4. Remove and clean nozzle; replace if needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Pump malfunction</td>
<td>5. Check pump operation, particularly pump relief valve</td>
</tr>
<tr>
<td>B. Foam wet spot</td>
<td>Resin- or isocyanate-rich spots at beginning or end of pour, giving soft, hard, or sticky spot</td>
<td>1. Hydraulic oil contamination</td>
<td>1. Check for hydraulic oil leaks at mix head and from hoses</td>
</tr>
<tr>
<td>C. Voids</td>
<td>Irregular voids with open cell structure or “ratty” appearance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Defect</td>
<td>Description</td>
<td>Possible Cause</td>
<td>Suggested Remedy</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>C. Voids (continued)</td>
<td>Irregular voids with open cell structure or “ratty” appearance</td>
<td>2. Mold release contamination</td>
<td>2. Avoid overuse or overspray of mold release</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Mold not clamping properly</td>
<td>3. Check mold operation, adjust clamps</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Mold overfill</td>
<td>5. Reduce shot size</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6. Contamination on substrate or skin</td>
<td>6. Ensure that substrate and skin are free of oil, mold release, or other contaminants</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7. Improper component temperatures</td>
<td>7. Check and reset temperatures as needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8. Movement of substrate during foam injection</td>
<td>8. Check substrate fixing points or devices</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9. Mold sealing failure</td>
<td>9. Check mold operation for proper clamping; replace seals as needed</td>
</tr>
<tr>
<td>D. Underfill</td>
<td>Areas of the part not filled with foam</td>
<td>1. Low shot weight</td>
<td>1. Check shot timer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Mold clamps open</td>
<td>2. Check mold for proper operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Blocked vents</td>
<td>3. Check and clean vents</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Mold cold</td>
<td>4. a. Check and adjust temperature controller as needed&lt;br&gt;b. Start mold preheat before start of operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Components cold</td>
<td>5. Check and adjust component temperatures</td>
</tr>
<tr>
<td>E. Splits</td>
<td>Larger areas of foam with tears that are generally parallel to the surface of the part</td>
<td>1. Improper stabilization of the foam</td>
<td>1. Adjust catalysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Movement of the upper and lower mold halves before foam gels</td>
<td>2. Check mold for proper operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Movement of the substrate before the foam gels</td>
<td>3. Check substrate fixing points or devices</td>
</tr>
<tr>
<td>F. Tears</td>
<td>Foam separation due to stress occurring during demolding</td>
<td>1. Foam sticking to the mold</td>
<td>1. a. Clean mold&lt;br&gt;b. Check mold release application</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Substrate sticking</td>
<td>2. Check substrate fixing points or devices for proper release</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Negative draft angle</td>
<td>3. Modify mold</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Vacuum holding skin not released before demold</td>
<td>4. Check for proper vacuum control</td>
</tr>
</tbody>
</table>

(continued)
## TABLE 12-5—(continued)

Troubleshooting for Composites Such As Instrument and Door Panels

<table>
<thead>
<tr>
<th>Defect</th>
<th>Description</th>
<th>Possible Cause</th>
<th>Suggested Remedy</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. Gassing</td>
<td>Large gas bubble that blows foam apart at demolding, generally resulting in a split that is parallel to the surface; may also blow skin away from the foam</td>
<td>1. Mold too hot</td>
<td>1. Cool mold to approximately 105˚ F (41˚ C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Demold time too short</td>
<td>2. Extend demold time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Components too hot</td>
<td>3. Reduce component temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Vents blocked</td>
<td>4. Clean vents</td>
</tr>
<tr>
<td>H. Delamination</td>
<td>Foam separates from skin or substrate</td>
<td>1. Basic incompatibility of materials</td>
<td>1. a. Add adhesion promoter to foam system&lt;br&gt;b. Surface treat substrate (such as with corona discharge or charring with flame)&lt;br&gt;c. Mold plastic substrate with slightly rough surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Contamination by mold release or oil</td>
<td>2. Ensure that parts are clean and free of contaminates</td>
</tr>
<tr>
<td>I. Waviness</td>
<td>Unevenness of part surface not due to mold configuration</td>
<td>1. Foam shrinkage</td>
<td>1. a. Check calibration for proper ratio&lt;br&gt;b. Check component temperature and adjust if too high&lt;br&gt;c. Check mold temperature and adjust if too high</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Overfill</td>
<td>2. Reduce fill time</td>
</tr>
<tr>
<td>J. Wrinkles</td>
<td>Distortion of the skin</td>
<td>1. Improper forming of skin</td>
<td>1. Check vacuum-forming or skin-casting operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Mold shape and skin forming mold do not match</td>
<td>2. Tune molds</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Unexpected skin shrinkage</td>
<td>3. Check skin compound against standards; adjust as needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Inadequate vacuum to hold skin to shape in mold cavity</td>
<td>4. Check vacuum pump and control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Improper loading of skin into mold</td>
<td>5. Check operator attention to skin loading</td>
</tr>
<tr>
<td>K. Surface dent</td>
<td>Depression in the skin surface after demolding</td>
<td>1. Foreign matter in the mold</td>
<td>1. Ensure that mold cavity is clean before loading skin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Mold defect</td>
<td>2. Check mold condition and repair as needed</td>
</tr>
</tbody>
</table>
Bibliography

Bender, R.J., Handbook of Foamed Plastics, Lake Publishing Corporation, Libertyville, IL, 1965.


Thermosetting molding compounds (thermosets) that undergo a chemical reaction or cure (called polymerization or molecular growth) during the molding operation, include phenolic (phenol-formaldehyde), urea, melamine, melamine-phenolic, diallyl phthalate, alkyd, polyester, epoxy, and silicones. Thermosetting molding compounds processed from the individual heat-reactive resin systems are available in a wide range of formulations to satisfy specific end-use requirements. Depending on the type of material, products may be supplied in granular, nodular, flaked, diced, or pelletized form. Polyester materials are supplied in granular, bulk, log, rope, or sheet form, and polyurethanes are made in many forms, ranging from flexible and rigid foams to rigid solids and abrasion-resistant coatings.

**PRINCIPLES OF PLASTICS MOLDING**

Thermosets, when placed in a heated mold under pressure, will conform to the shape of the mold and cure into a hard infusible product.

**Molding Conditions**
Successful plastics molding is dependent on good mold design and construction, the mold temperature, material temperature, molding pressure, etc.

**Molding Methods**
All of the thermoset compounds, except epoxies and silicones, may be molded by the following methods: compression, transfer, thermoset injection, and the runnerless injection/compression process. This chapter will only discuss compression and transfer molding. Table 13-1 lists factors to be considered in the selection of compression or transfer molding.

The design and construction of the mold is the single most important factor in a plastics molding project. Without a mold built and engineered to produce good molded parts in an economical fashion, other factors are of little importance.

Mold temperature. Thermoset molding compounds may be molded in a temperature range of 285–400°F (141–204°C). Material suppliers should be consulted for recommended temperatures for a specific material and molding method. Molds may be heated by steam, hot oil, electric cartridge or strip heaters, or any combination of these.

Material temperature. Minimum cure time is a function of increased mold temperature and maximum material temperature when loaded in the mold. It is desirable to preheat most compounds. Extrudates are formed from screw feed material in a heated barrel. The temperature range is 180–260°F (82–127°C) depending on the type of preheat equipment.

Molding pressure. The pressure causes the compound to flow within the confines of the mold cavities and forces it to completely fill out the part with minimum flash thickness. The required pressure is dependent on the method of molding.

**COMPRESSION MOLDING**
In compression molding, the thermoset compound is placed in the open heated mold. The material may be in powder form or as a preform, a cold pressed slug that contains the exact charge weight required. As the mold closes, the heat and pressure cause the material to flow, compressing it to the required shape and density as defined by the mold. Continued heat and pressure produce the chemical reaction (polymerization or cure) that hardens the material. The thinner the part, the shorter the cure; conversely, thicker pieces take longer to cure. Part design should have as uniform a wall thickness as possible.

**Molding Equipment**
The mold is fastened in a vertical molding press, either up-acting or down-acting, usually hydraulically driven. Small bench presses may be air driven. Presses may be self-contained or on a common hydraulic system. They have provision for an ejection system for the parts, usually both up-acting and down-acting. The press operation may be either automatic or semi-automatic, in sizes up to 2000 tons (17.9 MN).

Preform presses, high-frequency preheaters, and preheat extruders are commonly used as auxiliary equipment in the compression-molding process.

**Auxiliary Equipment**
Preform presses. These are either hydraulic or mechanically operated, with various die sizes and shapes to squeeze the material in the cold state into a preform or briquette of the exact charge weight required. These presses work automatically.

The Contributors of this chapter are: F. Reed Estabrook, Jr., President and Senior Consultant, The Taim Corporation; Alan Low, Marketing Manager, Husky Injection Molding Systems.

The Reviewer of this chapter is: F. Reed Estabrook, Jr., President and Senior Consultant, The Taim Corporation.
Molding Process

The mold consists of two halves, one containing the cavity or cavities (the female section) and one containing the force or forces (the male section). Each is mounted on press supports or grids which are in turn fastened to the stationary or moving platens. Generally, the cavities are in the lower half to permit easy loading of the molding compound. This operation may be manual or automatic. In the case of automatic operation, movable loading trays are incorporated, in conjunction with trays or forks to receive molded parts from the mold. A predetermined amount of molding material is placed into the open mold. By closing the mold and compressing the material, the desired shape is achieved.

Both thermosets and thermoplastics may be compression molded; the process is used mostly for thermosets and thermoplastics containing significant amounts of fillers which reduce their viscosity (flowability), required for injection molding. (Examples: phenolics with up to 60% mineral fillers, for insulators; polysulfones up to 80% ceramic, for engineering uses.) Flashing is necessary to allow the air or gases to escape.

A typical cycle, with the mold at recommended temperature and with adequate pressure available, would proceed as follows:

1. Air-clean the mold of all flash or foreign matter.
2. Load the material into the cavities.
3. Close the mold completely; or before closing it, interject a brief “breathe cycle” by opening the mold slightly to release any air and gases trapped in the molding compound.
4. Complete the cure time.
5. Open the mold and activate the knock-out assembly.
6. Remove the molded parts.
7. Clean the mold with an air blast.

The cure duration is dependent on the type of molding compound, mold temperature, pressure on the material, and material temperature. Cross-sections 0.125–0.500 in. (3.18–12.7 mm) thick may cure in 30 seconds–2 minutes when preheated material is used (which is always desirable).

For thermosets, the material can be cold, but more often it is preheated close to the “setting” temperature. The mold is heated using steam or electric heaters, and remains closed until the parts are “cured” or “set”; the hot part is then ejected. Typical parts produced using this technique are tires, components for the electrical industry, dinnerware, and under-the-hood automotive parts.

For thermoplastics, the hot (melted) material is placed into the relatively cold mold; the mold closes and compresses the material into the desired shape. When the part has cooled down enough to be handled without deformation, it is ejected.

With the materials processed by compression molding, the mold is open while the material is loaded. During the closing, it is unavoidable to have excess material escape at the parting line (flash). It is necessary to provide an excess of material with every shot, which is wasted (scrap) with thermosets, but can be reused with thermoplastics. In either case, the flash must be removed to provide a finished part, either by tumbling manually (parts permitting) or mechanically.

Molding Conditions

Factors to be considered during compression molding include the type of molding compound, the mold temperature, and the molding pressure.

Compound. When using a molding compound with the desired functional performance characteristics, the specifications should provide a bulk factor not greater than 3:1 (solid to liquid ratio), good funnel flow rating, and proper plasticity.

Temperature. The mold temperature should be specified after consulting with the material supplier. As stated previously, temperatures range from 285–400°F (141–204°C).

Pressure. Generally, all thermoset compounds recommended for compression molding require the same molding pressure. Uniform shrinkage, all directions, mold erosion, sprues, runners, gates, Molded-in inserts. A mold with movable sections or gates, Mold erosion, sprues, runners, gates, Generally higher mold cost.

Factors influencing mold construction include the mold cavity and forces, and the materials and method of construction.

TABLE 13-1

<table>
<thead>
<tr>
<th>Selection of Molding Method–Compression or Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages–Limitations</td>
</tr>
<tr>
<td>Close tolerances, projected area</td>
</tr>
<tr>
<td>Close tolerances, over flash line, minimum flash</td>
</tr>
<tr>
<td>Lowest mold shrinkage</td>
</tr>
<tr>
<td>Uniform shrinkage, all directions</td>
</tr>
<tr>
<td>Maximum uniform density</td>
</tr>
<tr>
<td>Reduced cure, thick sections</td>
</tr>
<tr>
<td>No weld lines, less molded-in strains</td>
</tr>
<tr>
<td>Small holes, longer length, through holes</td>
</tr>
<tr>
<td>Extremely thin mold sections, telescoping</td>
</tr>
<tr>
<td>No venting problems</td>
</tr>
<tr>
<td>Impact strength</td>
</tr>
<tr>
<td>Molds with movable sections or cores</td>
</tr>
<tr>
<td>Molded-in inserts</td>
</tr>
<tr>
<td>Large projected area parts</td>
</tr>
<tr>
<td>Lowest mold-flash scrap</td>
</tr>
<tr>
<td>Generally less mold maintenance</td>
</tr>
<tr>
<td>Gate or sprue removal necessary</td>
</tr>
<tr>
<td>Maximum number cavities per clamp force</td>
</tr>
<tr>
<td>Mold erosion, sprues, runners, gates</td>
</tr>
<tr>
<td>Generally higher mold cost</td>
</tr>
</tbody>
</table>

High-frequency preheaters heat the preforms in the 200–300°F (93–149°C) range so the molding material is ready to flow as soon as it is loaded into the heated mold.
Cavity and forces. The molds may contain a single cavity or multicavities. The number of cavities is determined by the production requirements, part size, type of material, and clamp capacity of the molding press.

Determining factors that dictate design of the mold cavity and operational force include the type of material, part design, flash-line restrictions, part dimensions and tolerances, and end-use requirements. Shrinkage of material during curing and cooling is built into mold dimensions.

Mold types. Five basic types of compression mold cavity and force are available for selection:

Flash type. The flash-type mold, illustrated in Fig. 13-1, is simple in construction and low in cost. Disadvantages are that it creates minimal back pressure within the cavity (needed to control density and molded part dimensions) and it has high flash scrap loss. The flash mold is not recommended for parts requiring maximum density and strength.

Semipositive, vertical-flash type. The semipositive, vertical-flash type mold, shown in Fig. 13-2, requires double fitting of force to cavity and is costly. It controls maximum density and critical dimensions as related to cavity and force, offers ease of flash removal on large parts, and leaves no flash line scar on the side of the part.

Semipositive, horizontal-flash type. The semipositive, horizontal-flash type mold, shown in Fig. 13-3, controls conditions in a manner similar to that of the horizontal-flash type, but it is less costly and more popular. It is recommended for close-tolerance parts and assures minimum flash finish.

Direct-positive type. The direct-positive-type mold, illustrated in Fig. 13-4, is used for high-bulk materials and deep-draw parts when maximum density is required. It is a single-cavity mold that uses an accurately weighed charge of material.

Landed-positive type. The landed-positive type mold, shown in Fig. 13-5, is used as a single-cavity mold on a rotary press. Molding pressure is controlled at each station. Maximum density may be maintained by clearance between the side wall of the force and the cavity. Overall height of the part is controlled by land areas on mating surfaces of the force and cavity.

Mounting and retainer plates. Cavities and forces are assembled on mounting plates and may be held in the confines of a retainer plate. Heat sources are contained in one or both units.

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**Fig. 13-1 Flash-type compression mold.** (Courtesy R. W. Bainbridge)

**Fig. 13-2 Semipositive, vertical-flash compression mold.** (Courtesy R. W. Bainbridge)

**Fig. 13-3 Semipositive, horizontal-flash-type compression mold.** (Courtesy R. W. Bainbridge)
Part-removal systems. A top and bottom knockout system is necessary in automatic operations. One set of pins may act as hold-down or hold-up pins while the second set facilitates part removal.

Mold design. Mold design is a special area and requires expertise in steel types and hardness specifications, machining methods, and other factors that may vary in the molds for producing different parts.

Mold making. The principal kinds of steel used for making plastics molds are prehardened, carburizing, oil hardening, air hardening, stainless, and maraging. These materials are supplied in rolled, forged, and cast sections. The primary methods used to form cavities in steel molds are conventional machining hobbing and electrical discharge machining (EDM). Heat treatment is part of the mold-making process, unless a prehardened steel is selected. Finishing of the mold cavity surface is usually done by grinding and polishing. For additional information, refer to Volume 2 of this handbook series entitled Forming. See chapter 2 “Die and Mold Materials.”

TRANSFER MOLDING

Transfer molding is a method of molding specific parts using a mold with two halves that is closed before any material is introduced. The material is loaded into a pot or transfer sleeve, and transfer pressure is applied to cause material to flow into the closed section of the mold. In a single-cavity mold, the material flows generally through a sprue bushing and is gated directly into the part. In the case of a multicavity mold, it flows from a sprue bushing or transfer sleeve into a runner system and is gated into each cavity and part.

There are two distinct transfer methods of molding. One is known as pot-type transfer, and the other is the plunger transfer method.

Molding Equipment

Pot-type transfer molding is generally done in a bottom-clamp compression press. Plunger transfer molding is done in a vertical press. A transfer press has a hydraulic clamp cylinder with a separate transfer cylinder applying pressure in the direction opposite to the clamp pressure. For automatic operation, a top-clamp force and a bottom-transfer force are desirable for ease of loading preheated preforms. Plunger-transfer presses are generally self-contained and have provisions for top and bottom knockout systems that are available for semiautomatic or automatic operations. Users should contact press manufacturers or molders for information on available press sizes.

Molding Processes

Depending on whether the molding method is pot-type or plunger, one of two mold types are employed in transfer molding. The mold cavity is closed (clamped), and connected at a gate via a runner to the transfer pot. The material is loaded into the pot and a plunger drives the material into the cavity. There is no flash on the part, but the runners and a certain amount of scrap (cull) remaining in the bottom of the pot must be removed before the next shot. This method is used almost exclusively for thermosets, requiring the pot to be heated. To reduce the molding time, the material charged into the pot should be well preheated, and as close as possible to the curing temperature of the material.

Pot-type mold. A pot-type transfer mold as shown in Fig. 13-6 generally has one cavity. The mold consists of two halves with the cavity section assembled to the lower mounting plate which is fastened to the supports or grids and bolted to the movable lower platen. The lower platen is moved up and down by the clamp ram. The force section is assembled to the lower surface of the movable floating platen. The pot or chamber is contained in the upper area. These components are fastened together as a complete assembly. The plunger that enters the pot area is mounted to the head of the press or to the grids.

In a typical cycle using the recommended mold temperature, the operator loads preheated preforms or extrudates into the pot area. Then the press is activated upward using low pressure, and the press picks up the floating member (see Fig. 13-6a) which engages the plunger. High pressure is applied, forcing the material...
through the sprue bushing directly into the cavity and force area (or through a diaphragm gate if it is a circular part). The cure cycle is completed under pressure, the clamp ram is moved downward, and the mold opens. The pot and plunger separate, and the removable floating platen is pulled away from the lower half of the mold by rods fastened to the head of the press. The part-removal assembly raises the part from the cavity, and the operator removes the part. The operator removes cull and sprue from the plunger,
uses an airblast to clean the remainder of the mold, and places the preforms in a preheater or activates the extruder for the following cycle, as shown in Fig. 13-6b.

Plunger mold. A plunger transfer mold (shown in Fig. 13-7) consists of two halves, one containing the cavity or cavities and one containing the force or forces. The transfer sleeve and plunger are located in the center of the mold; the plunger is fastened to the transfer cylinder. The press design dictates location of the clamp ram and transfer cylinder. The halves of the mold are mounted on grids or support pillars in the proper location. In a typical operation with a bottom plunger transfer press and with molding performed at recommended mold temperature, the preheated preforms or extrudates are loaded into the transfer sleeve. The press is then closed. Activation of the transfer plunger forces material into the runner system, through a gate, into the mold cavity. After completing the cure cycle, the press is opened, and parts and runners are removed from the mold. The cull is removed from the top of the transfer plunger, and the transfer plunger is activated downward. An airblast is used to clean the mold and vents. The final step is to activate the preheater or extrudate equipment. Figure 13-7 shows a plunger transfer mold at the beginning (a) and the end of a cycle (b).

The injection molding technology developed as an improvement of compression molding technique.
Molding Conditions

Factors to be considered during transfer molding include the type of molding compound, the mold temperature, and the molding pressure.

- Compound. The molding compound should be suitable for preforming and/or making extruded shapes in equipment using a screw to feed and preheat material in a temperature-controlled barrel.
- Temperature. Mold temperature can range from 285–400° F (141–204° C), depending upon the specific plastic materials used.
- Pressure. Technical considerations related to pressure specification differ for pot and plunger-type transfer molds. Polyester, epoxy, and silicone molding compounds require less transfer pressure than other materials. The plastics supplier should be consulted for recommended pressure.

Pot-type transfer. The transfer pressure in this type of mold is the pressure developed within the pot area. The projected pot area must be equal to or 10% greater than the projected area of the part. Failure to provide sufficient area in the pot can cause the mold to "blow open" at the parting line of the cavity and the force. Recommended transfer pressure developed in the pot area is 6000–10,000 psi (41–69 MPa).

Plunger type transfer. The transfer pressure recommended is 6000–8000 psi (41–55 MPa). The significant area is made up of the combined projected areas of the pots and the transfer plunger, plus total runner and gate area of all cavities. Clamp force must be sufficient to keep the mold from flashing at the parting line of the cavities, runners, and cull area.

Pellets

For ease of handling, the powder-like molding material for phenolics and ureas is usually pressed cold into pellets (each one, or sometimes more than one, representing the part- or shot-weight). The weight of these pellets can be closely controlled during pelletizing. They are loaded, cold or preheated, by hand or mechanically, into each mold cavity or into the shooting pot. Preheating is done either in electric, steam, or microwave ovens.

Because of the loading method for both compression and transfer molding, it is more practical to utilize gravity, that is, keep the mold parting line horizontal and use a vertical clamping arrangement. In some machines, the lower platen is fixed and the upper platen moves up and down. In others, the upper platen is fixed and the lower platen is movable. These differences in the design of the machines have no bearing on the molding process itself.

The plunger is normally driven by a separate hydraulic cylinder mounted on the platen. It is possible to move either the lower or the upper platen, but usually, the platen with the transfer plunger is not moving.

With a bottom-mounted plunger, the material is loaded into the pot while the mold is open; after the mold is closed, the plunger rises to push the plastic into the cavities. With a top-mounted plunger, the mold closes first, the plastic is loaded into the pot, and the plunger descends to push the plastic into the cavities. This is similar to injection molding.

In another method, the plastic is extruded from a side-wall hole into the shooting pot from an extruder below the platen. In this process, the plunger must move below the opening to pick up the charge.

The transfer method is the same as the two-stage injection molding system. Practically any injection pressure and shot volume can be achieved by varying the diameter of the plunger. (Smaller plunger, higher pressure but smaller volume, and vice-versa.) Of course, the shot volume also depends on the stroke of the plunger.

<table>
<thead>
<tr>
<th>MOLDING PROCESS COMPARISON</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transfer Molding</strong></td>
</tr>
<tr>
<td>Originally, operators were needed to load the raw material and to unload the molded articles. During the curing time, they removed the flash from the parts while attending one, two, or more machines. Later on, automation was introduced to both load and unload. At about the same time period, the use of thermoplastic materials increased dramatically and processing thermoplastics was performed using plunger machines. These are the forerunners of the present day injection molding machines.</td>
</tr>
<tr>
<td><strong>Compression Molding</strong></td>
</tr>
<tr>
<td>Although it is the oldest method of molding, compression molding probably will continue to be a major technique for processing most thermosets molding compounds. The following applications are representative of the market areas for which many parts are molded by compression:</td>
</tr>
<tr>
<td>- Wiring devices—wall plates, outlet boxes and receptacles, switches.</td>
</tr>
<tr>
<td>- Closures—bottle and tube caps for drugs and cosmetics.</td>
</tr>
<tr>
<td>- Electrical switch gear—home and low-voltage circuit breakers.</td>
</tr>
<tr>
<td>- Automotive parts—brake and transmission parts, grilles and body parts, ignition parts.</td>
</tr>
<tr>
<td>- Dishware—melamine dishware.</td>
</tr>
<tr>
<td>- Small appliances—knobs, handles, bases for motor mounts and cookers.</td>
</tr>
<tr>
<td>- Housing—sanitary tubs, stall shower units or bases, electrical outlet boxes.</td>
</tr>
</tbody>
</table>

Transfer molding is the same as the two-stage injection molding system. Practically any injection pressure and shot volume can be achieved by varying the diameter of the plunger. (Smaller plunger, higher pressure but smaller volume, and vice-versa.) Of course, the shot volume also depends on the stroke of the plunger.
Other Methods of Molding

With the trend toward more automatic operations requiring no operators or one operator for several presses, there have been some conversions to the injection process and some new parts are being molded using it. Currently, the runnerless injection/compression process is being adopted for some applications. Faster cycles are generally possible when the part and material are adaptable to this process. Process engineers must consider and evaluate the significant factors and parameters and make the decision as to the most suitable operation.

COMPRESSION MOLDING

The compression molding cycle is simple enough that problem solutions are generally obvious. Instrumenting load and thermal parameters can resolve many difficult problems. As in all casting processes, part design is a major factor in success.

PRINCIPAL COMPRESSION MOLDING PARAMETERS

Table 13-2 shows the principal parameters in compression molding. Material properties, part/mold design, and operating characteristics are the key essentials in problem solving.

TROUBLESHOOTING

Table 13-3 lists the types of problems found on parts. Table 13-4 describes causes and solutions to many of the problems occurring in compression molding. Additional suggestions are presented in the Reference section at the end of this chapter.

<table>
<thead>
<tr>
<th>Surface Texture</th>
<th>Internal</th>
<th>Gloss</th>
<th>Dimension</th>
<th>Color</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blisters</td>
<td>Scales</td>
<td>Bubbles</td>
<td>Frosting</td>
<td>Dishing</td>
<td>Clarity loss</td>
</tr>
<tr>
<td>Burns</td>
<td>Scratches</td>
<td>Crack</td>
<td>Gloss loss</td>
<td>Daming</td>
<td>Discoloration</td>
</tr>
<tr>
<td>Chalking</td>
<td>Sheeter lines</td>
<td>Dry-spot</td>
<td>Granularity</td>
<td></td>
<td>Dull-surface</td>
</tr>
<tr>
<td>Crazing</td>
<td>Short</td>
<td>Let-go</td>
<td>Haze</td>
<td></td>
<td>Filler specks</td>
</tr>
<tr>
<td>Pinholes</td>
<td>Sink mark</td>
<td>Ream</td>
<td>Lubricant-bloom</td>
<td></td>
<td>Fisheye</td>
</tr>
<tr>
<td>Orange peel</td>
<td>Warp</td>
<td>Slip plane</td>
<td>Mica specks</td>
<td></td>
<td>Foreign matter</td>
</tr>
<tr>
<td>Pimples</td>
<td>Waviness</td>
<td>Waviness</td>
<td></td>
<td></td>
<td>Mottle</td>
</tr>
<tr>
<td>Pits</td>
<td>Weld mark</td>
<td></td>
<td></td>
<td>Segregation</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td></td>
<td></td>
<td></td>
<td>Stria</td>
<td>Two-tone</td>
</tr>
<tr>
<td>Precure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Possible Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pieces blistered</td>
<td>Molding cycle too short</td>
<td>Increase time of cycle.</td>
</tr>
<tr>
<td>Air or gases trapped in mold</td>
<td>Close mold more slowly; provide sprue grooves to allow escapement of gas; preheat* material.</td>
<td></td>
</tr>
</tbody>
</table>

(continued)
### TABLE 13-4—*Common Faults, Causes, and Remedies in Compression Molding*¹

<table>
<thead>
<tr>
<th>Problem Description</th>
<th>Possible Causes</th>
<th>Possible Remedies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pieces blistered</td>
<td>Material has absorbed water by exposure</td>
<td>Preheat* material.</td>
</tr>
<tr>
<td></td>
<td>Mold too hot</td>
<td>Reduce temperature.</td>
</tr>
<tr>
<td></td>
<td>Insufficient pressure</td>
<td>Increase pressure or adjust powder weights if multiple-cavity mold is used.</td>
</tr>
<tr>
<td></td>
<td>Mold too cold</td>
<td>Increase temperature.</td>
</tr>
<tr>
<td></td>
<td>Mold charge too bulky, contains too much air</td>
<td>Preform material, or distribute in most suitable manner to allow air to escape. If powder, arrange in a pile similar to a mountain peak, rather than a volcano.</td>
</tr>
<tr>
<td></td>
<td>Nonuniform heating</td>
<td>Rearrange steam channels or place mold in press in a way to promote uniformity of heating.</td>
</tr>
<tr>
<td></td>
<td>Piece designed with thick non-uniform walls</td>
<td>Tablet the charge; preheat* material; reduce molding temperatures.</td>
</tr>
<tr>
<td>Parting line porous but bottom and flash thick, Finish good where piece is properly filled out and pressure is directly on it</td>
<td>Material too “hard”, does not flow freely</td>
<td>Use a softer material.</td>
</tr>
<tr>
<td></td>
<td>Pressure insufficient</td>
<td>Increase pressure.</td>
</tr>
<tr>
<td></td>
<td>Mold too hot resulting in precuring</td>
<td>Lower temperature.</td>
</tr>
<tr>
<td></td>
<td>Mold closed too slowly, resulting in precuring</td>
<td>Increase speed of closing by more rapid supply of pressure; preheat* material.</td>
</tr>
<tr>
<td></td>
<td>Mold charge too great to allow proper escapement and closing of the mold</td>
<td>Adjust charges properly or provide sprue grooves for escapement.</td>
</tr>
<tr>
<td>Appearance as in previous problem, but bottom and fins of proper thickness</td>
<td>Charge is insufficient</td>
<td>Increase charge to proper weight.</td>
</tr>
<tr>
<td></td>
<td>Mold is closed too fast, “splashing” material from mold</td>
<td>Close more slowly, permitting material to soften and flow properly.</td>
</tr>
<tr>
<td></td>
<td>Mold allows too fast escapement of material.</td>
<td>When a flash mold is used, increase width of cutoff; where fit is poor between mold parts, it must be corrected: use a harder material; use abnormal charge of material.</td>
</tr>
<tr>
<td>Molded piece is flexible on discharge</td>
<td>Piece is insufficiently cured</td>
<td>Increase curing cycle; if temperature is too low, raise it.</td>
</tr>
<tr>
<td></td>
<td>Material has absorbed water by exposure</td>
<td>Preheat* material.</td>
</tr>
<tr>
<td></td>
<td>Too much lubricant used on mold, causing material to be plasticized</td>
<td>Reduce or do not use lubricant.</td>
</tr>
<tr>
<td>Molded piece sticks or adheres to mold</td>
<td>Temperature too high and resin fails to come to surface and cover it. (Common with mineral filled material.)</td>
<td>Reduce temperature.</td>
</tr>
<tr>
<td></td>
<td>Mold fouled by improper lubricant or previous materials. Phenolic material will stick after cellulose acetate has been used when molds are not chromium-plated</td>
<td>Clean surface of mold and polish.</td>
</tr>
<tr>
<td></td>
<td>Mold is undercut by scratches, dents, etc.</td>
<td>Repair mold.</td>
</tr>
<tr>
<td></td>
<td>Mold is poorly polished</td>
<td>Polish mold.</td>
</tr>
<tr>
<td></td>
<td>Mold is irregularly heated, leaving cold spots</td>
<td>Heat properly.</td>
</tr>
<tr>
<td></td>
<td>Pieces are undercured—too short a cycle or too low a temperature</td>
<td>Increase cycle; increase temperature.</td>
</tr>
</tbody>
</table>

*(continued)*
<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Possible Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molded piece sticks or adheres to mold</td>
<td>Distortion caused by knock-out pins due to flexibility of piece, Charge has trapped gas or air pockets, distorting piece and binding it to mold</td>
<td>Increase curing or use material with more rigidity at discharge. Slower closing of mold; breathe mold; preheat*; provide vents; use preform.</td>
</tr>
<tr>
<td>Surface of piece dull</td>
<td>Mold too hot or too cold, Mold improperly polished, Mold stained by previous material, Poor grade of steel used for mold</td>
<td>Correct temperature. Polish mold. Polish and chromium plate.</td>
</tr>
<tr>
<td>Surface of piece peeled orange</td>
<td>Mold closed too fast under too high pressure, Material too soft, Material too coarse, A number of preforms used for charge, Material contains excessive moisture</td>
<td>Close mold more slowly; preheat* material and load hot. Use a harder material, or preheat* and load hot. Use a finer material, or preheat* and load hot. Use one preform or place preforms far apart and close mold slowly; preheat* material.</td>
</tr>
<tr>
<td>Surface of piece pitted or has small fissures</td>
<td>Material contains foreign matter, particularly oil or grease</td>
<td>Protect material against contamination.</td>
</tr>
<tr>
<td>Surface of piece clouded and/or color segregated</td>
<td>Mold too hot, causing precuring, Material too hard and/or pressure too low</td>
<td>Reduce mold temperature; tablet the charge. Increase pressure and/or use softer material.</td>
</tr>
<tr>
<td>Surface of piece has inverted blisters similar to dimples</td>
<td>Material too soft, Mold closed too fast, Material too soft (common), Too little charge or too much leakage</td>
<td>Use harder material. Close mold more slowly. Use a harder material; reduce temperature, which increases viscosity of flow. Increase charge; slower closing of mold; use stiffer material; preform to more accurately approximate shape of piece.</td>
</tr>
<tr>
<td>Pieces warped</td>
<td>Mold heated nonuniformly, Material too soft, Insufficient cure, Mold too hot, causing case-hardening of piece</td>
<td>Correct heating methods. Use harder material and/or preheat* material. Increase cycle. Decrease temperature.</td>
</tr>
<tr>
<td>Piece of irregular wall thickness and shape resulting in complex flow, cure, and shrinkage</td>
<td>Use lower shrinkage material; adjust temperature of various parts of mold accordingly; preheat* material and load hot; redesign piece to uniform section.</td>
<td>Close faster.</td>
</tr>
<tr>
<td>Charge left too long in mold before closing</td>
<td>Molding placed where it cools very unevenly; for example, on cold metal plate</td>
<td>Provide means for uniform cooling; provide shrink fixtures.</td>
</tr>
<tr>
<td>Material has absorbed moisture due to exposure</td>
<td>Preheat* material and load hot or cold.</td>
<td>Cool uniformly.</td>
</tr>
<tr>
<td>Pieces cracked nonuniformly (one side cooling faster than the other after molding)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pieces crack at once or afterward in storage</td>
<td>Wall around inserts too thin, Pieces strained on ejection, Shrink plugs too large</td>
<td>Increase wall and/or use lower shrinkage material. Eject evenly. Correct plugs, mold and/or use lower shrinkage material.</td>
</tr>
</tbody>
</table>
CHAPTER 13

TRANSFER MOLDING

Because transfer molding utilizes the same basic process as compression molding, most of the issues are the same. In this process, the transfer mold is closed before the previously plasticized compound enters it. In compression molding, the molding material is plasticized in the open compression mold prior to mold closing. In transfer molding, the plunger enters the die well as the press closes, the material is plasticized by heat and pressure and is forced through the sprue orifice, along the runners and into the mold cavity, which gradually fills under reduced pressure until the part formation is completed. Pressure is maintained on the mold until the cure period has ended. After this, the mold is opened and the part is ejected in a manner similar to that in compression molding.

PRINCIPAL TRANSFER MOLDING PARAMETERS

The parameters of this process are the same as compression molding. These parameters are listed in Table 13-2.

TROUBLESHOOTING

Table 13-3 describes the problems found in both compression and transfer molding. The problems and solutions shown in Table 13-4 are also applicable to transfer molding. Additional troubleshooting guidance is shown in Table 13-5. Additional suggestions for transfer molding are presented in the Reference section at the end of this chapter.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Possible Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pieces crack at once or afterward in storage</td>
<td>Where piece is cooled too much in mold, strains are set up</td>
<td>Reduce cooling cycle.</td>
</tr>
<tr>
<td>Pieces have poor electrical properties</td>
<td>Pieces case-hardened by too rapid closing of mold and too high temperature</td>
<td>Close mold more slowly; preheat* material and load hot; reduce temperature.</td>
</tr>
<tr>
<td></td>
<td>Material has absorbed moisture</td>
<td>Preheat* material.</td>
</tr>
<tr>
<td></td>
<td>Pieces undercured</td>
<td>Increase curing cycle.</td>
</tr>
<tr>
<td></td>
<td>Foreign matter in material</td>
<td>Protect against contamination.</td>
</tr>
<tr>
<td>Pieces weak mechanically and have poor chemical resistance, particularly to water and solvents</td>
<td>Pieces undercured generally due to too low temperature</td>
<td>Increase temperature and cycle.</td>
</tr>
<tr>
<td></td>
<td>Pressure not sufficient on piece (a common fault where charge is too low, escapement too great, or pressure is absorbed by abnormal landed areas on mold)</td>
<td>Increase pressure and/or charge.</td>
</tr>
<tr>
<td>Surface has hard small spots on pieces similar to small blisters, commonly known as pimples</td>
<td>Time of cure too short</td>
<td>Increase time of cure.</td>
</tr>
<tr>
<td></td>
<td>Material contains foreign matter, particularly wood splinters or metal chips</td>
<td>Protect against contamination.</td>
</tr>
<tr>
<td></td>
<td>Material has hard particles in it and/or is too coarse</td>
<td>Use softer and/or finer material.</td>
</tr>
</tbody>
</table>

* Preheat: 180–225° F (82–107° C) for 20 minutes–1 hour. Material should be loaded hot wherever possible.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Possible Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short molding (all powder cleared from pot)</td>
<td>Insufficient molding powder</td>
<td>Increased charge to pot.</td>
</tr>
<tr>
<td>Short molding (cull left in pot)</td>
<td>Insufficient flow of material caused by incorrect temperature; insufficient pressure; flow of powder too stiff; or gates and runners too small</td>
<td>Check and adjust temperature to proper range; check and adjust to proper pressures; use freer flowing powder; increase sizes of gates and/or runners.</td>
</tr>
<tr>
<td>Blisters or soft molding</td>
<td>Undercured</td>
<td>Increase cure time.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increase mold temperature.</td>
</tr>
</tbody>
</table>

(continued)
TABLE 13-5—continued
Problems, Causes and Solutions in Transfer Molding

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible Causes</th>
<th>Possible Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blisters or soft molding</td>
<td>Undercured</td>
<td>Preheat material.</td>
</tr>
<tr>
<td>Excessive flash</td>
<td>Transfer pressure too high</td>
<td>Reduce pressure or increase locking force.</td>
</tr>
<tr>
<td>Gas marks</td>
<td>Trapped gas—particularly with UF material</td>
<td>Preheat material prior to charging pot.</td>
</tr>
<tr>
<td>Burn marks</td>
<td>Air trapped in mold</td>
<td>Arrange for proper venting of mold.</td>
</tr>
<tr>
<td></td>
<td>Pot or mold temperature too high</td>
<td>Reduce temperature.</td>
</tr>
<tr>
<td></td>
<td>Molding cycle too long</td>
<td>Reduce time cycle.</td>
</tr>
<tr>
<td>Precure</td>
<td>Preheating temperature too high</td>
<td>Reduce time or temperature of preheating, use radio frequency heating, reduce power input.</td>
</tr>
<tr>
<td></td>
<td>Mold or pot too hot</td>
<td>Reduce temperature.</td>
</tr>
<tr>
<td></td>
<td>Time of dwell in pot too long before flow commences</td>
<td>Apply pressure sooner after charging pot.</td>
</tr>
<tr>
<td>Ripples or orange peel</td>
<td>Uneven flow in mold</td>
<td>Use a freer flowing powder and pre-heat.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Apply pressure more slowly and thus reduce jetting.</td>
</tr>
</tbody>
</table>

References

Bibliography
Wright, Ralph, Injection-transfer Molding of Thermosetting Plastics (Hanser-Gardner Publications, 1995).
GLOSSARY OF TERMS

A stage An early stage in the reaction of certain thermosetting resins in which the material is still soluble in certain liquids and fusible.

B stage An intermediate stage in the reaction of thermosetting resins in which the material swells when in contact with certain liquids and softens when heated, but may not entirely dissolve or fuse.

catalyst A substance that, when added in minor proportions, can change the rate of a chemical reaction but is not changed itself. Differs from a curing agent in the respect that curing agents react and initiate a chain reaction.

Class-A surface The highest-quality surface technically achievable on exterior automotive body panels.

CLTE Coefficient of linear thermal expansion. The change in length per unit length for every change in degree of temperature in/in°F [cm/cm° C]).

condensation A chemical reaction in which two or more molecules combine, with the separation of water. If a polymer is formed, the process is called polymerization.

creep The dimensional change of a material under load for a specific time and temperature following the instantaneous elastic deformation caused by the initial application of load. Sometimes called cold flow or deformation under load.

C stage The final stage in the reaction of thermosetting resins, in which material is relatively insoluble and infusible. The resin is a fully cured thermoset molding at this stage.

cure The total polymerization of the molecules of a resin that change it from a liquid to a solid.

cycle time The amount of time required to complete a full molding cycle from mold preparation to part removal.

dimensional stability Ability of a plastic part to retain the precise shape in which it was molded and fabricated.

draft The degree of taper allowed on the sides of a mold so the part can be removed.

drox The heat given off when a resin cures by chemical reaction.

fabric Cloth sheeting woven or knit with yarns of spin fibers or filaments.

fiber-reinforced plastic (FRP) Plastic material strengthened by strands or chopped filaments.

gel coat A primer coating applied directly to the mold surface prior to flowing the reinforced resin composition. Employed in hand lay-up, preform molding, panel fabrication, and SMC molding.

glass mat thermoplastic (GMT) Ready-to-mold fiberglass composite, typically polypropylene, used for high-speed compression molding.

hardness The ability of a substance to resist penetration or scratching by another substance.

heat deflection temperature (HDT) The temperature at which a material specimen deflects a given distance under a given load using ASTM test procedures.

impact strength The resistance to failure as a result of an instantaneous force of a moving body against another body either at rest or in motion.

in-mold coating A resin that is introduced into the mold cavity after the base resin is cured. Typically used to fill pits and porosity on the Class-A side of the base resin surface.

laminate A dense solid product produced by bonding together layers of fibrous sheet materials impregnated with a resin and consolidating them by simultaneous application of heat and pressure. A continuous glass fiber mat A fabric with random fiber orientation. The continuous glass fiber is coated with a liquid resin bath that solidifies to produce a continuous solid part.

exotherm The heat given off when a resin cures by chemical reaction.

flexural strength The ability of a material to withstand failure due to bending when a load is applied in the center of a simple beam.

glass mat thermoplastic (GMT) Ready-to-mold fiberglass composite, typically polypropylene, used for high-speed compression molding.

inspection A critical examination by an independent person of a product for Continued or improved reliability and serviceability.

jar test A mechanical test for serviceability by subjecting a product to impact loads, typically with a pendulum or a drop test.

key A raised portion of the mold cavity that is used to position the core in the mold during the injection molding process.

laminate A dense solid product produced by bonding together layers of fibrous sheet materials impregnated with a resin and consolidating them by simultaneous application of heat and pressure.
INTRODUCTION TO REINFORCED PLASTICS

Plastics are very versatile and can be tailored to meet various chemical and physical parameters for specific applications. Thus, multiple compositions (composites) can be developed and are grouped into families based on the monomers and the reaction sequence used to form the polymer. Both thermostet plastics (rigid 3D polymer networks), and thermoplastic polymers (which can be fused and refused a number of times) can be used in developing reinforced-plastic objects. Following is a description of several resins commonly used in reinforced-plastic compositions.

POLYESTER RESINS

Unsaturated polyester resins are formed by condensing stoichiometric mixtures of unsaturated and saturated dibasic acids or anhydrides with dihydric alcohols or oxides. In commercial production, the anhydride is normally preferred and an excess of the glycol is employed to drive the reaction to completion. Unsaturated acids, such as maleic acid, are essential to form an unsaturated polyester resin. The commercial unsaturated polyester resins are solutions in a reactive monomer such as styrene or diallyl phthalate. When initiated with a free-radical catalyst, this reactive monomer reacts to cross-link the unsaturated polyester molecules to form a rigid thermostet plastic. Both the dihydric alcohol and dibasic acid components can be modified with other similar chemicals to obtain a range of chemical and physical properties. For example, dibasic acids might include o-, m-, or p-phthalic acid.

The success of unsaturated polyesters in reinforced plastics has been achieved by use of glass fiber and other types of reinforcing materials. The performance characteristics, associated with the versatile range of compositions possible, has made unsaturated polyester the leading polymer in reinforced plastics.

VINYL ESTER RESINS

Vinyl ester resins are unsaturated esters of epoxy resins. The most common versions are reaction products of bisphenol A epoxy resin with acrylic acid dissolved in styrene monomer. They have the chemical characteristics of epoxy resins, but have the processing characteristics of polyester resins. Fabricators can frequently use them interchangeably with little processing modification.

EPoxy RESINS

This family of resins refers to a variety of cross-linking materials that contain an epoxy or oxirane group. This epoxy group is reactive with a number of curing agents or hardeners. When an epoxy resin is cured, a rigid 3D thermoset structure is formed that provides a number of valuable properties. Raw materials for these resins are usually bisphenol-A and epichlorohydrin, although other types of multifunctional structures can be employed. Curing
or cross-linking agents include polyamines and polyamides for ambient temperature cures, and anhydrides, phenol novolac resins, melamine, urea or phenol/formaldehyde condensates, and aromatic amines for higher-temperature cure systems. Epoxy resins have excellent chemical and physical properties and their operating temperature ranges are higher than that of polyester resins. However, economic considerations tend to restrict their use to areas requiring superior properties and to matrices for composition in the aerospace industry.

PHENOLIC RESINS

There are two types of phenolic resins formed by the reaction of formaldehyde with phenol—one-step (resole) and two-step (novolac). The resole phenolic reaction product is produced in an excess of formaldehyde with a basic catalyst. The novolac phenolics are produced with less than stoichiometric amounts of formaldehyde with an acid catalyst; to complete the reaction, more formaldehyde is added later.

General-purpose phenolics are compounds of fillers, reinforcements, and phenolic resin including mica, clay, wood flour, cellulose, mineral fibers, and chopped fabric. Both resole and novolac resins are used in general-purpose phenolic compounds. Engineering phenolics use a novolac-type resin and are usually glass-fiber-reinforced, although some grades use carbon or organic fiber reinforcements. Engineering phenolic resins can be highly filled (greater than 70%), which greatly enhances their ability to resist creep at elevated temperatures. The excellent dimensional stability and ability to be molded to tight dimensional tolerances makes them suitable for applications such as engine intake manifolds.

AMINO RESINS

Melamine/formaldehyde and urea/formaldehyde resins both belong to the amino resin family. Both melamine and urea react with formaldehyde under similar conditions in aqueous solution and undergo a second final catalyzed cure during molding to a hard-surfaced, rigid plastic composition. The initial aqueous polymer mixture is blended with pulp that swells and reacts with the resin; this mixture is dried to a solid product and granulated to a powder. The solid powder is mixed with a solid acid catalyst (phthalic anhydride) and cured in a compression press. Since these resins are clear, a diamine with a dibasic acid (nylon 6/6) or by the polymerization of a lactam (nylons 6, 11, 12). Nylons fall into three categories: unreinforced, reinforced, and toughened. Glass-mineral hybrid grades are used in industrial equipment, and mineral-reinforced nylons with maximum chemical and warp resistance are used for carburetor components. The intake manifold on automobile engines is a promising application.

THERMOPLASTIC POLYOLEFIN RESINS

Polyolefins include a large family of ethylene- and propylene-based polymers and copolymers. In general, these materials have good chemical properties, but are limited in their temperature range for continuous use. Therefore, a number of glass reinforced/filled compositions are commercially available and used in many applications. Polypropylene with glass reinforcement has considerable potential in structural applications such as bumper systems for automobiles.

THERMOPLASTIC POLYMERS

Polyethylene terephthalate (PET) is a high-performance, semi-crystalline resin that is very tough, has broad chemical resistance, and a wide operating temperature range. It is commonly supplied with glass and/or mineral fillers. It can be blended with numerous other commercial plastics to provide a range of properties. PET blends are used in applications where high rigidity and dimensional stability are required, particularly at high temperatures. PET is used in a number of automotive and industrial applications.

OTHER THERMOPLASTIC REINFORCED ENGINEERING POLYMERS

Polyphenylene Sulfides (PPS)

Polyether sulfones (PES, PESV) and polysulfones (PSU) are available in glass- and mineral-filled reinforced grades and are injection-molded to make automotive and industrial products.

Polyamide-imide (PAI)

PAI has a single glass transition temperature (525°F [274°C]) which is above its use temperature. This gives it exceptional dimensional stability throughout its use temperature.

Ketone Polymers

Ketone polymers include polyaryletherketone (PAEK), polyetherketoneketone (PEKK), and polyetheretherketone (PEEK). They are used as reinforced plastics in the automotive, aerospace, and electronics industries for high-temperature applications.

PROPERTY DESIGN BY COMPOUNDING

The matrix resin represents the fingerprint of any reinforced material and its corresponding performance properties. However, a major asset of plastic materials is that the property profile can be modified or extended to achieve a wide array of chemical, thermal, and mechanical properties. Thus, materials can be designed with additives, extenders, and reinforcing agents to meet specific processing requirements, handling and storage characteristics, and property profiles for specific product applications. This has resulted in many application areas where they replace metals, glass, ceramics, wood products, etc., with superior-quality and cost-effective products.
REINFORCING AGENTS

Reinforcing agents are critical in achieving the mechanical properties for many plastic applications. Various fibers including glass, carbon, aramid, and metal are employed in making a wide array of plastic products. Some of the more important reinforcing agents are described as follows.

Fiberglass

Fiberglass is the most common reinforcement used in engineering plastics. Glass fiber reinforcement provides stiffness, improved tensile strength, and impact resistance. However, an anisotropic structure is created in the material, which results in significant differences in the stiffness, coefficient of thermal expansion, and mold shrinkage of the molded parts, depending on whether the measurements are parallel or perpendicular to the direction of the reinforcement. Mold shrinkage is also dependent on the type of resin used. These characteristics can lead to warpage and distortion of molded products. Glass fibers are amorphous and have elastic character until they reach their breaking point.

E-type glass is used in over 90% of the reinforcement for polymers. It has good mechanical properties and bonds well to most plastics because appropriate coupling agents have been applied to the fibers. S-glass is higher in strength, but is primarily used in aerospace applications where strength and stiffness are critical. A wide variety of configurations are available including cloth; continuous strand mat; roving, twisted, or parallel strands; chopped fibers; and prepregs. C-glass is a chemically resistant glass that is sometimes used as a veil or cover layer on composites.

Carbon Fibers

Carbon fibers are manufactured from three different starting materials: rayon, polyacrylonitrile, and pitch. Depending on the temperature of carbonization, the surface roughness of these fibers will vary with the smoothest surface produced at the highest temperatures. Although the tensile strength and modulus of the fiber increases with increasing temperature, the ability to achieve matrix-to-fiber bonding decreases as the fiber becomes smoother. Since the resulting fiber is highly crystalline, these fibers are very stiff and temperature-resistant.

Aramid Fibers

Aramid fibers are synthetic polymers that have much higher tensile strength and modulus than most other polymeric fibers. The tensile strength is comparable to graphite fibers, although the compression strength is lower. Because aramid fibers are tougher than graphite fibers, they have better resistance to impact and abrasion.

REACTIVE REINFORCING MATERIALS

Some natural-fiber-reinforced plastics have been used for a number of years. Materials such as pulp, sisal, and wood flour react during the formation of the plastic to become part of the plastic structure. Since these reinforcing materials are not as abrasive as glass and some other materials commonly used, they offer low tool and equipment wear.

Pulp

Pulp is used extensively in amino, urea, and phenolic resins, where it is reactive with the curing polymer system. Since it is white, it lends itself well to production of colored or decorative plastics such as dinnerware and countertops. It is available in sheet or roll stocks, which are mixed and swelled with the aqueous solution of the resin to disperse the fibers. These fibers add stiffness, impact strength, and tensile properties. Recent work with waste newsprint in polypropylene has produced a reinforced polypropylene with improved mechanical properties.

Sisal

Sisal has been used in polyester bulk-molding compounds to provide a high gloss surface and high fiber background on the finished-molded parts.

FILLERS AND EXTENDERS

Common fillers and extenders include talc, mica, glass flakes, spheres, wood flour, and calcium carbonate.

Talc

Talc was used initially as an extender to reduce cost. However, additional benefits are realized by incorporating talc, including improved stiffness, better dimensional stability, and increased resistance to heat. Usually the tensile strength is relatively unaffected, although impact strength will be reduced. Since talc is a natural mined product, it can vary from white to tan.

Calcium Carbonate

Calcium carbonate is available in various grades. It is used extensively in sheet molding compounds, bulk molding compounds, and panels where excellent surface properties are an asset. It usually improves the flexural modulus with only marginal effect on the impact strength. It will, however, tend to reduce tensile strength, elongation, and compression strength.

Mica

Mica is a natural-mined product consisting of plate-like particles with a high aspect ratio. Its contribution to the properties of a plastic composition varies with the particle size. Stiffness and tensile strength tend to be proportional to the particle size. Mica, because of its tan or brown color, is mostly used in applications where color is not critical. Mica is used to enhance the heat stability and dimensional stability of plastics.

Spheres

Spheres are manufactured from glass, phenolics, quartz, and other materials. Since they are hollow, they have a very low bulk density and are used where weight reduction is important without deteriorating the mechanical properties. Since they are small and similar to talc in appearance, they mix well in resin, have good flow properties, and are physically very strong. Mixing and processing, if not done properly, can shatter the glass spheres.

Other Additives

To meet the required performance of reinforced plastics, other materials are added. Many options are available to meet specific parameters; the choice depends on the particular system employed. The following is a list of some of the important additives commonly used in reinforced plastics:

- Antioxidants
- Heat stabilizers
- Optical brighteners
- Pigments and dyes
- Coupling agents
- Compatibility
- Lubricants
- Mold release agents
- Tack additives
- Ultraviolet stabilizers
- Antistatic agents
- Low-profile agents
- Flame retardant
- Plasticizers
- Curing agents
This section will discuss the following:
- Hand lay up.
- Resin injection.
- Spray up.
- Preform molding.
- Resin transfer molding.
- Sheet molding compound.

HAND LAY UP

In hand lay-up, an open-faced mold is used, producing a finished part with only one surface finished to high quality. These parts have no shape or size limitation except those imposed by handling considerations. Typically a polyester resin is used for most commercial applications because of its low cost. However, epoxies are used in many aircraft applications where performance becomes the primary concern. In general, laminate physical properties improve with increased fiber length, optimum properties are obtained at specific resin to fiber ratios, and higher pressures during curing give better physical properties. Because of the improved properties with pressure, presses are used even for very large parts.

Mats, woven cloth, rovings, woven rovings, chopped strand mats, etc., can all be employed in the lay-up process. The first step is to apply a release agent to the surface of the mold, followed by a gel coat if a smooth, colored surface is required. The gel coat is a viscous coating, containing pigments, ultraviolet (UV) stabilizers, and other additives, that is spray applied to a thickness of 0.02–0.04 in (0.5–1 mm). Next a thin mat is applied and coated with resin using brushes or rollers. Successive layers are applied until the desired thickness is achieved and all of the preweighed resin has been applied. The entire surface is rolled to remove trapped air and completely wet the fibers. Although hand lay-up requires skill and is labor-intensive, it is still used extensively in the fabrication of low-volume products.

The hand or spray lay up (Fig. 14-1) is an open-mold system. The mold may be a simple wood or plaster unit (male or female) or a cast or sheet metal construction for which permanence is required. The size can vary from a 12 in. (305 mm) box to a large yacht.

The mold surface must be heavily waxed and then sprayed with a polyvinyl alcohol (PVA) solution to prevent the laminate from sticking to the surface. To make a smooth surface, a gel coat is applied. Thickness of the gel coat, which is either brushed or sprayed on, is approximately 0.020 in. (0.51 mm). The gel is a catalyzed polyester resin that is highly filled (may be pigmented for color) and stabilized for weather resistance. It must be allowed to partially cure before the subsequent resin and glass system is applied. A smooth surface is produced if the mold has a smooth surface. The laminate is built up by spraying catalyzed polyester resin onto the gel coat, then laying a glass mat on it and working the resin up through the mat with a hand (squeegee) tool. Subsequent resin and glass layers are applied to attain the required thickness.

An alternative is to use a chopper spray gun to build up the thickness. The hand tool is used to compact the laminate and force entrapped air out. The laminate is cured by either allowing the mold to stand at room temperature, or it is force cured in an oven. Room-temperature curing takes much more time (overnight), but it gives the mold a longer life. Oven curing shortens the curing time and the mold life.

RESIN INJECTION MOLDING

Resin injection molding (Fig. 14-2) as an intermediate volume process uses tooling and equipment that is lower in cost than that used in conventional compression or injection molding techniques. Molding cycles are much slower than those for compression and injection methods, but production rates far exceed those for the open-mold techniques.

The closed mold made from plastics, spray metal, or cast aluminum produces parts with smooth surfaces on both sides. A gel coat may be used to obtain a desired color, improve weatherability, increase corrosion resistance, and permit postfinishing operations. The mold has cooling coils for exotherm control, a perimeter gas- ket to prevent resin and pressure leakage, and air vents to bleed off air and determine part fill. The resin compound, including catalyst and filler, is pumped into the mold through an injection port. The curing cycle is about 10-20 minutes because the resin is injected rapidly and thus allows for the faster gelling and curing permitted in lay-up systems. This closed-mold technique also allows for foam encapsulation and the use of ribs and inserts.

SPRAY UP

A mixture of chopped fibers and matrix resin can be applied to a gel-coated mold using an airstream and a spray gun specifically designed for this purpose. Several styles of guns are available that involve external mixing of the catalyst system and resin with the fiber; however, the catalyst system and resin are normally mixed in the cavity of the spray gun. Pressurized vessels that eliminate air pressure in the gun can also be used. Hand-held guns allow design of the distribution pattern for chopped glass and resin to optimize the properties of the final product. Robotic spray guns can be employed to automate large molds or mold clusters for smaller parts.
CHAPTER 14

METHODS OF FABRICATING REINFORCED PLASTICS

Fig. 14-2 Resin injection molding. (Courtesy T. H. Meister)

Hand-spray lay-up techniques are common for fiberglass shower stalls, tubs, pools, camper tops for pickup trucks, temporary shelters, boats, canoes, surfboards, and signs. A huge soda bottle, 42 ft (13 m) tall, is an example of a large molding possible with these techniques.

PREFORM MOLDING

Glass preforms are used in compression molds for parts finished on both surfaces. Chopped fiber with a binder is sprayed from a gun or tube onto a screen through which air flows (see Fig. 14-3). The fibers mat to the surface as the binder cures, creating a preform that is trimmed to size. Normally the excess fibers of the preform are removed after compression molding by manually trimming the final part. If a water jet is used prior to molding, the preform may have to be dried.

Steel rule dies and laser trimming are alternate methods. The preform is inserted into a mold, resins are applied to the surface, and the part is molded. This technique is used where deep draws and difficult contours make it hard to achieve the desired properties with sheet molding composites or bulk molding compounds. Farm tractor bodies, industrial housings, truck cabs and hoods, concrete forms, bus seating, boats, bins and boxes, pallets, etc., are molded by this technique.

The slurry process for making preforms uses chopped glass roving in water. Chopped fiber and a fibrous binder are mixed in a water bath. A screen in the shape of the preform is dropped to the bottom of the bath. When the screen is pulled up, water running through the screen deposits fibers on it. The size and placement of holes in the screen control the fiber distribution and location. This technique has been used to make preforms with all types of chopped fibers. Scrap is minimal because fibers that are not deposited on the screen mix with the new charge of fiber at the beginning of the next cycle. If the preform is not correct, it can be dispersed back into the slurry and the fibers and binder rede-
posited. Trim scrap is minimal because a near net edge can be produced. Preform cycle times of 45 seconds can be achieved. The wet preform must be dried on the screen.

Compression presses capable of delivering up to 4000 psi (28 MPa) are used to mold structural parts. The size of the press is determined by the profile of the part, which can be quite large, such as an entire pleasure boat hull or truck hood. A high quality spray coating is applied to the finished part.

RESIN TRANSFER MOLDING

Resin transfer molding (RTM) combines the versatility of hand lay up with the speed and low volatile emissions of closed-mold processes. In this process, the resin is injected directly into the closed mold with no direct exposure of the resin to the air. The reinforcement is prepositioned in the mold, although in some cases the reinforcement fibers can be added to the resin before injection. High-quality surfaces can be achieved with relatively low-mold temperatures (140–194°F [60–90°C]) and low pressures (2–4 psi [14–28 kPa]), which have a substantial impact on reducing the cost of tooling. Steel tooling is not required, since the temperature and pressure involved are relatively low. This system offers advantages for short runs and prototyping.

SHEET MOLDING COMPOUND

Liquid thermosetting resin, glass fiber, and filler are converted to sheet molding compound (SMC) which is normally about 0.125–0.187 in. (3–4.8 mm) thick and 45 in. (1.1 m) wide. The length of the sheet is determined by molder preference. The sheet is handled on a roll or festooned into bins. Before SMC can be used for molding, it must age or mature. During this maturation time, the residual polymer acid functions react with the calcium oxide or other metal oxide thickener, which results in thickening of the low-viscosity resin. The thickened SMC prevents resin paste from being squeezed out of the glass-fiber matrix, making it easier to handle and mold.

Approximately three to five days are required to reach the desired viscosity (20–30 million cP). The SMC product is pliable, like a piece of leather. Since the SMC will continue to thicken, it has a limited shelf life, usually about two weeks, but it can be adjusted to meet specific demands. SMC is marketed as a thickened sheet, but may also be manufactured at the molding site.

In the manufacture of SMC, all of the ingredients, except the glass fibers, are blended together to form a thick paste. The paste is applied to top and bottom carrier films with doctor boxes that control the thickness of each carrier film (see Fig. 14-4). A rotary chopper is used to cut glass fiber roving to length. Normally fibers are chopped to 1 in. (25.4 mm), but the length can vary from 0.25–2 in. (6.4–51 mm) depending on the application. The glass fibers are deposited randomly on the paste-coated carrier film and are generally oriented more or less parallel to the direction of film travel. The amount of glass fibers deposited is controlled by the speed of the rotary chopper and the speed of the carrier film. The glass fibers are sandwiched between the resin paste coated top and bottom carrier film. The sandwich proceeds through a series of
compaction rollers where the glass fibers are wet with the resin paste and air is squeezed out of the sheet. After the compaction rollers, the SMC is taken up on a storage roll or festooned into bins.

When the SMC is ready for molding, the material is spread onto a cutting table and cut into pieces of predetermined size and shape. Cutting is usually done manually by the press operator with a template and mat knife. Some large volume applications have an automated slitter table. Stacked and assembled pieces are arranged into a charge pattern that has been determined to provide the optimum shape and volume to fill the mold cavity. It is important to trim and assemble the charge pattern as accurately and consistently as possible to avoid process variation. A charge pattern for a Class-A part usually covers 20–40% (40–80% with vacuum assist) of the mold surface. For structural parts, a charge pattern may cover up to 90% of the mold surface. The mold is heated to 250–325°F (121–163°C) with pressures for low profile SMC of 800–1200 psi (5516–8273 kPa). The cure time for SMC varies from 30–150 seconds. The cure time is determined mainly by the formulation of the SMC and the part thickness.

The resin system initially has a low viscosity to ensure complete mixing of the additives and wettability of the glass reinforcement. The viscosity is increased after the sheet compound has been formed. This creates a tack-free sheet for handling purposes.

A typical manufacturing process is shown schematically in Fig. 14-5. The numbers on this illustration correlate with the following steps:

1. The thermoset polyester is mixed with a thermoplastic resin (low-shrink additive), fillers, catalysts, thickeners, and internal release agents. This mixing operation can consist simply of batch weighing the ingredients by hand and funneling them into a tank with a mixer, or it may be a sophisticated operation for weighing and mixing ingredients by means of a highly automated system controlled by computer.

2. The blended resin compound is pumped to the upper and lower carrier film and spread in a uniform layer at the required thickness with a doctor blade (a movable bar that regulates the amount of viscous material on the rollers of the spreader).

3. The fiberglass rovings are in creels and are set in racks to facilitate the feeding of the required number of rovings to the cutter. This depends on the width and percentage of glass needed for a specific SMC.

4. Rovings are chopped to the required length and fed by gravity to the lower carrier film or sheet, which has the resin compound spread on it.

5. The two carrier sheets are brought together with the chopped fiberglass between them.

6. The combined systems are pressed together with heated rollers to wet the surface of the glass fibers and eliminate the entrapped air. The heat from the rollers initiates the required increase of the resin viscosity.

7. The SMC sheet is cut off when a predetermined weight per roll is obtained. The carrier sheets then are used as a barrier to prevent the evaporation of volatile ingredients in the resin system. The carrier sheets are polyethylene or nylon. Nylon is used when greater control over the loss of volatile compounds is required.

8. The resin system is sent to the maturation room where it is brought to the required viscosity. This is a time/temperature related precuring reaction. It requires several hours and is required for specific formulations.

9. After maturation, the rolls are sent to the press area where the sheet is slit and cut or diecut to a predetermined size, shape, and weight. The carrier sheets are stripped off at this location.

10. A specific charge pattern for the sheet is determined by experimentation. A charge pattern’s weight and placement is dictated by the part design and by the flow characteristics.
of the SMC. These factors must be consistent to maintain the desired quality of parts. For additional reinforcement, glass cloth may be added at stress locations.

11. The SMC process is performed on a hydraulic press. Pressures are dependent on the formulation and part complexity. Curing time is controlled by the thickest section on the part (bosses and/or ribs).

To obtain Class-A surfaces, the overall glass fiber content is limited to less than 30% to optimize surface smoothness. A typical composition for a low-profile SMC is shown in Table 14-1.

The surface appearance of low profile SMC has been documented in some cases to be superior to sheet steel. Additional mechanical property enhancement can be achieved by increasing the glass fiber content, but with some sacrifice of surface quality. Table 14-2 provides a comparison of a typical low-profile SMC with 25% glass fiber content, a more structural SMC with 50% glass fiber content, and SAE 1008 low-carbon cold-rolled steel.

SMC offers several advantages when compared to steel for body panels in automobiles.

Corrosion Resistance

The corrosion resistance of SMC panels is well-documented in some of the most demanding conditions including heavy truck hood assemblies and aerodynamic fairings.

Mass Savings

As shown in Table 14-2, SMC has a definite advantage in specific gravity over steel components. In general, it is expected that a 25–35% mass savings over steel will be realized. Part consolidation also contributes to mass savings because of the design options available with SMC. Hoods, doors, lift gates, and deck lids are examples where the mass savings are particularly large. As fuel economy requirements become more stringent, the advantage of SMC’s lower mass will become more important.

Part Consolidation

Complex shapes with steel are often limited by the depth of draw and require a multipiece assembly. Frequently the same design in SMC can be made in one piece, including bosses and localized variations in thickness to incorporate any number of

<table>
<thead>
<tr>
<th>Component</th>
<th>Percent by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester Resin</td>
<td>20–27</td>
</tr>
<tr>
<td>Glass</td>
<td>25–30</td>
</tr>
<tr>
<td>Filler</td>
<td>40–50</td>
</tr>
<tr>
<td>Additives</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

**TABLE 14-1**

Typical Composition for Low-profile SMC
standardized fasteners. An example would be a Class-A SMC grille opening panel (GOP).

**Shorter Tooling Lead Time**

Major body panel tooling for SMC production can be completed in 8–12 months from receipt of complete design data. In contrast, most major steel body panels require 16–24 months to tool.

**Lower-cost tooling.** With secondary tooling included, tooling costs for SMC are about 40% of the cost of stamping dies.

**COMPATIBILITY WITH STEEL BODY ASSEMBLY**

The body assembly prior to primer application is a hybrid of steel and composite materials. The physical property match of SMC and steel components is acceptable in the thermal and chemical environment to which they are exposed during the finish coating.

Polyurea or urethanes are reinforced reaction injection molded (RRIM) into heavily contoured surfaces such as facia and fenders. Because of the lower heat-deflection temperature of these materials they tend to be used only in vertical panel applications. Engineering thermoplastics such as acrylonitrile-butadiene-styrene (ABS)/polycarbonate blends, polyphenylene oxide (PPO)/nylon 6 blends, and polycarbonate/PBT blends also tend to be restricted to vertical panels.

Production of SMC for automotive components was almost 181 million lb (82 million kg) in 1994. The distribution of these SMC applications is shown in Table 14-3. Total production of SMC in the United States in 1994 for all applications was about 240 million lb (109 million kg).

**BULK MOLDING COMPOUNDS**

The bulk molding compound (BMC) manufacturing process predates the SMC and TMC systems and has been used to produce a large number of automotive and electrical parts. The automotive companies use large amounts of BMC for heater and air conditioning housings. Some compounders have used sisal as the primary reinforcing fiber.

A typical BMC process is shown in Fig. 14-6. The following list corresponds with the numbers in the illustration:
1. This process is a batch system using a sigma blade mixer that gives versatility in the compound selections. Bulk molding compound is low in strength because of glass length degradation during mixing. When a large quantity of the same compound is being produced day after day (heater housings, etc.) a continuous compounding unit can be used. The fiberglass may also be purchased as a chopped roving and introduced by hand. The resin compound consists of a polyester resin, filler, catalyst, internal lubricants and, in some instances, a low-shrink additive. Sheet molding compounds and thick molding compounds were derived from similar basic formulations.

2. The bulk compound is dumped from the mixer into a ram extruder to form billets that are cut to length for a given weight. The billets then are taken to the molding area. Polyethylene sheeting covers the billets to prevent evaporation of volatile constituents if storage for more than a few hours is required.

3. Compression molding is accomplished on a heated (280–325°F [138–163°C]), matched metal mold using a standard hydraulic press capable of producing 300–700 psi (2.0–4.8 MPa). Molding pressures vary with part design (thickness, intricate ribbing, bosses, and dimensional tolerances). A modification of the compression method is transfer molding. This involves working to a closed mold; the BMC is introduced through a pot with a ram that forces it into the closed mold. This method is used when close thickness tolerance is needed or when inserts are contained in the molded part.

4. Injection molding of BMC is accomplished in much the same manner as injection molding of TMC using a reciprocating screw (or a plunger); heated barrel (100°F [38°C] or higher); or heated, matched metal mold; and a stuffer. Injection pressure is in the 5000–12,000 psi (34.5–82.7 MPa) range.

Some companies produce BMC for sale to custom molders who do not have sufficient requirements to warrant in-house compounding facilities. These companies have also developed highly specialized compounds that are beneficial to a small custom molder who does not have development capabilities.

Bulk molding compounds (BMCs) are available in a wide range of grades and blends to meet application specifications. They are made by blending resin, usually polyester resin, catalyst, minerals, reinforced chopped fibers, pigments, and other additives in a bulk mixer to form a dough-like composition. This BMC is molded by injection, compression, or transfer molding into a wide range of products including microwave cookware, circuit breakers, exterior automotive panels and automotive headlight mountings, and industrial housings. BMCs have a good continuous high-temperature operating level, 450°F (232°C), which makes them suitable for motor housings and household appliances such as the skirts on steam irons.

THICK MOLDING COMPOUND

TMC uses a mixture of chopped fiberglass and thermosetting polyester resins that is formed into a sheet up to 2 in. (51 mm) thick or into a billet shape for compression and injection molding. The thick molding compound system has a 50% advantage in production rates over SMC systems. Greater filler contents can also be tolerated. The production of thick sheets reduces handling costs and consumption of carrier sheets.

The use of the TMC process for some large automotive parts (grille opening panels) has been successful in providing good

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**Fig. 14-6** Bulk molding compound (BMC) manufacturing process. (Courtesy T. H. Meister)
strength and improved surfaces (in comparison to the use of the SMC process). The injection-molding method is used.

A typical process is shown schematically in Fig. 14-7. The following list corresponds with the numbers in the illustration.

1. Resin compounding and reinforcing is basically the same as that for the SMC process, except it does not require a thickening agent and uses higher filler loadings. Fiberglass rovings are chopped in the cutter and introduced along with the metered resin compound into the impregnating rolls. The secondary wiping rolls deposit the resin-coated fiberglass onto the carrier sheets or films to provide improved wettability of the fibers.

2. The carrier sheets (polyethylene or nylon) sandwich the TMC.

3. The compaction rolls reduce the compound to the desired thickness and also lower the entrapped air content.

4. The finished TMC is slit and cut to predetermined width and length. The slabs or billets are shipped to the molding area (injection and/or compression).

5. The injection-molding method uses billets that are introduced into the barrel with a hydraulic stuffer. Depending on the temperature required for specific formulations, the barrel is heated in excess of 100˚ F (38˚ C) to obtain a consistent flow characteristic. The reciprocating screw is of a special design for handling TMC, since standard screws could break the glass fibers. The compound is injected at 5000–12,000 psi (34.5–82.7 MPa) into the heated mold at 325˚ F (163˚ C) where its curing is accomplished. The curing time depends on the geometry of the part. The heaviest sections (bosses, etc.) are the governing factor, as they are with SMC. Experience has shown that the higher pressure applied in this process minimizes surface porosity, which is a serious problem with SMC parts. This problem is a major concern for automotive applications requiring high-temperature finishes. Also, the TMC process has the ability to produce thinner sections with greater dimensional accuracy. Injection gives directional orientation of the reinforcing fiber, and this can create weak areas parallel to the fiber flow. Also, it sometimes happens that material flowing around core pins adjacent to mounting lugs can produce areas that are rich in resin and weak in reinforcement. These problems can be minimized through careful part design. Parts produced by this system have minimal deflashing requirements when compared with compression molding.

6. Compression molding of TMC is performed by the same method as SMC. Fewer sheets are required (only one may be used) in the load pattern, compared to the multiple plies needed with SMC. Also, improved physical properties and minimal porosity are attained. All of these factors tend to make TMC superior to SMC.

**Fabrication**

Most TMC and SMC parts require some secondary fabricating operations, depending on part design (injection molded TMC requires much less). For automotive components, typical SMC and TMC secondary operations consist of:

- Deflashing or trimming edges.
- Punching large openings.
- Drilling or piercing small holes.
- Driving attachment studs.
- Light surface sanding and pit filling.
Most deflashing is done at the press by the press operator during the closed-mold phase of the molding cycle. This is a manual operation utilizing a rasp file if the flash is minor, or a hand power sander to remove a lot of flash. The outer periphery of the part is cleared of flash, and large openings are cleared, depending on the amount of time the operator has available. This is best done at the press while the part is still hot from the mold.

Large openings are molded in the tool either with a small amount of flash or with a thin web of material covering the entire opening. This is removed with a trim die in a mechanical or hydraulic punch press.

Smaller openings may be molded in the tool in the same way if they are in the direction of the mold opening; if not, they may be molded in the tool by retractable cores. Often, if the holes are in areas in which problems of material flow in the mold may exist, or if an effort is being made to reduce costs, it is preferable to drill holes in automatic drill fixtures or pierce them in a punch press.

For purposes of parts attachment in assembly operations, parts are designed with bosses molded on the back side. Attachment studs are driven into the bosses either manually or in gang stud-driving operations performed in a single unit that operates sequentially under pneumatic logic control.

Exterior automotive parts produced by the SMC and TMC processes are painted and must achieve a Class-A surface. This means that the plastic's painted surfaces must be free of blemishes and must match the adjacent sheet metal painted surfaces.

Wiping with a penetrating sealer to detect any voids or porosity on the surface and light scuff sanding are combined with inspection of parts before priming. Additional information on fabrication and assembly is provided in Volume 4, Assembly, Testing, and Quality Control, of this Handbook series.

Vacuum Bag

The vacuum bag method uses a film of styrene resistant plastics (mylar or cellophane). The film is sealed around the mold, and a vacuum is created under the bag. This flattens the fibers, draws air from the resin, and produces a glazed surface on the back of the part.

Pressure Bag

The pressure bag process differs from the vacuum bag process in that positive pressure is applied to the top surface of the film. Steam heat sometimes is introduced into the mold cavity.

Autoclave

The autoclave method is widely used in the aerospace industry to produce parts from impregnated epoxy. A woven fabric is impregnated with epoxy resin. It is then dried and heated to a stage at which it is partially polymerized and is susceptible to heat.

The impregnated fabric is cut and placed in a mold, which may have a phenolic or aramid honeycomb core. The mold is then covered with a vacuum bag and placed in an autoclave. Vacuum is held at 28 in. (711 mm Hg) [4 kPa], while the autoclave is pressurized to 50 psi (345 kPa). The mold is heated to 250–350˚ F (121–177˚ C) for about 2½ hours.

PULTRUSION PROFILES FOR CONSTRUCTION MATERIALS

Pultruded fiberglass profiles are very stiff, corrosion-resistant, and transparent to electromagnetic waves. Common uses include handrail systems, gratings and grids, decking, structural fabrication, stairways and ladders, bridges and walkways, and construction wall panels. Buildings have been constructed using 24-in. (61-cm) fiberglass I-beams, which create entirely new architectural and design possibilities. Corrosion resistance is a primary consideration in many of these projects. However, other unique properties are equally important. For example: a 37 ft (11 m) tall, all-fiberglass, gold-leaf-clad spire was installed on top of a 55-story building. The spire is transparent to electromagnetic waves and houses communication antennas (see Fig. 14-10). All-fiberglass buildings including the sub flooring and flooring have been constructed for computer testing facilities.

Although glass is frequently used in these reinforced pultrusion products, other specialized reinforcements such as carbon fibers, aramid, and polyester fibers are also used. Various combinations of
fibre orientation are used in building up a pultruded product. Thus, the core will be unidirectionally aligned glass fibers bonded with resin. This core is sometimes covered with a continuous glass fiber mat with random fiber orientation to add strength in the transverse direction, then with a veil. Many applications have the continuous strand mat in the center. The continuous glass fibers, continuous glass fiber mat, and synthetic veil are pulled through a liquid resin bath. Following the resin-coating bath, the components are pulled through a heated shaping die where the resin solidifies, producing a continuous, solid part. The continuous glass fiber mat surrounds the surfaces to prevent lineal splitting and chipping. The surface veil is an integral part of the pultrusion and enhances corrosion and UV resistance. It is made from material similar to the resin used in manufacturing the part, and pushes the glass fibers away from the surfaces of each part, producing a thick 100% resin surface. The finished product has extremely long life, even when exposed to salts, acids, and caustics. Since ultraviolet radiation found in sunlight can degrade exposed resin surfaces, a UV inhibitor is added to the resin at the time of manufacture. UV coatings can also be applied when UV inhibitors are not adequate for optimum protection.

Resins used in pultrusion include thermosetting polyester, vinyl esters, epoxy resins, and phenolic resins. Since the prime applications are in structural applications, a flame retardant is normally included in the formulations. Polyester resins with antimony trioxide added exceed the requirements for Class-1 rating of 25 or less as defined in ASTM E-84 and meet the self-extinguishing requirements of ASTM D-635. Fire-retardant vinyl ester is used for severe corrosion applications. It has better resistance to caustic and certain acid environments than the fire-retardant polyester resins. Fire-retardant vinyl ester will meet the ASTM E-84 Class-1 flame rating and the self-extinguishing requirements of the ASTM D-635. Phenolic resins are naturally fire-retardant and do not need additives.

Because of their excellent corrosion resistance, pultruded products often replace steel or aluminum gratings and grids. In addition to being corrosion-resistant, they are structurally strong, lightweight, easy to fabricate, nonconductive and nonsparking, and nonmagnetic (electromagnetic transparency). They have high impact strength, high-fatigue strength, and low-thermal conductivity but are not isotropic. Typical mechanical properties of pultruded parts are shown in Table 14-4.

Pultruded fiberglass foam core building panels are fabricated using either an isophthalic polyester or vinyl ester resin. The core material is a rigid closed-cell urethane foam. Both resins provide flame retardance (UL94 VO). These panels are lightweight, nonconductive, integrally insulated, and transparent to electromagnetic emissions. The tongue-and-groove design allows the panels to be assembled on vertical walls; roofs; tank and pit covers; radar, microwave, radio, and TV enclosures; and buildings for electromagnetic interference (EMI) testing (computer testing). Composite wood-grain structural shapes look like wood but retain all of the properties of fiberglass.
Fiberglass studs and nuts are employed for applications requiring mechanical fasteners that must be strong, noncorrosive, and/or nonconductive. They are used as replacements for steel and other metal fasteners in chemical process equipment, air and water pollution control equipment, marine applications, and in applications requiring all nonmetallic materials (that is, structures that must be nonconductive and/or transparent to electromagnetic waves). The studs are pultruded, machined fiberglass reinforced vinyl ester. The hex shaped nut is thermoplastic. The maximum recommended operation temperature based on 50% retention of ultimate thread shear strength is 203˚ F (95˚ C).

CURED-IN-PLACE REINFORCED PLASTICS

Damaged municipal and industrial pipeline systems can be reconstructed using trenchless technology with reinforced plastic.8,9 This trenchless technique employs pipe-in-a-pipe technology with a curing system that is initiated after the pipe has been positioned. Over 21 million feet of pipes have been reconstructed worldwide, with over 10 million feet in the United States. This system has been employed in both gravity and pressure applications such as sanitary sewers, storm sewers, process piping, drinking water systems, electrical conduits, and ventilation systems.10 Pipes ranging from 4–99 in. (10.2 cm–2.5 m) in diameter have been reconstructed in continuous lengths up to 2700 ft (823 m).11

A flexible, resin-absorbent, polyester fabric tube is coated on the outside with an elastomeric material. This tube is fabricated to fit the cross-section length, and required design thickness for the damaged pipe (see Fig. 14-11). The coated tube is vacuum-impregnated (wet out) with a liquid thermosetting resin. The impregnated tube is installed in the existing pipe through a temporary inversion standpipe and inversion elbow. The tube is secured to the existing pipe with a collar and water is pumped into the inversion standpipe. The force of the water pushes the tube inside-out, an action termed inversion, and into the pipe being reconstructed.

![Fig. 14-11 A flexible, resin-absorbent, polyester fabric tube is custom-engineered and manufactured to fit the cross-section, length, and required design thickness for repairing a damaged pipe. (Courtesy Insituform Technologies)](image-url)

### TABLE 14-4

<table>
<thead>
<tr>
<th>Properties</th>
<th>Typical Values</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
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<td>Tensile stress, psi × 10^3 (MPa)</td>
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<td>ASTM D-638</td>
</tr>
<tr>
<td>Tensile modulus, psi × 10^6 (GPa)</td>
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<td>ASTM D-695</td>
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<td>Compressive modulus, psi × 10^6 (GPa)</td>
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<td>ASTM D-695</td>
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<td>4.4 (7.9)</td>
<td>ASTM D-696</td>
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</tbody>
</table>

* All values are in lengthwise direction. (Courtesy Morrison Molded Fiber Glass Company, Bristol Division)

Crosswise mechanical tests are usually two to four times lower in value.
CHAPTER 14

METHODS OF FABRICATING REINFORCED PLASTICS

Missing pipe sections, 90° bends, and offset joints, as well as vari-ations in elevation and diameter, are accommodated. The inversion process results in the elastomeric coating of the tube becoming the new interior surface of the pipe (see Fig. 14-12). The inversion process causes no relative movement between the tube and the deteriorated existing pipe wall, minimizing potential damage to the flexible tube material. In addition, any incoming and standing fluids are forced ahead of the inverting tube, eliminating any trapping that might inhibit cure of the tube or change its shape. When the tube has reached the desired length, the water is passed through a heat exchanger and the thermosetting resin is cured. Once the resin is cured and cooled down, the water pressure is released and the ends are trimmed. Service connections are reinstated internally with a remote control cutting device or by human-entry techniques (see Fig. 14-13).

The finished pipe-in-pipe is normally stronger than the original pipe and has greater flow capacity than the original pipe. In addition, the following benefits are realized:

- Eliminating infiltration of groundwater through joints, breaks, and missing sections of gravity pipes.
- Smoothing the interior surface and providing smooth transitions over joints and protrusions.
- Protecting the pipelines from attack by corrosive chemicals, effluents, and gases.
- Reducing maintenance by eliminating joints and openings for root intrusion into gravity pipelines, smoothing irregularities that trap sediment and deposits, and reducing grease and scum buildup due to a nonwetting plastic surface.
- Eliminating leaks in pressure piping systems by sealing pin-holes, joints, and cracks.

The thermosetting systems normally used fall into three major groups: (1) unsaturated polyesters, (2) vinyl esters, and (3) epoxy resins. Polyester resins are the most commonly used, as they are highly resistant to normal domestic sewage and sulfuric acid produced by hydrogen sulfide activity. Vinyl ester and epoxy resins are employed where special corrosion and/or solvent resistance are required, such as industrial sewage or industrial process lines. A comparison of the typical physical properties of cured composites using these resins is shown in Table 14-5.

Aramid fabric has been used for reinforcement in some pressure pipe applications.

Cured-in-place reinforced plastics have been used experimentally on pillars and piers for elevated roadways to strengthen and protect them against the horizontal shear forces experienced during earthquakes. Some of the early reports have been encouraging and additional studies are being made. This is an area of great interest because of the large number of elevated roadways and bridges in the United States interstate highway system, particularly in highly populated areas.

Wooden utility poles have a maximum service life of 25–35 years. However, deteriorated or mechanically damaged wooden poles can be wrapped with alternating layers of fiberglass and phenolic resin to extend their useful life. The composites give the poles outstanding strength and fire resistance, along with increased service life.

PLASTIC PANELS IN AUTOMOTIVE AND CONSTRUCTION APPLICATIONS

Because of the excellent weathering characteristics and stiffness, reinforced plastic panels have found a wide range of applications including roofing, siding for buildings, glazing, signs, greenhouse siding, wall and ceiling panels, recreational vehicles, see-through panels for truck trailers, tank covers, and carport enclosures. Frequently, the panels are stripped with gel coat on the exterior surface to produce decorative effects. Normally, polyester resins are employed, although vinyl esters are used in applications where additional chemical resistance is required. In applications like recreational vehicles, opaque panels of various colors are produced and usually have an exterior gel coat which enhances the surface appearance and provides an additional UV stabilizer system to improve color retention. Opaque colored panels are also used in vertical wall and ceiling applications. The United States Department of Agriculture (USDA) has approved use of these panels in meat packing plants where the surface coating on the panels makes them up to 10 times more cleanable than alternative materials. These panels are recommended as wainscot in institutional buildings, fast food restaurants, and wherever cleanability, durability, aesthetic appearance, and safety to human and/or animal life is critical. Shower stalls, lavatory tops, and wall paneling are frequently used in hotels and motels where severe and frequent use and cleaning are common. These panels will not rust, mildew, or rot, and never need painting. Nonpigmented clear panels are used for glazing and in greenhouses. The thicknesses and densities of these panels are given in Table 14-6.

Liquid thermosetting resin and glass fiber are converted to reinforced panels in a continuous process. In the manufacture of the panel, all of the additives and pigments, except the glass fibers, are blended together to form a thick syrup. This thickened paste is applied to the bottom carrier film using doctor boxes that control the thickness of the resin syrup. This film, coated with resin, passes over a heated table to reduce the viscosity. A rotary chopper is used to cut glass fiber rovings to lengths which are then deposited on the resin. Normally fibers are chopped to 2 in. (51 mm), but lengths can vary depending on the application. The glass fibers are deposited randomly on the syrup-coated carrier film. The amount of glass fibers deposited is controlled by the speed of the rotary chopper and carrier film. Frequently a squeeze roll and knife blades are used to push the glass fibers into the resin. The top film is normally dry except when a gel coat is applied. The glass fibers are sandwiched between the two film layers, and this sandwich proceeds through a curing oven. Initially the viscosity decreases as the resin exotherms, but later the resin thickens and finally cures to a solid product. During the curing process contours or ribs can be produced in the panel. When the panel exits the oven, it is solid and is then cut to length for shipping. Typical physical properties of the final panel are given in Table 14-7.

Filament Winding

Filament winding (Fig. 14-14) uses continuous fiberglass rovings fed through a catalyzed resin bath (polyester or epoxy) onto a revolving mandrel by a traveling head on the winder. The fiber is wound to a predetermined pattern under an applied tension that provides an even share of load bearing by the fiberglass reinforcement. In some instances, inflatable or soluble mandrels are used to facilitate their removal from the completed part. The filament winding process produces storage tanks and various aerospace items, as well as high-strength, lightweight pipes and tubes.

This process is also used to make high-strength molding sheet. A spun wound mandrel is used to produce a laminate that is formed by a wide-angle winding operation. When the desired thickness is reached, the laminate is slit lengthwise to make a flat sheet. This sheet is cut into suitable strips and compression molded with SMC into parts that have high-strength areas provided by the filament-wound material. Filament winding is generally used to manufacture cylindrical parts, although newer winding equipment
Fig. 14-12 The three stages in installing an in-place repair tube are (a) the tube is installed through an existing manhole or other access point using an inversion standpipe and inversion elbow (b) water from a nearby hydrant or other convenient source is used to fill the standpipe and the force of the water column turns the repair tube inside out and (c) with the tube fully extended, the water in the line is circulated through a heat exchanger and the hot water cures the reinforced thermosetting resin. (Courtesy Insituform Technologies)
allows complicated geometric structures. Continuous fibers are wound on a rotating mandrel in a precisely controlled and repeatable pattern. These systems are automated with computer control. After the mandrel is wound, the winding is cured and the mandrel is removed. Directional strength through the part can be varied by aligning the fibers in the direction of the loads, which allows very efficient use of the materials. The fibers can be glass, carbon, aramid, boron, ceramic, or metal. Resins can be polyesters, epoxies, bismaleimides, polyimides, phenolics, silicones, or thermoplastics. Resins can be applied wet at the time of winding, or as a prepreg, in which the fibers have been previously impregnated with the resin. In some cases, the winding is completed dry and the entire part is impregnated under pressure. Commercial products manufactured by this process include helicopter rotor blades, tennis rackets, baseball bats, chimney liners, rocket motor cases, fuel tanks, pressure vessels, lighting poles, pipes, and tanks. Very large storage vessels can be made by this process.

**POLYMER CONCRETE UNDERGROUND PRODUCTS**

Polymer concrete is typically used for construction of precast service box assemblies, meter box assemblies, panel vaults, equipment pads, traffic signal bases, modular trenches, cable TV enclosures, and fiber-optic splice boxes. The polymer concrete is reinforced by a heavy-weave fiberglass, resulting in an exceptionally strong and rigid structure with minimal weight—the weight from

---

**TABLE 14-5**

<table>
<thead>
<tr>
<th>Property</th>
<th>Polyester/ Vinyl Ester</th>
<th>Premium Poly/ Vinyl Ester</th>
<th>Epoxy</th>
<th>ASTM Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural strength, psi ( \times 10^3 ) (MPa)</td>
<td>4.5–5.0 (31–34)</td>
<td>4.0–5.0 (28–34)</td>
<td>5.0 (34)</td>
<td>D-790</td>
</tr>
<tr>
<td>Flexural modulus, psi ( \times 10^6 ) (GPa)</td>
<td>0.25–0.35 (1.7–2.4)</td>
<td>0.35–0.50 (2.4–3.4)</td>
<td>0.30 (2.1)</td>
<td>D-790</td>
</tr>
<tr>
<td>Tensile strength*, psi ( \times 10^6 ) (MPa)</td>
<td>2.5–3.5 (17–24)</td>
<td>Not recommended</td>
<td>4.0 (28)</td>
<td>D-638</td>
</tr>
</tbody>
</table>

*Measured on pressure pipe only.

(Courtesy Insituform Technologies)

---

**TABLE 14-6**

<table>
<thead>
<tr>
<th>Type of Panel</th>
<th>Nominal Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse panels</td>
<td></td>
</tr>
<tr>
<td>lb/ft(^2)</td>
<td>0.25</td>
</tr>
<tr>
<td>kg/m(^2)</td>
<td>1.22</td>
</tr>
<tr>
<td>Wall and ceiling panel (0.9 in. [2.3 cm] thick)</td>
<td></td>
</tr>
<tr>
<td>Class-A fire rated</td>
<td></td>
</tr>
<tr>
<td>lb/ft(^2)</td>
<td>0.67</td>
</tr>
<tr>
<td>kg/m(^2)</td>
<td>3.27</td>
</tr>
<tr>
<td>Gel-coated exterior panels, recreational vehicle siding (0.45–0.6 in. [1.1–1.5 cm] thick)</td>
<td></td>
</tr>
<tr>
<td>lb/ft(^2)</td>
<td>0.38</td>
</tr>
<tr>
<td>kg/m(^2)</td>
<td>1.86</td>
</tr>
<tr>
<td>Translucent truck trailer roofing (0.075 in. [0.19 cm] thick)</td>
<td></td>
</tr>
<tr>
<td>lb/ft(^2)</td>
<td>0.48</td>
</tr>
<tr>
<td>kg/m(^2)</td>
<td>2.34</td>
</tr>
<tr>
<td>Insulating refrigerated van roofing (0.175 in. [0.44 cm] thick)</td>
<td></td>
</tr>
<tr>
<td>lb/ft(^2)</td>
<td>1.3</td>
</tr>
<tr>
<td>kg/m(^2)</td>
<td>6.3</td>
</tr>
</tbody>
</table>

(Courtesy Crane Kemlite Company)
one-tenth to one-third less than traditional concrete boxes. In addition, resistance to temperature extremes is improved and deterioration by sunlight, chemicals, warpage, and water absorption is reduced. The improved impact strength is a benefit in areas of high vibration such as railroad tracks, roadways, and city streets. Many miles of fiber-optic cable have been installed through mountains, forests, and swamps where the light weight, easy-to-install polymer concrete boxes do not require heavy equipment for installation. Mechanical properties are shown in Table 14-8.

A unique fast-curing isophthalate polyester concrete was used to apply a new overlay on the approaches to the Golden Gate Bridge in San Francisco. Typical traffic load is 110,000 vehicles per day. To minimize disruption, the surface refurbishing was done in sections of about 7000 ft² (650 m²) between the hours of 8 PM and 6 AM. The polymer concrete was completely cured and ready to accept traffic three hours after application. By comparison, it takes ten days to two weeks before conventional concrete cement is ready for traffic. Latex-modified formulations of cement accept traffic in about four days. The polymer concrete was laid down with a new 80-ft (24.4-m) long custom paving train. At the front of this line of equipment, the surface to be overlaid was shot-blasted to improve adhesion to the old surface. After loose shot and debris were collected through a vacuum, the polymer concrete mix was applied by automated equipment. The overlay was 1 in. (2.5 cm) thick, compared to 2–3 in. (5–7.6 cm) for a typical cement overlay, and 1.5 in. (3.8 cm) for a latex-modified cement. The resin content in the polymer concrete was about 11%. The polymer concrete also formed a nonporous barrier against moisture and deicing salts protecting steel reinforcing bars against rust and failure.

ENGINEERING PHENOLIC COMPOSITES

A phenolic composite undergoes an irreversible chemical reaction when molded, resulting in a highly cross-linked, 3D network structure. These engineering composites are reinforced with mineral fillers, cellulose fibers, or glass fibers. This provides good creep resistance, property retention during temperature extremes (both cold and hot) with no melting point, low water absorption, and high surface hardness. In addition they have a low coefficient of linear thermal expansion, a glass transition temperature of over 450˚ F (232˚ C), and they exhibit high self-ignition temperature of about 1112˚ F (600˚ C). This makes them highly desirable for many automotive, electrical/electronic, and space program applications. A comparison of the typical properties of engineering phenolic composites with aluminum and steel is presented in Table 14-9.

Molded phenolics are used in commutators on the shaft in automotive starter motors as well as in automotive auxiliary, appliance, and industrial motors. A phenolic shaft will retain dimensions.

### Table 14-7
Typical Physical Properties of Polyester Panel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural strength, psi × 10⁶ (MPa)</td>
<td>16 (110) ASTM D-790</td>
</tr>
<tr>
<td>Flexural modulus, psi × 10⁶ (MPa)</td>
<td>0.8 (5.5) ASTM D-790</td>
</tr>
<tr>
<td>Tensile strength, psi × 10⁶ (MPa)</td>
<td>9 (62) ASTM D-638</td>
</tr>
<tr>
<td>Tensile modulus, psi × 10⁶ (MPa)</td>
<td>1.8 (12) ASTM D-638</td>
</tr>
<tr>
<td>Izod impact strength, ft-lb/in. (j/m)</td>
<td>12 (641) ASTM D-256</td>
</tr>
<tr>
<td>Barcol hardness</td>
<td>55 ASTM D-2583</td>
</tr>
<tr>
<td>Water absorption, %</td>
<td>ASTM D-570</td>
</tr>
<tr>
<td>24 h at 77˚ F</td>
<td>0.16</td>
</tr>
<tr>
<td>24 h at 25˚ C</td>
<td>0.20</td>
</tr>
</tbody>
</table>

(Courtesy Crane Kemlite Company)

### Table 14-8
Material Properties of Polymer Concrete* Versus Concrete

<table>
<thead>
<tr>
<th>Property</th>
<th>Polymer Concrete</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength, psi × 10⁶ (MPa)</td>
<td>11 (76)</td>
<td>4 (28)</td>
</tr>
<tr>
<td>Tensile Strength, psi × 10⁶ (MPa)</td>
<td>1.7 (12)</td>
<td>0.8 (5.5)</td>
</tr>
<tr>
<td>Flexural Strength, psi × 10⁶ (MPa)</td>
<td>7.5 (52)</td>
<td>0.4 (2.8)</td>
</tr>
</tbody>
</table>

*Material consisting of aggregate of sand and gravel bound together with a polymer and reinforced with continuous woven glass strands.

(Courtesy Quazite)

### Table 14-9
Phenolic/Aluminum/Steel Properties Matrix*

<table>
<thead>
<tr>
<th>Property</th>
<th>Phenolic</th>
<th>Aluminum</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.5–1.8</td>
<td>2.6–2.9</td>
<td>7.6–7.9</td>
</tr>
<tr>
<td>Elastic modulus, psi × 10⁶ (GPa)</td>
<td>1.5–3.0  (10–21)</td>
<td>10 (69)</td>
<td>28–30 (193–207)</td>
</tr>
<tr>
<td>Tensile strength, psi × 10⁶ (MPa)</td>
<td>8–15 (55–103)</td>
<td>17–40 (117-276)</td>
<td>60–175 (414-1207)</td>
</tr>
<tr>
<td>Compressive strength, psi × 10⁶ (MPa)</td>
<td>30–40 (207–276)</td>
<td>30–50 (207–345)</td>
<td>80–220 (552–1517)</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, ppm/˚ F (ppm/˚ C)</td>
<td>36–54 (207–276)</td>
<td>40–45 (22–25)</td>
<td>22 (12)</td>
</tr>
<tr>
<td>Thermal conductivity, Btu-in./h-ft²-˚ F (W/m²-˚ C)</td>
<td>2.8–4.9 (0.4–0.7)</td>
<td>694–1180 (100–170)</td>
<td>278–347 (40–50)</td>
</tr>
</tbody>
</table>

*Properties for molded, not pultruded, materials.

(Courtesy Rogers Corporation)
TIONAL STABILITY when subjected to spin speeds of 25,000–50,000 rpm over a temperature range of 302–482 °F (150–250 °C), or when subjected to soldering temperatures of 752 °F (400 °C) for 33 seconds, and will hold the copper bars in place with bar movement of less than 0.0002 in. (0.005 mm). Glass-reinforced polyurethanes are used for pulleys on water pumps, power steering, and air conditioning compressors, where they offer reduced weight, corrosion resistance without surface treatment, noise reduction, reduced belt wear, lower belt temperature, and eliminate the need for balancing. The smooth, glossy phenolic surface and the hydrodynamics of the blade can improve water pump performance up to 30%. Superior chemical resistance to automotive fuels such as methanol, gasoline, diesel fuel, and cleaning solutions makes phenolics useful for the housing (inlet cover) and the impeller in fuel pumps, and suitable for fuel rails and throttle bodies. Glass-reinforced phenolics are used in engine cooling components, providing weight reduction, parts integration, and flatness without machining. These components are molded with phenolic threads, and, in some designs, metal core technology is utilized to produce the coolant channel in a one-piece molding. Molded-to-net-shape camshaft sprockets reduce belt noise and vibration because of the damping characteristics of the phenolic, and taper is not needed for the sprocket teeth.

Converting a transmission reactor from metal to a transfer-molded, glass-reinforced phenolic results in improved profile accuracy and less variation in performance characteristics. Fewer parts is another benefit—10 components with the fabricated aluminum reactor versus three with phenolic. Molding as a single operation eliminates assembly and the need for balancing.\(^{13}\)

Phenolics are also used in applications in the chemical processing industry and well-drilling fields, where resistance to attack from chemical environments and the ability to operate at elevated temperatures are important. They are also used in the food processing industry where chemical resistance is essential.

A suggested molding guide for start-up conditions for compression/transfer molding and injection molding of engineering phenolic is given in Table 14-10.

Engineering diallyl phthalate molding materials are the materials of choice for commercial, high-performance military and commercial electrical components where long-term reliability is demanded. Engineering epoxy molding materials are the premier material for military firewall connectors and is also used extensively in encapsulation of electronic components.

### SEMIRIGID AND RIGID POLYURETHANES

The isocyanate group (\(\text{N}=\text{C}=\text{O}\)) will react with hydroxyl and amine groups to form polyurethane resins (PUR). Toluene diisocyanate is the largest volume of the isocyanates and is more reactive and less expensive than the aliphatic diisocyanates. Because a large variety of properties are obtained by combining basic components in different compositions, the polyurethanes find use in foams, adhesives, fibers, and elastomers, as well as in semirigid and rigid engineering applications. The chemical addition reaction is usually carried out by the manufacturer of the finished or semi-finished product in high-pressure equipment specifically designed for this purpose. The isocyanates and polyols are introduced separately, metered and mixed, and the reacting liquid is delivered into the mold where the reaction proceeds until the solid state is achieved (RIM molding). Additional components and additives can be either metered directly into the mixing head or premixed in the isocyanate or polyol liquids. Steel molds and compression presses are preferred for products with a finished surface on all sides. Reinforcement can be achieved by placing a random glass mat in the mold and forcing the flowing liquid mixture through the glass mat to form high-performance parts (structural RIM). Because of the low viscosity of the liquids prior to curing, the glass distribution in the mat can be maintained. A constant mold temperature between 122–158 °F (50–70 °C) must be maintained, about 110 °F (61 °C) below the maximum reaction temperature reached in the mold. Typical properties for long-glass-fiber-reinforced polyurethanes are shown in Table 14-11.

Urethane hybrids are formed by the reaction of two liquid components, an acrylester and a modified diisocyanate (di-phenylmethane-4,4 ft-diisocyanate). The acrylester is a hybrid of a urethane (monoalcohol) and an acrylic (unsaturated monoalcohol). As the urethane is formed in the mold, the exothermic heat of reaction increases until a secondary free-radical acrylic reaction is initiated and the mixture cures rapidly. This polymer is highly cross-linked in structure. Typical heat deflection temperatures of acrylate composites are in excess of 465 °F (241 °C). Typical properties of random glass-reinforced acrylate composites are shown in Table 14-12.

### THERMOPLASTIC INJECTION MOLDING COMPOUNDS

Nylon resins are formulated with dispersed short glass fibers specially treated with a coupling agent to produce an effective glass/nylon bond. Glass-fiber reinforcement of nylon resins significantly improves tensile strength and stiffness, dimensional stability including resistance to creep under load, impact properties, and fatigue resistance. Glass-fillednylons are best processed on conventional injection-molding machines with a melt temperature of 550–590 °F (288–310 °C). Polyester resins contain uniformly dispersed glass fibers or mineral/glass-fiber combinations mixed with polyethylene terephthalate resin specially formulated for rapid crystallization during the molding process. Thermoplastic polyesters have high strength, stiffness, excellent dimensional stability, good chemical and heat resistance, and good electrical properties. These resins are hygroscopic, and a hydrolysis reaction will occur in an injection-molding machine if excess moisture is present. This reaction degrades
Thermoplastic composites offer advantages over metal and thermoset plastic components in a range of applications including automotive, communication, furniture, lawn and garden tools, material handling, construction, and recreational vehicles.

### THERMOPLASTIC COMPOSITES

Most of the engineering thermoplastics are available commercially in reinforced compositions with and without fillers. Improvement of several important properties for structural applications is realized. High modulus and impact resistance, far above the limitations of metals and traditional thermoset compositions, present new opportunities for both designers and manufacturers. Various glass reinforcements are used including continuous-strand-glass random mats, chopped strands, and a combination of random glass and unidirectional fibers. A comparison of three thermoplastic compositions with other structural materials is shown in Table 14-13.

These laminated composites are made with custom film overlays that are prepared in rolls and cut to width on a continuous laminator. The plastic film overlays surround two layers of fiberglass mat and a core of hot plastic to form the composite structure. The continuous glass mat becomes impregnated with the thermoplastic resin in the hot zone of the laminator. A continuous stainless steel belt moves the laminate in and out of the high-pressure zone in the laminator. Following the transition cooling zone, the composite material emerges from the laminator as a 52-in.-wide (1.3-m) sheet showing complete glass and plastic integration. This composite sheet is cut into blanks to meet customer requirements, charge weight, and dimensions.

The thermoplastic blanks are shipped to the customer's plant for molding. The composite blanks are preheated prior to molding in an infrared oven (see Fig. 14-15). During the preheating, temperatures above the melting point of the resin are achieved. Inside the preheating oven, lofting of the glass occurs as the softening point of the resin is passed and the blanks go into full melt. The glass mat, no longer confined by the resin, actually recovers its original loft. As the glass expands, it carries the liquid resin with it, expanding the surface of the resin. This hot molten material is loaded into a compression press and molded in a 30- to 60-second cycle. The compression pressures range from 500–4000 tons (4.5–36 MN). Parts can also be thermoformed from the blanks.

Thermoplastic composites offer advantages over metal and thermoset plastic components in a range of applications including automotive, communication, furniture, lawn and garden tools, material handling, construction, and recreational vehicles.

### Impact Strength and Toughness

Thermoplastic composites have high impact resistance over a broad temperature range. The glass-fiber reinforcement localizes damage caused by impact. The ductile mode of failure exists from -140 to +220°F (-96 to +104°C). There is no ductile/brittle transition.

### Modulus and Strength

One of the key features of thermoplastic composites is high modulus. Flexural moduli in excess of 670,000 psi (4619 MPa) are available. Thermoplastic composites retain their high modulus over a wide temperature range. They also offer good tensile and flexural strength over a broad temperature range. New high-performance grades targeted bumper beams offer a 20–25% increase in mechanical properties when compared to existing grades.

### TABLE 14-11

<table>
<thead>
<tr>
<th>Property</th>
<th>30% Glass</th>
<th>40% Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, psi × 10³ (MPa)</td>
<td>24.2 (167)</td>
<td>28.6 (197)</td>
</tr>
<tr>
<td>Tensile modulus, psi × 10⁶ (GPa)</td>
<td>1.1 (7.6)</td>
<td>1.5 (10)</td>
</tr>
<tr>
<td>Flexural strength, psi × 10³ (MPa)</td>
<td>35.3 (243)</td>
<td>44.4 (306)</td>
</tr>
<tr>
<td>Flexural modulus, psi × 10⁶ (GPa)</td>
<td>1.1 (7.6)</td>
<td>1.5 (10)</td>
</tr>
<tr>
<td>Izod impact strength, ft-lb/in. (J/m)</td>
<td>6.2 (331)</td>
<td>8.4 (448)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.43</td>
<td>1.52</td>
</tr>
</tbody>
</table>

### TABLE 14-12

<table>
<thead>
<tr>
<th>Property</th>
<th>30% Glass</th>
<th>40% Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, psi × 10³ (MPa)</td>
<td>16.6 (114)</td>
<td>22.3 (154)</td>
</tr>
<tr>
<td>Tensile modulus, psi × 10⁶ (GPa)</td>
<td>1.1 (7.6)</td>
<td>1.3 (8.9)</td>
</tr>
<tr>
<td>Flexural strength, psi × 10³ (MPa)</td>
<td>24 (165)</td>
<td>36 (248)</td>
</tr>
<tr>
<td>Flexural modulus, psi × 10⁶ (GPa)</td>
<td>1.0 (6.89)</td>
<td>1.3 (8.9)</td>
</tr>
<tr>
<td>Izod impact strength, ft-lb/in. (J/m)</td>
<td>12 (641)</td>
<td>14 (747)</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, ppm/° F (ppm/° C)</td>
<td>16 (29)</td>
<td>15 (27)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.41</td>
<td>1.47</td>
</tr>
</tbody>
</table>

### TABLE 14-13

<table>
<thead>
<tr>
<th>Property</th>
<th>Polypropylene Composite</th>
<th>PBT and PET Composite</th>
<th>PC and PC/PBT Alloy Composite</th>
<th>Die-cast Aluminum</th>
<th>Low-carbon Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Izod impact strength, ft-lb/in.</td>
<td>14 (747)</td>
<td>13 (694)</td>
<td>8.5 (454)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Tensile strength, psi × 10³ (MPa)</td>
<td>14 (97)</td>
<td>15 (103)</td>
<td>13 (90)</td>
<td>8–20 (55–138)</td>
<td>29–33 (200–228)</td>
</tr>
<tr>
<td>Flexural modulus, psi × 10⁶ (GPa)</td>
<td>0.8 (5.5)</td>
<td>1.2 (8.3)</td>
<td>1.1 (7.6)</td>
<td>10 (69)</td>
<td>30 (207)</td>
</tr>
<tr>
<td>Heat resistance, ° F (° C)</td>
<td>310 (154)</td>
<td>425 (218)</td>
<td>290 (143)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, ppm/° F (ppm/° C)</td>
<td>8.3 (15)</td>
<td>11 (20)</td>
<td>9.4 (17)</td>
<td>6.7 (12)</td>
<td>4.4 (8)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.19</td>
<td>1.59</td>
<td>1.42</td>
<td>2.5–2.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

(Courtesy Azdel, Inc.)
**Mass Savings**
The low specific gravity of thermoplastic composites provides a definite advantage over metal.

**Production of High-quality Finished Parts**
Thermoplastic composites can be used for the production of large parts. Detailed reproduction of precise parts, part consolidation, increased part function, and reduction of secondary off-line operations can be achieved in components that even include molded-in ribs, bosses, and metal inserts.

**RECYCLING OF WASTE-REINFORCED PLASTIC MATERIALS**
One method to increase automobile mileage is to decrease its weight. Automakers have pared hundreds of pounds from the body and chassis by redesigning and consolidating parts and replacing traditional steel components with lighter-weight materials such as aluminum and a variety of plastics. Moreover, for every pound removed from the body/chassis system, another half-pound can be saved in drive train components. For these reasons, the average passenger car content of plastics and composites went from 176 to 222 lb (80 to 106 kg) between 1987 and 1990. This has introduced a new problem of material separation and recycling of cars when they reach the end of their useful life.

Because of the weight savings realized with plastics, energy is conserved. A number of studies have shown that additional energy savings over metals are realized in manufacture of the plastic resins, consolidation and reduction of the number of parts in an assembly, and fabrication of the parts.

Despite the various technologies for recycling plastic waste, collection, separation, and final distribution (marketing) remain major factors in the cost of recycling.

**Sheet Molding Compounds**
Technology exists for recycling SMCs on a high-volume basis. SMC panels as large as 15–30 ft² (1.4–2.8 m²) are not uncommon, and reducing them to manageable size is essential. Shredding usually reduces SMC panels to pieces approximately 2 × 8 in. (5 × 20 cm). These can be reduced further, depending on the ultimate use. Ideally, chemical recycling uses pieces about 2 × 2 in. (5 × 5 cm). Particle recycling by grinding requires further size reduction of the pieces.

Pyrolysis is the controlled thermal decomposition of an organic material into one or more recoverable substances through the application of heat in an oxygen free environment. The waste plastics and rubber are converted into chemical by-products that can be reused. Pyrolysis is not new and has been used in both the United States and Europe to reduce plastic and rubber wastes. A plastics pyrolysis demonstration plant has been in existence in Ebenhausen, Germany, since the early 1980s, and another plant in Linz, Austria, is designed for automotive commingled plastic wastes. In the United States, a pyrolysis plant in Chehalis, Washington, has been used primarily for scrap tires for several years. Initial trials using automotive SMC waste have been encouraging. A facility for recycling SMC by grinding to recover powder, or glass fiber and powder, is operational in Toronto, Canada.

Particle recycling or grinding of thermoset SMC can be carried out in several different ways. If the product is to be used as a filler, the entire SMC article, including the glass fiber, is ground to a fine powder. The reground SMC waste material can be used as a calcium carbonate substitute in SMC or BMC, and its use depends largely on whether or not it is cost-effective. Coarser grinds can be separated into powder and fiber fractions that could provide a value-added reinforcement for SMC or BMC compositions. Both SMC and BMC have been evaluated using granulated...
SMC (0.375 in. [9.5 mm] and smaller particles). Table 14-14 shows the effect of adding SMC powder with various degrees of granulation on the physical properties of BMC. In BMC, the structural properties measure about 70% of standard BMC when all the glass and filler is replaced with granulated SMC.

When only part of the glass and filler in BMC is replaced with granulated SMC, the property deterioration is not as severe. In Table 14-15, the properties of BMC containing granulated SMC to replace 10% and 20% of the total glass and filler are shown.

Phenolic Plastics

Recycling is an important issue in many industries. In the automotive industry, much of the emphasis has been on recycling thermoplastic components, largely because the weight ratio of thermoplastics to thermosets used in automobiles is roughly 3:1.17 However, the use of thermosets in automobiles is expected to grow very rapidly. There are two general sources of molded phenolic plastics to thermosets used in automobiles is roughly 3:1.17

When only part of the glass and filler in BMC is replaced with granulated SMC, the property deterioration is not as severe. In Table 14-15, the properties of BMC containing granulated SMC to replace 10% and 20% of the total glass and filler are shown.

Amino Plastics

In the molding of melamine dinnerware, each cavity of the mold has a flash ring to allow gas escape and sealing of the cavity as the pressure builds. The flash ring typically represents as much as 7% of the resin molded. Unfortunately, this material is usually in multiple colors. However, this melamine plastic waste can be collected, preground to about 0.25 in. (6.4 mm) and finally ground to below 0.001 in. (0.025 mm) by a hammer mill. About 10% by weight spray-dried foil melamine resin and recycle are mixed in a ball mill with black pigment. The resulting powder can be molded into attractive large salad bowls.

Polyurethanes

It is possible to grind waste polyurethane parts to a fine powder and recycle them into the liquid feed stocks (polyls) to form new products. Larger particles can be compression-molded using particle board technology and used for flooring or furniture. Mixtures of polyurethane/rubber (25/75) chips have been used for athletic fields, tennis courts, golf cart roads, etc. Glycolysis of urethanes can be done rather easily, and the glycolysis product can be incorporated into the polyol stream of rigid foam systems.

Other Reinforced Thermoplastics

Since thermoplastics can be remelted and formed again, they can usually be remolded. The deterioration level of physical and chemical properties varies between resins and is usually related to the additives originally used to stabilize the resin. Thus, design of new additive packages for use with recycled material frequently becomes the major technical barrier. In most cases, secondary applications are essential, as the quality requirements of the original application are normally designed to maximize the resin properties and any deterioration cannot be tolerated. Postconsumer recycling is more difficult because secondary contamination can be difficult to completely remove. Commercial facilities are operational for recycling of postconsumer clean polyolefins, PET, PVC, ABS, and other engineering plastics.

### TABLE 14-14

<table>
<thead>
<tr>
<th>Property</th>
<th>0.375 in. (9.5 mm) Reground SMC</th>
<th>0.187 in. (4.7 mm) Reground SMC</th>
<th>Virgin Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, psi $\times 10^3$ (MPa)</td>
<td>2.78 (19)</td>
<td>3.74 (26)</td>
<td>4.05 (28)</td>
</tr>
<tr>
<td>Flexural strength, psi $\times 10^3$ (MPa)</td>
<td>7.29 (50)</td>
<td>6.03 (42)</td>
<td>14 (97)</td>
</tr>
<tr>
<td>Flexural modulus, psi $\times 10^6$ (GPa)</td>
<td>0.92 (6.3)</td>
<td>0.93 (6.4)</td>
<td>1.5 (10.3)</td>
</tr>
<tr>
<td>Notched izod impact, ft-lb/in. (j/m)</td>
<td>2.5 (133)</td>
<td>1.7 (91)</td>
<td>5.1 (272)</td>
</tr>
<tr>
<td>Unnotched izod impact, ft-lb/in. (j/m)</td>
<td>2.9 (155)</td>
<td>2.1 (112)</td>
<td>6.8 (363)</td>
</tr>
</tbody>
</table>

* 30% resin, all glass and filler replaced

(Courtesy SMC Automotive Alliance)

### TABLE 14-15

<table>
<thead>
<tr>
<th>Property</th>
<th>10% Reground SMC</th>
<th>20% Reground SMC</th>
<th>Virgin Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength, psi $\times 10^3$ (MPa)</td>
<td>2.33 (16)</td>
<td>2.11 (15)</td>
<td>4.05 (28)</td>
</tr>
<tr>
<td>Flexural strength, psi $\times 10^3$ (MPa)</td>
<td>9.95 (69)</td>
<td>7.97 (55)</td>
<td>14 (97)</td>
</tr>
<tr>
<td>Flexural modulus, psi $\times 10^6$ (GPa)</td>
<td>1.4 (9.7)</td>
<td>1.4 (9.7)</td>
<td>1.5 (10.3)</td>
</tr>
<tr>
<td>Notched izod impact, ft-lb/in. (j/m)</td>
<td>5.1 (272)</td>
<td>3.0 (160)</td>
<td>5.1 (272)</td>
</tr>
<tr>
<td>Unnotched izod impact, ft-lb/in. (j/m)</td>
<td>5.2 (278)</td>
<td>3.4 (181)</td>
<td>6.8 (363)</td>
</tr>
</tbody>
</table>

* Loading is percent of total mix

(Courtesy SMC Automotive Alliance)
Pultrusion is a continuous filament-reinforced plastic (FRP) manufacturing process used to produce highly reinforced plastic structural shapes. Unlike filament winding, which places the primary reinforcement in the circumferential (hoop) direction, pultrusion provides the primary reinforcement in the longitudinal direction. The typical pultruded product will exhibit higher mechanical properties in the longitudinal (lengthwise) direction rather than the transverse (crosswise) direction. The purpose of this section is to describe pultrusion from a processing viewpoint. The goal is to emphasize the practical considerations in manufacturing, although the theoretical issues will be mentioned. The process described below applies to a thermoset polymer; this section will not discuss the pultrusion of thermoplastics.

THE BASIC PROCESS

Figure 14-16 depicts the basic components of a pultrusion machine. The pultrusion process combines longitudinal reinforcements (roving doffs in the figure) and transverse reinforcements (mat creels) to form a composite by impregnating these reinforcements with the polymer and curing the composite in a die. Roving resembles a glass rope, while mat resembles a glass sheet.

The roving doffs are the storage area for the longitudinal reinforcement, which is packaged as a spool of glass in cylindrical form. The term roving is used for glass reinforcement, but other longitudinal reinforcements such as carbon fiber or Kevlar™ could be placed on the racks containing the roving doffs. The roving doff design will change as the form of the reinforcement changes because various generic reinforcements are packaged differently. For example, the glass reinforcement (roving) will be delivered from the inside of the cylindrical package, while carbon-fiber reinforcement (known as tow) will be delivered from the outside of the cylindrical package. Thus, the glass reinforcement can be placed directly on a rack while the carbon-fiber reinforcement requires a mandrel system because of the outside pull. The mat creel adds the transverse reinforcement to the system and is pulled from the outside of a roll. Only two mat stations are shown in Fig. 14-16, but multiple mat layers could be added to the pultruded profile at different points within the composite. Adding more than two layers of transverse reinforcement would require alternating it with layers of the roving or other longitudinal reinforcement, which in turn would require a more complex arrangement than shown.

The reinforcements are pulled through a guide plate that helps to locate the reinforcing materials correctly in the final pultruded part. The aligned materials are then passed through a resin impregnation chamber, which contains the polymer solution. The polymer solution impregnating the reinforcements acts as a glue connecting the various components of the reinforcement. The polymer solution (sometimes known as resin mix) contains the polymer resin in addition to filler, catalyst, and other additives that enhance the performance of the pultruded structural shape.

Surfacing material is generally added to pultruded structural shapes after the impregnation step. The surfacing material has insufficient tensile strength to withstand pulling in the wet impregnation area and also tends to wet out (become completely saturated with the resin mixture) more easily than the reinforcements. It should be noted that the reinforcements generally do not pass directly through the impregnation chamber in a straight line, but over traverse breaker bars, which spread the reinforcement layers so that the solution can better impregnate the reinforcement.

The saturated reinforcements exiting the resin impregnation chamber area are generally flat and shaped into an approximation of the final configuration imparted to the product in the preformer to reduce stresses in the part. The curing of the product (changing from a wet saturated reinforcement to a solid part) occurs in the curing die. Most pultrusion processors use an electrical or oil-heated system with one to four separate heating zones on the die surface. The number of heating zones is dictated by the speed of the process, the type of resin to be cured, the length of the die, and the type of heating source.

After exiting the die, the part passes through a pull system. Figure 14-16 shows the caterpillar type of puller, in which a series of rotating blocks pull the product. Unlike extrusion, which pushes the part from the entrance end of the die, pultrusion pulls the part from the exit end of the die. Another common type of pultrusion puller is the hand-over-hand pull system (see Fig. 14-17). In the hand-over-hand system, puller number-one drives the part exiting the die and transports it some distance to puller number-two. Puller number-two will then grab the part, and puller number-one releases and returns to its original position; puller number-two moves the part to the saw. The arrows beneath puller number-one and puller number-two in the figure indicate the motion of the two pullers, which pull the part consecutively (one at a time) instead of operating simultaneously. During the return
step, the puller not functioning is not in contact with the part. The choice of pull system is one of the possible variations in basic pultrusion machine design. The caterpillar system supplies more pull force but may crush weaker pultruded product designs.

Two other potential variations are the use of a coolant system and the use of radio-frequency (RF) heating. Some pultruders will utilize air and/or water cooling in the space between the curing die and the pull blocks to cool the hot part (from the exothermic reaction) before it enters the pull blocks. The pull block material is generally some form of urethane, and the pressure applied by the pull blocks could distort the pultruded shape if the product enters the pull blocks at too high a temperature. If the area between the pull blocks and the curing die is sufficiently long, no supplemental cooling is required, but this may not be possible for some industrial layouts. In the second potential variation, a radio-frequency heating unit is placed after the resin impregnation step and before the curing die. This is a form of preheating the composite and is very useful in accelerating the curing reaction for pultruded composites consisting of only longitudinal glass reinforcement. Carbon fiber reinforcement cannot be heated in a radio-frequency unit because of potential fire hazards.

**RESIN**

Some thermoset resins are processible using pultrusion. Polyster, vinyl esters, epoxies, and phenolics are currently processed commercially, and each of the resins has particular characteristics advantageous for processing and performance. Each of the four generic classes of resin can be further subdivided for other attributes.

**Polyester Resins**

Polyester resins processed in pultrusion are generally isophthalic polyester, terephthalic polyester, or orthophthalic polyester. Orthophthalic polyesters offer a cost advantage in pultrusion but are not as corrosion-resistant as isophthalic or terephthalic polyesters; there is a substantial amount of pultrusion performed with the isophthalic polyester resins. Besides cost and corrosion resistance, factors affecting resin selection are resistance to high temperatures and the compatibility of the polyester resin with the glass. A high-heat distortion temperature (HDT) or glass transition temperature (Tg) indicates a resin with higher temperature resistance. However, such resins tend to be more brittle and are processible only in thinner shapes. The compatibility of the polyester resin with the glass is measured by the wet-out (degree of saturation of the reinforcement). Strengths will be lower if the wet-out is deficient. Functionally, the wet-out of the reinforcement can be described as:

\[ \text{Wet-out} = f(Br, V, Ti, S, T, Bi, Te, R) \]  

where:

- \( Br \) = breaker bar system design in the resin impregnation chamber
- \( V \) = viscosity of the resin mix (a function of unfilled polymer resin viscosity, filler type, and particle size, plus any release agent effect)
- \( Ti \) = time in the resin impregnation chamber (a function of resin impregnation size and line speed)
- \( S \) = squeeze-out system in the preformer, removing excess resin from the reinforcement
- \( T \) = temperature of the resin in the impregnation chamber (higher temperatures will more easily wet out but may cause problems with premature gelation and excess styrene emissions)
- \( Bi \) = the compatibility of the glass binder with the polymer resin
- \( Te \) = the tension of the reinforcement in the guidance system; too much tension inhibits wetting of the individual filaments in the roving and too little tension inhibits proper reinforcement location in the part
- \( R \) = the resin matrix itself. Some resins such as epoxies adhere better to the reinforcements.

The composite arrangement also influences resin selection. Roving is a glass strand composed of many individual, very small filaments that must be individually wet out to optimize the strength characteristics; lower viscosities enhance roving wet-out. The continuous strand mat that is often used in pultrusion requires a thicker resin to prevent the resin mix from bleeding through the porous continuous-strand mat.

**Polyester Cure Properties**

The cure properties of the polyester (reaction rate) must be selected in conjunction with the heating and the catalyst systems. A common measure of reaction rate that has been utilized for years in the pultrusion industry is the 180˚ F (82˚ C) SPI gel time; newer techniques using a differential scanning calorimeter (DSC) can be used. The material having the lowest gel time is not always the fastest-curing resin. In addition to the usual catalyst and heating system adjustments to resin curing, some pultruders will heat the resin bath to accelerate the cure reaction. In this case, the catalyst must be selected with special care to prevent the resin mix from gelling prematurely.

**Vinyl Ester Resins**

Vinyl ester resins tend to wet out (saturate) reinforcements more efficiently and produce higher test results. Vinyl ester resins tend to have a higher temperature capability with improved flexibility (toughness) and improved corrosion.

**Epoxy Resin**

Epoxy resin systems are a further extension of vinyl ester resins for strength and can be produced with an amine or anhydride curing system; the vinyl ester and the polyester resin matrices are peroxide-cured. The epoxy resin system requires a significantly higher reinforcement content than either the polyester or the vinyl ester resin matrices. In addition to their higher reinforcement content, epoxy resins also have a significantly shorter pot life than polyester or vinyl ester systems increasing the difficulty in processing epoxies. Pot life is the amount of time that the resin mix maintains stable properties (viscosity, curing) in the resin impregnation area. A 24-hr resin mix pot life is required for pultrusion although shorter pot lives can be accommodated with special provisions.

**REINFORCEMENT**

The reinforcement material is selected by chemical type and form. The chemical types include glass, carbon fiber, aramid, and polyester fibers; other types of reinforcements may be selected for special applications. The forms of reinforcement include rovings...
(tows, for carbon fiber), stitched rovings in different orientations, continuous strand mat, chopped strand mat, woven rovings, and bulk rovings. The effects of resin and reinforcements are discussed in “Composite Selection” which follows.

Carbon Fiber
Carbon fiber increases the stiffness of the composite significantly in the lengthwise direction. It is difficult to find a continuous-strand mat type of carbon fiber product, and carbon fiber products requiring transverse reinforcement are either mixtures of transverse glass reinforcements with lengthwise carbon fibers or stitched carbon-fiber products. A stitched carbon-fiber product is significantly more expensive than the all-longitudinal carbon-fiber product. Carbon fibers produce a stiffer composite than glass fibers, which produce a stiffer composite than polyester fibers.

Mixing reinforcement types may cause warpage problems because of differential shrinkage; carbon fiber has a negative coefficient of thermal expansion. Reinforcements compatible with one type of resin matrix may not be compatible with another type.

OTHER RAW MATERIALS
Other raw materials include filler, catalyst, anti-ultraviolet additives, and release agents in the standard pultrusions. Filler acts as a resin extender and reduces porosity in the surface of the pultruded composite. The filler must be selected judiciously because of the wet-out requirements described previously. A small amount of filler is used with all-rovings composites while larger amounts of filler are used with the mat/rovings composite. The particle size of the filler is an important design characteristic, as smaller particles will absorb more resin on the surface and tend to increase the resin mix viscosity. Calcium carbonate filler is used where cost is a consideration, while clay filler (kaolin) is preferred for corrosive applications. Aluminum trihydrate filler can enhance the performance in some flame-retardance tests, but once the water of hydration is consumed, the remaining aluminum oxide does not prevent flaming.

Initiators
Pultruders commonly call the peroxide initiators catalysts, although these additives are not catalysts in the true sense of the term, since they are consumed in the thermoset reaction. Various catalysts can be utilized in pultrusion, and the choice is determined by the thickness of the part and the heating package available for the pultrusion process. Thermoset pultrusion is an exothermic reaction, and parts will generate higher levels of heat within themselves; systems running too hot can cause a crack in the center of a thick part. Many pultruders use a multiple catalyst system although many successful commercial pultrusions have been produced using only a single type of catalyst system, benzoyl peroxide (BPO). Catalysts are classified as high-, low-, or medium-temperature catalysts by their 10-hour half-life; catalysts with low 10-hour half-lives initiate at lower temperatures. Thicker parts tend to have higher levels of low-temperature catalysts and lower levels of high-temperature catalysts, and the reverse is true for thinner parts.

Ultraviolet Inhibitors
Ultraviolet (UV) inhibitors are often placed in pultruded parts to enhance discoloration resistance. There are two forms of weathering damage in pultrusion: discoloration and fiber exposure. The UV inhibitor will help to prevent discoloration, while a synthetic surfacing veil will help to prevent glass-fiber exposure. Glass-fiber exposure gives a prickly feel to the surface of a part. If the surface veil degrades, it gives a powdery appearance to the part surface.

Release Agents
Release agents are added to the pultrusion resin mix to enhance part separation from the surface of the metal die. Release agents, both in powder and liquid form, may be processed successfully. Most pultruders favor a liquid release agent; powders can cause a problem if the die surface is not hot enough to melt the powder. Acidic release agents (pH less than 7) tend to function very well in pultrusions, although they have a negative effect on the die surface. Steel dies exposed to acidic release agents must be cleaned thoroughly between uses.

CYCLE TIME
Cycle time depends on of the choice of the catalyst system, resin matrix, and heating package for the die. Working in conjunction, these factors determine the cycle time for the pultrusion process. These factors are extremely important if the cycle time is equated to line speed and inches per minute (meters per minute).

One of the more subtle effects on cycle time is the choice of composite. Some reinforcement materials can be processed substantially faster than others, and some shapes can be processed faster than others. Complicated shapes requiring substantial bending of the reinforcements will be processed slower to prevent folds during the bending operation. Pultruded parts that process very well at 36 in./min (91 cm/min) may not process well at all at 60 in./min (152 cm/min) with the same tooling (preformer and guide plates); the tooling must be optimized for a particular speed. Composites containing higher reinforcement levels will process slower because of the increase in pull force. Reinforcements holding too much resin must have the excess resin stripped at the die entrance. Thus, processing can be slower than composites containing less resin. Stitched fabrics may inhibit line speed because of their tendency to deform. Continuous strand mat, which tears easily, will also reduce line speeds.

COMPOSITE SELECTION
The selection of resin and reinforcement will be driven by the desired product performance. Some rules of thumb for selecting a composite are:

- Systems exposed to caustic chemicals will require a vinyl ester resin.
- Some mechanical properties are enhanced by using epoxy resin rather than vinyl ester resin, and vinyl ester resin is superior to polyester resin for mechanical performance.
- The binder on the reinforcement must be matched to the resin.
- Epoxy resins tend to offer more fatigue resistance than vinyl ester or polyester resins.
- Epoxy resins tend to be significantly more difficult to process than polyester or vinyl ester resins. Epoxy resins require higher reinforcement levels.
- Phenolic systems can process easily.
- Stitched reinforcement improves the transverse mechanical properties but also increases the cost.
- Chopped strand mat will reduce the mechanical property performance in coupon and structural testing.
- Higher roving levels in composites tend to have a reduced 24-hour water absorption rate when compared to a mat/roving composite (ASTM D-570).
- +45° stitched reinforcement enhances torque or twist properties within the composite but is not an efficient way to add a 90° orientation coupon for tests.
- The higher the roving content in the pultruded shape, the better the lengthwise mechanical properties.
- Phenolic resins require higher reinforcement levels.
COST ESTIMATING

The cycle time is a significant factor in the final cost of the pultrusion process. Another significant factor is the number of cavities processed on each machine; as the number of cavities are increased, the machine utilization also increases. One caution must be exercised: adding cavities may require adding operators at some point in time. The reinforcements must be added to the process almost continuously because these are consumed during the normal running and require constant attention to the material end of the machine. At the same time, the part must be cut, which requires some attention to the saw end of the machine. An automatic saw may aid in removing cut parts, but such a device will often be sensitive and, from an expense viewpoint, practical only for a long running profile.

Considerations

The part length is a factor in cost estimating, in addition to cycle time. Shorter parts may require more attention to the cutting operation and perhaps even a separate operator if the part is extremely short (less than 10 ft [3 m]) from a pultrusion viewpoint. This could also have an impact on the line speed in that shorter parts may require a slower line speed for the operators to perform all of their tasks.

A more subtle but a very real cost consideration in pultrusion is the environmental concerns. It is not clear to what extent controls will be placed on the pultrusion industry, but it is clear that any control will add cost to the system. The disposal of waste resin mixture and/or reinforcement into land fields will be a continuously-increasing expense. The replacement of currently acceptable raw materials by “safer” versions will be an ever-increasing expense; the last such cost expense to the pultruder was the substitution of pigments without heavy metals. The normal pultrusion process uses a styrenated resin, incurring the rising costs of removing or controlling the styrene, and the possibility of incinerators required for the pultrusion process. An incinerator might cost $250,000 to install, and it has been estimated that the cost of disposing one pound (half a kilogram) of styrene might exceed $10; charcoal filters may not provide much cost savings when compared to the incinerator.

Various Costs

Die costs begin at approximately $2,500 and escalate quickly. In addition to the cost of the die, other costs would include the tooling cost to develop the preformer, the tooling cost to develop the guide plates for custom composites, and the cost of chrome plating or other heat-treatment processes that are considered useful for the die life. Pultruders of standard shapes would amortize these tooling costs throughout the product life cycle, but those customers seeking a specialized pultruded shape must consider the costs of utilizing a specialized shape with specialized tooling as opposed to using a standard shape. It may be more cost-efficient for the particular part to use a slightly larger standardized shape instead of a custom shape.

DESIGN CONSIDERATIONS

There are several issues involved in design such as the choice of the composite (see “Composite Selection”), the choice of the actual shape, and the possible use of standard structural shapes available in pultrusions. The performance of any structural shape is governed by the material properties and the geometry of the structural shape. In some situations, it may be more cost-efficient to increase the size of the structural shape rather than to spend more on raw materials to obtain certain composite properties; this is the choice of the individual designer. The designer must also select the appropriate safety factor for the application. Table 14-16 presents some basic comparative information of pultrusion with stainless steel and aluminum. Some pultruders provide detailed design manuals for pultruded structural shapes; a correctly developed design manual contains both bending and column load tables. In many instances, applications will fail in compression before failing in tensile loading, hence the need for the column load tables for the structural shapes. It should be noted that the load tables from a manufacturer of pultruded products will be applicable only for that product and not for another manufacturer’s pultruded products; there is currently no consistency in the formulation of composites for the same structural shapes within the pultrusion industry. This lack of consistency among pultruders prevents the use of a generalized load table for pultrusion.

Connections

One of the primary considerations in designing pultruded structural shapes is the connections. Pultruded products cannot be welded and must be connected by adhesives and/or bolts (either FRP or steel). The size of the bolt and the edge distance are the most important considerations in the design of the bolted connections. Better connections are obtained by using a combination of bolts and adhesives, with the epoxy adhesives a preferred choice. Possible attachment schemes for different pultruded structural shapes can generally be found in pultrusion suppliers’ design guides. One of the concerns with adhesively bonding a pultruded structural shape to another structural shape is the removal of the surfacing veil. The surfacing veil will impede successful bonding in the composite design, and the designer may require sanding the bonding surface or that the structural shape contain no surfacing veil.

### TABLE 14-16

<table>
<thead>
<tr>
<th>Property</th>
<th>Polyester</th>
<th>Polyester</th>
<th>Stainless</th>
<th>Wrought</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BMC</td>
<td>Pultrusion</td>
<td>Steel</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Reinforcement, %</td>
<td>22</td>
<td>55</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.82</td>
<td>1.69</td>
<td>8.03</td>
<td>2.74</td>
</tr>
<tr>
<td>Elongation, %</td>
<td>0.50</td>
<td>—</td>
<td>40</td>
<td>23</td>
</tr>
<tr>
<td>Tensile strength, psi × 10^3 (MPa)</td>
<td>6.0 (41.4)</td>
<td>30.0 (206.8)</td>
<td>80.0 (551.5)</td>
<td>49.0 (337.8)</td>
</tr>
<tr>
<td>Tensile modulus, psi × 10^6 (GPa)</td>
<td>1.75 (12.1)</td>
<td>2.50 (17.2)</td>
<td>28.0 (193.0)</td>
<td>10.20 (70.3)</td>
</tr>
<tr>
<td>Compressive strength, psi × 10^3 (MPa)</td>
<td>20.0 (137.9)</td>
<td>30.0 (206.8)</td>
<td>80.0 (551.5)</td>
<td>49.0 (337.8)</td>
</tr>
<tr>
<td>Flexural strength, psi × 10^3 (MPa)</td>
<td>12.80 (88.2)</td>
<td>30.0 (206.8)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Flexural modulus, psi × 10^6 (GPa)</td>
<td>1.58 (10.9)</td>
<td>2.50 (17.2)</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Shape Considerations

There are some generalized design considerations for the actual shape of the pultruded part. Sharp edges are more difficult to pultrude than an edge with a radius because it is very difficult to exactly place the reinforcement on the sharp edge. A large radius is better than a small one. Hollow sections are formed using a mandrel in the center of the pultrusion die; increasing the number of cores in the center die will increase the complexity of the pultruded part.

Glass is an abrasive material and can cause excessive wearing within a steel die. The dies are generally chrome-plated or heat-treated to reduce wear, and it may also be necessary to chrome-plate or heat-treat the preforming and guide-plate material to prevent excessive wear.

Excess resin applied to the reinforcements during the saturation stage (in the resin bath) must be removed before the composite enters the die. Some pultruders will utilize multiple stations to strip away the excess resin; multiple stations are often found in large-diameter-rod-pultrusion. Parts with various thicknesses in the same cross-section may cause warpage because of the difference in cooling rates between the thicker and thinner sections, and this warpage will be difficult to control. Cooling fixtures may be tried, but occasionally the part will return to the original shape with time.

Thermal Expansion

The designer must also carefully note the differences in thermal expansion when combining a pultruded structural shape with a metal part. Metal parts and pultrusions have different thermal expansions. The differential thermal expansion can also be a problem when dissimilar reinforcements are utilized in the structural shape; for instance, a carbon-fiber composite has a different thermal expansion than a glass-reinforced composite.

TOLERANCES

The tolerances for pultruded structural shapes are occasionally governed by ASTM D-3917 and ASTM D-4385; these are only generalized tolerances, and the individual pultruder and the designer may require other tolerances. A common mistake is for the designer to expect the steel tolerances to be maintained in pultruded shapes. Different pultruders have different techniques for adjusting to tighter tolerances from the customer.

Metal is a homogeneous material with the same properties and composition throughout, while pultruded structural shapes are composite materials. Some examples of why the composite nature of the pultruded structural shape affects dimensional tolerances are given below.

Transverse Reinforcement

Transverse reinforcement is shipped to the pultrusion manufacturer on rolls and must be slit to the appropriate width of the part. The variation in the slitting widths will cause some variation in the localized reinforcement contents within the part. This localized variation will have some impact on mechanical property performance and will also impact the dimensional performances as reflected by part shrinkage.

Hollow shapes are formed by wrapping the transverse reinforcement around the hollow shape. If the transverse reinforcement is wrapped so that the two ends butt together, a localized weakness may occur at the butt joint. If the transverse reinforcement is wrapped so that the two ends overlap to prevent the butt joint weakness, then some differential glass content will occur, causing some dimensional variation.

The weights of reinforcements received from different reinforcement suppliers vary. This weight variation can reflect itself in localized variations of the part shrinkage. There is also a variation in the individual shrinkage rates of the received resin which can have a similar effect. The use of low-shrinkage additives in the resin reduces this variation, but at the cost of mechanical properties and possibly corrosion performance.

Straightness

The most confusing tolerance aspect of pultruded structural shapes is straightness. There are many different definitions of straightness, and it is incumbent on the pultruder and the customer to verify that they are using the same definition. Straightness is probably the single largest area of confusion between pultruders and their customers.

TROUBLESHOOTING

The troubleshooting procedure for a particular pultrusion process depends primarily on the composite, mode of processing, and the pultrusion machine. However, a few general statements can be made about troubleshooting.

Potential Problems

Many problems arise from excessive die wear, which shows up as an increased amount of scales on the pultruded structural shape. If it is not possible to change the heating profile and/or add wax to the pultruded structural shape to improve this situation, the best solution is to change and/or repair the die. This problem will most often appear in the tips of flanges. The choice of the filler and release combination is sometimes an occasion for concern. An acidic release (pH less than 5) should not be used with a calcium carbonate filler.

Many problems occur when the guide plates and/or preformers begin to wear from the abrasion of the glass reinforcements on the metallic or plastic surfaces. Improperly cut transverse reinforcement widths are often a cause for many scaling problems. This would have the same effect as a worn die.

An improperly specified polyester or vinyl ester resin can be the cause of some pultrusion problems. The resin supplier often specifies the 180˚ F (82˚ C) gel time, the peak temperature, and the peak time. Another specification is to define the 180˚ F (82˚ C) gel time, the peak temperature, and the time interval between the gel time and the peak time. The time interval between the gel time and the peak time is a better reflection of the inherent reactivity of the resin.

Contamination

Contamination can be found in the incoming resin, especially if tankwagons are used, and in the continuous strand mat or stitched reinforcements. The contamination might take the form of an off-colored (black or brown) speck, but contamination has also been seen as specks of other colors. Contamination can also be more subtle in that the continuous strand mat product may have been “overcooked,” giving a darker appearance on the pultruded part; this will be a problem with lightly shaded profiles.

Pigment and catalyst suppliers are generally very consistent in delivering quality products; however, catalyst stored at very cold temperatures may lose some of its potency in the pultruded product.

Improper Alignment

Common causes for lack of straightness (camber) are misalignment of the pultrusion machine and unequal tensioning of the reinforcements. Unequal tensioning of the reinforcements may
PULFORMING

Pulforming (Fig. 14-18) is a continuous process similar to pultrusion, except the finished product is not a uniform, straight section cut to length. This process is used to produce a curved part that has a constant volume, yet also has a changing geometry. An example is an automotive monoleaf spring that has a square cross section in the center and a flat, rectangular shape at each end. This is a recent development to meet high strength requirements.

Figure 14-18 illustrates the pulforming process. Numbers on the illustration correspond with the following list:

1. Initially this process is basically the same as pultrusion. Reinforcement is impregnated in a catalyzed resin (polyester or epoxy).
2. The low-viscosity resin impregnates the rovings, excess is wiped off at the control orifice, and the impregnated rovings pass through a radio-frequency preheater.
3. The die table rotates and acts as a capstan while containing the female cavities. The impregnated rovings are forced into these cavities by the stationary die shoe, which forms a closed cavity. The cured parts are cut off on the farside table after curing, and the empty cavity is rotated into position to receive a new charge. This technique is repeated continuously and can be used to produce a uniform cross-sectional part that requires a curvature. The curvature of the part is determined by the table diameter. Various curvature requirements dictate the need for different tables to satisfy those dimensions.

Pulforming can be adapted (without a circular table) to produce a straight-line pull product that has a changing geometry within a constant volume.
CHAPTER 14

PULFORMING

Fig. 14-18 Pulforming manufacturing process. (Courtesy T. H. Meister)

STRUCTURAL REACTION INJECTION MOLDING

PROCESS DESCRIPTION

Structural reaction injection molding (SRIM), or reinforced reaction injection molding (RRIM), is a process that involves mixing of two or more reactive liquid components and the addition of strands and/or a fabric cloth preform that will give added strength and other improved physical properties to the molded part. Different reactive liquid materials can be used such as epoxy, nylon, polyester, and polyurethane.

Polyurethane is the predominantly used material. It has a wider range of properties than other plastics, with a modulus of elasticity in bending of 730,000–2,400,000 psi (5033–16,547 MPa) and a heat resistance of 192°F (89°C) to over 392°F (200°C), depending on the fiber reinforcement used. A polyol resin blend and an isocyanate are metered, mixed, and injected into a closed mold at low pressure, 50–150 psi (345–1034 kPa).

The liquid reactants are pumped from separate temperature-controlled tanks to metering units and then to the static high-velocity mixing head attached to the mold (see Fig. 14-19). The preform is placed into the mold cavity.

MOLDING CYCLE

A typical molding cycle on a 10-lb (4.5-kg) automobile fascia can be 1.5–2 minutes. The sequence of steps is:

- Apply mold release compound.
- Insert the preform, which may be preheated.
- Close the mold.
- Inject the liquid. Typical time can be 1 to 2 seconds for up to 15 lb (6.8 kg).
- Cure (polymerize) the reactants for 20–60 seconds.
- Tilt the mold to work position.
- Remove part.
- Clean out flash for next shot.

Parts up to 40 lb (18 kg) are being reaction-injection-molded for a variety of applications. Since SRIM uses low-viscosity liquids, the process can fill complex molds and shapes with varying cross-sections and thicknesses without internal flow-generated stresses that result in sink marks or read-through of reinforcing ribbing (see Fig. 14-20).

Since the mold temperature and the exothermic reaction temperature of the liquids are both 130–160°F (54–71°C), part shrinkage is minimized. The low molding pressures result in lower-cost molds (see Figs. 14-21 and 14-22).

SRIM APPLICATIONS

Representative SRIM markets and end uses are listed below.

Aerospace. Wing ribs, wing leading edge, access doors, vertical stabilizers, interior panels, seats.

Automotive. Alternator end cap, hoods, bumper beams, spoilers, rear deck lids, rocker panels—running boards, energy absorbing systems, seat pans and backs, interior door panels, knee bolsters, instrument panel supports, floor pans, package shelves, spare tire covers, battery pans, body panels.

Consumer products. Suitcases, furniture, cabinets.

Industrial. Filter housings, electrical cabinets, machine bases, gears, rollers, bearings, wheels.

Medical. Orthotic knee braces.

Recreation. Small boats, tennis racquets, rifle stocks, golf club heads, ski poles, hockey sticks.

COMPARISON OF SRIM TO OTHER PLASTIC PROCESSES

Comparisons between SRIM, injection molding, SMC fabrication, and blow molding can be made, but considerations of part volume, material cost, mold and tooling cost, and paint finishing/decorating must be part of the overall comparison (see Tables 14-17 and 14-18).
COMPARISON OF COST

Table 14-19 compares the costs of fabricating a large automobile hood made by SMC and by SRIM.

In summary, SRIM offers these advantages:

- 15% weight savings for same part thickness as SMC.
- Part consolidation.
- Corrosion and dent resistance (although dent resistance is less than that of steel).
- Design flexibility.
- Cost competitive with other plastic technologies.
- High strength/good part performance.
- Short-cycle time and increased productivity.
- Excellent adhesion to carpet and decor.
- Wide range of properties.

IMPACT RESISTANCE

A bumper beam in an automobile is mounted behind the plastic fascia to provide impact resistance in the five mph impact test required on all automobiles. The steel beams are heavy. With an SRIM beam, a weight savings is realized. Tables 14-20 and 14-21 show the comparison.

The low viscosity and snap cure of SRIM yield excellent wet-out. The internal mold release (IMR) shortens cycle time. Long
gel IMR systems are good for more than 20 releases. They gel in 12 seconds and cure in 60 seconds.

EQUIPMENT
Standard RIM and resin transfer molding (RTM) machines can be used for SRIM with minimum modifications. The mixhead size may have to be changed, depending on the size of the parts. If the preform glass content is high (over 20%), flow rates may have to be slowed to assure good wetting of the fibers. See Table 14-22 for typical conditions.

Calculation of the shot cycle time and weight can be done easily from:
• Mold volume (cc).
• Machine output, g/sec.
• Resin density, g/cc.
• Density, g/cc.

The procedure is as follows:
1. Calculate the resin weight to fill mold without reinforcement.
   Mold volume × resin density = grams of resin (required to fill mold).
2. Calculate the volume of glass reinforcement.
   Grams of resin × weight percent of glass = grams of glass.
   Grams of glass ÷ glass density = volume of glass (cc).
3. Determine resin volume required.
   Glass volume – mold volume = resin volume (cc).
4. Calculate weight of resin required.
   Resin volume × resin density = grams of resin.
5. Calculate shot time.
   Grams of resin ÷ machine output = shot time, seconds.

PREFORM EQUIPMENT AND PROCESSES
Preform technology can be as simple as using a shaped wood piece with fiber mat or strands placed by hand over it, or as complex as using a robotic multihole directed- chopped-fiber (DCF) system over a multidiameter-hole PFTE-coated screen. Production rates as high as one preform every 30 seconds are possible.

Fiberglass is the most common material used for SRIM preforms. It is available in different configurations. Directed chopped fiber (DCF) is usually cut into lengths from 0.5–2 in. (1.27 to 5.08 cm). Different lengths in different areas may change the structural properties of the preform. This is the least expensive form of
fiberglass material, since there is a minimum amount of waste (see Fig. 14-23).

Chopped-strand mat (CSM) is available in rolls of various widths. It can be die- or knife-cut to approximate the shape of preform. Some waste may occur. CSM does not possess particularly good directional strength qualities, unlike cloth (see Fig. 14-24).

Woven roving (Fig. 14-25) is not as easy to wet out with the resin as CSM, but it produces a laminate that is much stronger, particularly when put in tension in the direction of the solid arrow in the figure. Its performance at right angles to the main run of rovings is less impressive, because there are fewer rovings running in this direction. To provide a satisfactory interlayer bond, successive layers of woven roving must be laminated with intervening layers of CSM.

Glass cloth, or fabric, is tightly woven from strands of glass fiber. It provides good resistance to tensile loads in two directions.

---

**TABLE 14-17**

Comparison of RIM and Injection Molding of Unreinforced and Reinforced Plastics for Production of Parts with Large Surface Areas

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pur-Rim</th>
<th>Injection Molding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic temperature, ° F (° C)</td>
<td>104–140 (40–60)</td>
<td>390–572 (199–300)</td>
</tr>
<tr>
<td>Plastic viscosity, Pa·s</td>
<td>0.5–1.5</td>
<td>100–1,000</td>
</tr>
<tr>
<td>Injection pressure, bar</td>
<td>100–200</td>
<td>700–800</td>
</tr>
<tr>
<td>Injection time, seconds</td>
<td>0.5–1.5</td>
<td>5–8</td>
</tr>
<tr>
<td>Mold cavity pressure, bar</td>
<td>10–30</td>
<td>300–700</td>
</tr>
<tr>
<td>Gates</td>
<td>1</td>
<td>2–10</td>
</tr>
<tr>
<td>Clamping force, tons</td>
<td>80–400 (0.7–3.6 MN)</td>
<td>2,500–10,000</td>
</tr>
<tr>
<td>Mold temperature, ° F (° C)</td>
<td>122–158 (50–70)</td>
<td>122–176 (50–80)</td>
</tr>
<tr>
<td>Curing time in mold</td>
<td>20–30</td>
<td>30–80</td>
</tr>
<tr>
<td>Annealing</td>
<td>30 min @ 248° F (120° C)</td>
<td>Rarely used</td>
</tr>
<tr>
<td>Wall/thickness ratio</td>
<td>1/0.8</td>
<td>1/0.3</td>
</tr>
<tr>
<td>Part thickness, typical maximum, in. (cm)</td>
<td>0.3 (0.8)</td>
<td>0.254 (0.6)</td>
</tr>
<tr>
<td>Shrinkage, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unreinforced</td>
<td>1.30–1.60</td>
<td>0.75–2.00</td>
</tr>
<tr>
<td>Reinforced, glass parallel to fiber</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>Reinforced, glass perpendicular to fiber</td>
<td>1.20</td>
<td>0.40</td>
</tr>
<tr>
<td>Inserts</td>
<td>Easy</td>
<td>Costly</td>
</tr>
<tr>
<td>Sink marks around metal inserts</td>
<td>Practically none</td>
<td>Distinct</td>
</tr>
<tr>
<td>Mold prototype, months</td>
<td>3–5 (epoxy)</td>
<td>9–12 (steel)</td>
</tr>
<tr>
<td>Mold alterations</td>
<td>Cost-effective</td>
<td>Costly</td>
</tr>
<tr>
<td>Mold cost</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

(Courtesy Dow Plastics)
at right angles to each other. Resistance to deformation on the bias is not good. Cloth is not easy to wet out because the strands are packed tightly together during the weaving process. As with woven roving, successive layers of glass cloth must have intervening layers of fine CSM surfacing tissue. Cloth is the most expensive material (see Fig. 14-26).

Combination material (Fig. 14-27), consisting of a layer of CSM (a) bound to a layer of a directional material, such as woven roving (b), cuts down the time needed to laminate. Modern combination materials wet out well, but again, it is essential that all air bubbles are worked out during consolidation.

Non-woven unidirectional rovings, made up of long tows of glass filament, are available loosely stitched across the direction of the tow. The material is very strong and resists stretching in one direction only (see Fig. 14-28).

A variety of equipment can be utilized to make preforms. Mat, for example, is cut to size and a binder or adhesive is added to hold the shape of the preform. There may be some waste after cutting. The process can be automated. Even fiber distribution and high directional fiber load content can be attained. A preform mold is required to make the shape (see Fig. 14-29).

The DCF process uses a chopper gun to direct the fiber to the different areas of the preform screen (see Figs. 14-30, 14-31, and 14-32). It can be done manually or with a robot. The suction velocity to hold the fibers to the screen should be at least 1000 ft/min (305 m/min). A dry powder or wet binder/adhesive is sprayed from a separate gun onto the fibers. The dry powder must be activated by a heat gun, gas, or electric. It hardens when it hits the fibers and screen. The wet binders are dried in a separate heating oven. When the suction fan is shut off, the preform is removed from the perforated screen. Hole sizes on the screen may vary in different areas of the screen to allow for different thicknesses in the preform. There is very little waste of fibers using the DCF method. Complex parts can be made.

### TABLE 14-18
Typical Physical/Mechanical Properties, Class-A SRIM and Class-A SMC*

<table>
<thead>
<tr>
<th>Property</th>
<th>SRIM</th>
<th>SMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass, wt. %</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>Specific gravity, ASTM D-792</td>
<td>1.58</td>
<td>1.86</td>
</tr>
<tr>
<td>Tensile strength, ASTM D-683, psi $\times 10^3$ (MPa)</td>
<td>14.3 (98.6)</td>
<td>10.2 (70.3)</td>
</tr>
<tr>
<td>Flexural strength, ASTM D-790, psi $\times 10^3$ (MPa)</td>
<td>27.5 (190)</td>
<td>21.2 (146)</td>
</tr>
<tr>
<td>Flexural strength, ASTM D-790, psi $\times 10^6$ (GPa)</td>
<td>1.4 (9.7)</td>
<td>1.4 (9.7)</td>
</tr>
<tr>
<td>5 mph impact, ASTM D-3763-86, ft-lb (j)</td>
<td>12.8 (17.3)</td>
<td>10.5 (14.2)</td>
</tr>
<tr>
<td>Coefficient of linear thermal expansion, ASTM D-696, ppm/° F (ppm/° C)</td>
<td>14.7 (26.5)</td>
<td>8.3 (14.9)</td>
</tr>
<tr>
<td>–22 to +68° F (−30 to +20° C)</td>
<td>11.7 (21.1)</td>
<td>5.9 (10.6)</td>
</tr>
<tr>
<td>68 to 176° F (20 to 80° C)</td>
<td>415 (213)</td>
<td>Above 428 (220)</td>
</tr>
<tr>
<td>Heat deflection temperature, ASTM D-648, ° F (° C)</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>DOI</td>
<td>99</td>
<td>158</td>
</tr>
<tr>
<td>Ashland index</td>
<td>8.9</td>
<td>8.5</td>
</tr>
<tr>
<td>Orange peel</td>
<td>0.00035 (0.009)</td>
<td>0.00045 (0.11)</td>
</tr>
</tbody>
</table>

* Both 0.120 in. (3 mm) thick

(Courtesy Miles, Inc.)

### TABLE 14-19
Part Cost Comparison—Fiero Inner/Outer Hood at 150,000/Year

<table>
<thead>
<tr>
<th>Item</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>$34.92</td>
</tr>
<tr>
<td>Tooling</td>
<td>2.67</td>
</tr>
<tr>
<td>Press</td>
<td>3.05</td>
</tr>
<tr>
<td>Assembly</td>
<td>2.25</td>
</tr>
<tr>
<td>Labor</td>
<td>3.08</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2.62</td>
</tr>
<tr>
<td>Total Part Cost:</td>
<td>$48.59</td>
</tr>
</tbody>
</table>

(Courtesy Miles, Inc.)

### TABLE 14-20
Material Cost and Weight Comparison—Bumper Beam

<table>
<thead>
<tr>
<th>Property</th>
<th>Steel</th>
<th>SMC</th>
<th>Azdel™</th>
<th>SRIM 55% Mat</th>
<th>SRIM Directed Chopped Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, lb/in.$^3$ (kg/m$^3$)</td>
<td>0.28 (7750)</td>
<td>0.07 (1938)</td>
<td>0.04 (1107)</td>
<td>0.06 (1661)</td>
<td>0.06 (1661)</td>
</tr>
<tr>
<td>Part thickness, in. (mm)</td>
<td>0.07 (1.8)</td>
<td>0.22 (5.6)</td>
<td>0.28 (7.1)</td>
<td>0.18 (4.6)</td>
<td>0.18 (4.6)</td>
</tr>
<tr>
<td>Part weight, lb (kg)</td>
<td>19.68 (8.93)</td>
<td>13.21 (6)</td>
<td>11.37 (5.16)</td>
<td>10.0 (4.54)</td>
<td>10.0 (4.54)</td>
</tr>
<tr>
<td>Resin/material cost, $</td>
<td>6.49</td>
<td>13.21</td>
<td>14.78</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Glass cost, $</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>8.08</td>
<td>4.85</td>
</tr>
<tr>
<td>Total material cost</td>
<td>$6.49</td>
<td>$13.21</td>
<td>$14.78</td>
<td>$13.08</td>
<td>$9.85</td>
</tr>
<tr>
<td>Per part</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>33%</td>
<td>42%</td>
</tr>
<tr>
<td>Weight savings compared to steel, %</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>49%</td>
<td>49%</td>
</tr>
</tbody>
</table>

(Courtesy Miles, Inc.)
The directed-chopped-fiber method utilizes cut fiberglass strands, sprayed on precision-manufactured tooling, to make a preform. The completed preform is then placed into a mold. Resin is injected and then cured (see Fig. 14-32).

**SLURRY PROCESS**

A container of chopped fiber and a binder are mixed in a water bath. The screen is shaped to the preform size. The screen is then dropped into the bath and lifted out. As it comes out of the bath, the water deposits fibers on the screen and drains out. The screen, with the fibers, is dried in an oven. Trim scrap is minimal. If the preform is not correct, it can be returned to the water bath before drying.

---

**TABLE 14-21**

<table>
<thead>
<tr>
<th></th>
<th>Directed Chopped Fiber</th>
<th>Fabmat™</th>
<th>Azdel™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.6</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Flexural modulus, psi (\times 10^6) (GPa)</td>
<td>2.62 (18)</td>
<td>2.51 (17)</td>
<td>0.445 (3)</td>
</tr>
<tr>
<td>Tensile strength, psi (\times 10^3) (MPa)</td>
<td>38.7 (267)</td>
<td>24.6 (170)</td>
<td>8.6 (59)</td>
</tr>
</tbody>
</table>

*(Courtesy Miles, Inc.)*

**TABLE 14-22**

Typical Conditions on a Test Plaque*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold temperature</td>
<td>150˚F (66˚C)</td>
</tr>
<tr>
<td>Shot weight</td>
<td>2.83 lb (1.28 kg)</td>
</tr>
<tr>
<td>Shot rate</td>
<td>2 lb/sec (0.9 kg/s)</td>
</tr>
<tr>
<td>A-ISO pressure</td>
<td>1000 psi (6890 kPa)</td>
</tr>
<tr>
<td>B-polyol pressure</td>
<td>1000 psi (6890 kPa)</td>
</tr>
<tr>
<td>A temperature</td>
<td>90˚F (32˚C)</td>
</tr>
<tr>
<td>B temperature</td>
<td>120˚F (49˚C)</td>
</tr>
</tbody>
</table>

* 4 ft\(^2\) (0.37 m\(^2\), 0.125 in. (3.2 mm) thick, 30% glass

*(Courtesy Polyrim Greenlane Manufacturing/Decoma Plastics)*

---

Fig. 14-23 Directed-chopped-fiber. (a) single strand wetted-out by the polyester resin, (b) glass fiber cloth completely wetted-out.

Fig. 14-24 Chopped-strand mat.

Fig. 14-25 Woven roving.

Fig. 14-26 Glass-fiber cloth mat.
The binder or adhesive should be compatible to the resin that is injected around the preform. It may be either a powder or a liquid, thermosetting or thermoplastic. The binder/adhesive constitutes about 5–10% of the preform weight. Commonly used binders are polyvinyl acetate, linear epoxy, acetate, polyester, and PET.

The powder must be heated with either an oxygen-propane torch or an electric heat gun. The powder turns to a liquid and usually sets up hard on the fibers and screen.

The liquid usually flows at room temperature and is dried by heat in an oven, microwaves, or another method. An advantage of the liquid is that additional pieces of fiber or inserts may be added when the fibers are still wet.

FEATURES AND DESIGN CONSIDERATIONS

There are seven primary reasons for using RIM for molding automotive parts:
1. Molds and tooling costs are significantly lower than molds for thermoplastic polyolefin (TPO) injection molding. More complex parts can be made, since they can be peeled off the molds.

2. Polyurethane RIM is easier to repaint and repair. TPO is difficult to repair and repaint by local body shops. Usually the whole TPO part has to be replaced.

Fig. 14-30 Directed-chopped-fiber process. (Courtesy Charles F. Alexander)

Fig. 14-31 Single-station directed fiber machines are built in turntable sizes from 36–120 in. (91–305 cm) diameter. This type of machine also requires an independent curing oven. (Courtesy Edgar Industries)
3. Painted polyurethane can be recycled into other RIM parts.
4. RIM has the lowest cost of energy consumption of any molded process (see Fig. 14-33). RIM consumes 75 BTU/ft³ (2792 kJ/m³), in contrast to injection molding TPO, which consumes 2098 BTU/ft³ (78,191 kJ/m³).
5. RIM polyurethane and polyurea have a lower shrinkage factor than TPO.
6. A wide variety of chemical formulations for large parts are available.
7. Structural RIM parts with glass fibers weigh only half as much as steel (see Tables 14-23 and 14-24).

MOLDS
A variety of materials can be used for SRIM. Mold pressures range from 50–150 psi (345–1034 kPa), and the strength required for the molds is similar to that for blow molding, but much less than for injection molding. Since the fiberglass preforms do not move in the mold, wear is not a problem (see Table 14-25).

Usually only one gate per part is required, because of the viscosity of the liquid. Two or more molds or cavities of different volumes can be mounted in the same press. This is an advantage over injection and blow molding. It allows full use of the platen. Most venting is by material dumps at the edges of the parts. Gasket-type seals can also be used to minimize flash. Gate location is developed from flow analysis and past history. SRIM gates are usually wide fan gates as shown in Figure 14-34 with static mixer (see Fig. 14-35). Part ejection of SRIM is similar to that of RIM, injection molding, and blow molding. PUR-SRIM can be peeled off the mold because the material is soft at that stage. This eliminates expensive pins, plates, and slides.

TROUBLESHOOTING
SRIM problems are similar to those of any other molding processes. The five most common defects in SRIM molding and finishing are:
1. Flash left in mold.
2. Contaminated material.
4. Tearing at sharp corners.
5. Distortion.

Other defects are pinholes, sink marks, trimming cuts, short shot, flow lines, and mold marks. The problems can be solved by the same methods used in standard RIM and other molding processes.
MAINTENANCE

Daily and weekly preventive maintenance are required. Since SRIM machines are hydraulic and electrical, the procedures are similar to those for injection and blow molding, except there is no barrel or screw. Liquid pumps are used for material flow. The forms in Figs. 14-36 to 14-38 are used in maintenance of 90–125-ton (0.8–1 MN) presses.

SAFETY

SRIM precautions are similar to those for any RIM or injection molding process. Gloves and goggles should be used when handling fiberglass preforms. Face masks are recommended when spraying binders and adhesives. Isocyanates can burn skin and react with water.

CONTINUOUS IMPROVEMENT/NEW DEVELOPMENTS

Improved preform technology is key to the critical success of structural composites. Many new materials are emerging for fibers and polymers.

SRIM thermoset polyurethane polymers can now be recycled. The regrind process offers one such route toward recycling RIM polyurethanes. There are several advantages to this route. It eliminates the cost and ecological problems of landfill. It offers potential material cost savings to the SRIM molder and the original equipment manufacturer. Most importantly, it enables the recycling of painted parts as well as unpainted parts back into the original application without any sacrifice of the polymer's performance or quality standards (see Fig. 14-39).

**TABLE 14-23**

Typical Mechanical Properties of Composites*

<table>
<thead>
<tr>
<th></th>
<th>Continuous Strand Mat, 0.125 in. (3.2 mm) thick</th>
<th>Chopped Strand Mat, 0.125 in. (3.2 mm) thick</th>
<th>Unidirectional Mat, 0.125 in. (3.2 mm) thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight % glass</td>
<td>29</td>
<td>45</td>
<td>28</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.39</td>
<td>1.59</td>
<td>1.39</td>
</tr>
<tr>
<td>Flexural modulus, psi $\times 10^3$ (MPa)</td>
<td>730 (5033)</td>
<td>1250 (8618)</td>
<td>1040 (7170)</td>
</tr>
<tr>
<td>Flexural strength, psi $\times 10^3$ (MPa)</td>
<td>25 (172)</td>
<td>40 (276)</td>
<td>35 (241)</td>
</tr>
<tr>
<td>Tensile modulus, psi $\times 10^3$ (MPa)</td>
<td>975 (6722)</td>
<td>1555 (10,721)</td>
<td>1500 (10,342)</td>
</tr>
<tr>
<td>Tensile strength, psi $\times 10^3$ (MPa)</td>
<td>17 (117)</td>
<td>30 (207)</td>
<td>25 (172)</td>
</tr>
<tr>
<td>Notched izod impact strength, ft-lb/in. (j/m)</td>
<td>9.4 (502)</td>
<td>14.1 (753)</td>
<td>13.5 (721)</td>
</tr>
<tr>
<td>Heat deflection temperature at 264 psi (1820 kPa), °F (˚C)</td>
<td>376 (191)</td>
<td>405 (207)</td>
<td>397 (203)</td>
</tr>
<tr>
<td>% elongation</td>
<td>2.3</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Spectrim

(Courtesy Dow Plastics)

**Note:** ASTM methods used. These properties do not represent sales specifications.

**TABLE 14-24**

SRIM Mechanical Properties

<table>
<thead>
<tr>
<th>Plaque ID</th>
<th>1010592-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass weight fraction, E type</td>
<td>43.1%, 1–2 in. (25.4–50.8 mm) fiber</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.51</td>
</tr>
<tr>
<td>Flexural modulus, psi $\times 10^3$ (MPa)</td>
<td>1300 (8963)</td>
</tr>
<tr>
<td>Flexural strength, psi $\times 10^3$ (MPa)</td>
<td>39.5 (272)</td>
</tr>
<tr>
<td>Tensile modulus, psi $\times 10^3$ (MPa)</td>
<td>1.6 (11)</td>
</tr>
<tr>
<td>Tensile strength, psi $\times 10^3$ (MPa)</td>
<td>24.5 (169)</td>
</tr>
</tbody>
</table>

(Courtesy Melvin Sweeney)
### CHAPTER 14

**STRUCTURAL REACTION INJECTION MOLDING**

#### Table 14-25

<table>
<thead>
<tr>
<th>Properties*</th>
<th>Epoxy</th>
<th>Nickel Shell</th>
<th>Spray Metal</th>
<th>Cast Aluminum</th>
<th>Cast Kirksite</th>
<th>Machined Aluminum</th>
<th>Machined Steel, P-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface temperature control</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Part surface duplication</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Susceptibility to damage</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Life expectancy</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Mold cost (% injection mold)</td>
<td>20</td>
<td>30</td>
<td>35</td>
<td>45</td>
<td>55</td>
<td>60</td>
<td>65</td>
</tr>
<tr>
<td>Rank as production tool</td>
<td>1–2</td>
<td>1–2</td>
<td>2</td>
<td>2–3</td>
<td>2–3</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

* Key: 1-poor, 2-fair, 3-good, 4-very good

(Courtesy Charles F. Alexander)

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**Fig. 14-34 Fan gate.**

**Fig. 14-35 Schematic of an aftermixer showing how elements are sized in the design.**
### CHAPTER 14

**STRUCTURAL REACTION INJECTION MOLDING**

#### Daily Machine Critical Parameter Sheet

**Mold name: __________________________**

**Press No.: ______________**

<table>
<thead>
<tr>
<th>No.</th>
<th>Points</th>
<th>Standard</th>
<th>Actual when checked</th>
<th>Actual now</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Injection parameters:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>Calibrate pressure transducer</td>
<td>A = 20, 2020 ± 0.2 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>03</td>
<td>&quot;A&quot; and &quot;B&quot; as per procedure</td>
<td>B = 85, 2085 ± 0.2 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>Pump performance @ 2100 PSIG (pump calibrate)</td>
<td>Pump 1 = , Pump 2 = , Pump 3 = , Pump 4 = 200 ± 10 GPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>Total pump flow during injection</td>
<td>160 GPM ± 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>06</td>
<td>Servo manifold pressure</td>
<td>2200 psi ± 200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07</td>
<td>Mixhead hydraulic pressure</td>
<td>2100 ± 100 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>Velocity profile chart</td>
<td>Straight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>Actual velocity performance</td>
<td>98 to 100%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Injection pressure profile pre-pressure</td>
<td>Injection pressure &quot;A&quot; and &quot;B&quot;</td>
<td>Null</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Repeatable spike</td>
<td></td>
<td>5 consecutive shots (± 2 sq)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Straight injection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Ratio performance (dynamic)</td>
<td></td>
<td>2% ± 1</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Polyol piston pump pressure and speed</td>
<td>240 ± 10 psi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Check power supply voltages (±0.01 volts)</td>
<td>(±10, ±15, ±24, 24)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Check ball valve for leaks</td>
<td>No leaks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Check nucleation display</td>
<td>St. = 4.00, P1 = 1.25, P2 = 4.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Check decompression settings (P110)</td>
<td>400 psi ± 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Mold protect for RIM 125 (P110)</td>
<td>200 psi ± 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Mold protect for machine No. 10 and 3</td>
<td>600 psi ± 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Mold protect for RIM 90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Check pilot pressure (P187)</td>
<td>RIM 90 = 1100 RIM 125 = 600 psi ± 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Check sequence valve settings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Check oil level</td>
<td>Sight glass marking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Check oil temperature</td>
<td>120 ± 10°F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Clean top of plate</td>
<td>No rags/oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Clean top of crown</td>
<td>No rags/oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Check grease system</td>
<td>Wet not good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Check core speed and core shaft cylindrical tight</td>
<td>Thin flash on part</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 14-36 Daily maintenance sheet—Injection parameters. (Courtesy Polyrim Greenlane Manufacturing/Decoma Plastics)
<table>
<thead>
<tr>
<th>No.</th>
<th>Points</th>
<th>Standard</th>
<th>Actual when checked</th>
<th>Actual now</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Clamp tonnage pump</td>
<td>Pressure</td>
<td>2300 ± 100 psi</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>Clamp tonnage</td>
<td>Pressure</td>
<td>2200 ± 100 psi</td>
<td></td>
</tr>
<tr>
<td>03</td>
<td>Core 1 hold</td>
<td>Pressure</td>
<td>1800 ± 200 psi</td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>Core 2 hold</td>
<td>Pressure</td>
<td>1800 ± 200 psi</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>Core 3 hold</td>
<td>Pressure</td>
<td>1800 ± 200 psi</td>
<td></td>
</tr>
<tr>
<td>06</td>
<td>Platen retract</td>
<td>Current draw</td>
<td>225 ± 25 amps</td>
<td></td>
</tr>
<tr>
<td>07</td>
<td>Crown book In</td>
<td>Current draw</td>
<td>225 ± 25 amps</td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>Bed book In</td>
<td>Current draw</td>
<td>100 ± 25 amps</td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>Platen close</td>
<td>Current draw</td>
<td>150 ± 25 amps</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Injection</td>
<td>Current draw</td>
<td>250 ± 50 amps</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Platen open</td>
<td>Current draw</td>
<td>250 ± 50 amps</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Crown book Out</td>
<td>Current draw</td>
<td>125 ± 25 amps</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Platen extend</td>
<td>Current draw</td>
<td>225 ± 25 amps</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Total auto</td>
<td>Cycle time</td>
<td></td>
<td>seconds ± 1 second</td>
</tr>
<tr>
<td>15</td>
<td>Check pressures and flows for smooth cycle</td>
<td></td>
<td>No shaking, no noise</td>
<td></td>
</tr>
</tbody>
</table>

PM completed by: ___________________________  Date: __/__/____

Comments:
___________________________________________________________________________________________________________________________________________
___________________________________________________________________________________________________________________________________________
___________________________________________________________________________________________________________________________________________

Outstanding work required must be transferred to the regular maintenance work list.

Copy to maintenance clerk for summary report.

Fig. 14-37 Daily maintenance sheet—press parameters. (Courtesy Polyrim Greenlane Manufacturing/Decoma Plastics)
### STRUCTURAL REACTION INJECTION MOLDING

#### Fig. 14-38 Weekly maintenance sheet. (Courtesy Polyrim Greenlane Manufacturing/Decoma Plastics)
Resin transfer molding is a process by which the resin system is transferred at low viscosities and low pressures into a closed mold die containing a preform of dry fibers. The RTM process produces low-cost composite parts that are complex in shape. These parts typically require continuous-fiber reinforcement along with inside and outside mold line controlled surfaces. It is the placement of continuous-fiber reinforcements in large structures that sets RTM apart from other liquid molding processes.

**Complex Shapes**

The most visible advantage to this molding process is its ability to combine multiple, detailed components into one configuration. For example, many traditional designs consist of individual details that are combined as a subassembly. These subassemblies usually require labor-intensive shimming, bonding, mechanical fastening, and sealing (see Fig. 14-39). Consequently, these subassemblies demonstrate high part-to-part variability due to tolerance buildup.

**Low-part Variability**

Individual components are integrated into one item with resin transfer molding. Therefore, the part-to-part variation is low because the parts are a product of the mold.

**Surface Finish**

Aerodynamic, decorative finish, and controlled fit-up surfaces are frequently required. RTM is ideal for producing these high-quality surface finishes. Because an RTM part is a product of the mold, its surface quality is comparable to that of the mold.

**Fiber/Resin Ratio Control**

Another reason to use RTM is the control ease of the reinforcement/resin ratio, which is typically 55–70% fiber by weight.

**No Autoclave Cycle**

Because the method for heat transfer is ideally integrated into the mold die, the need for an autoclave is eliminated. Therefore, autoclave costs, inherent size limitations, and staging issues are avoided.
Low Material Costs
In terms of raw material costs, RTM can offer savings by using bulk materials such as broad goods. Because dry goods are less expensive than preimpregnated materials, the cost of the wasted material during the ply-kitting operation is reduced. Also, bulk materials commonly do not need special handling requirements.

Minimal Training
The basic injection operation of RTM is straightforward and easily learned. Hence, minimal training is required to bring operators on line. On the other hand, with preforming the level of operator skill and training depends on the method used.

Low Capital Investment
The initial capital investment costs of RTM are low compared to those of many other molding processes. An elementary form of RTM can be achieved just by using a pressure pot, an oven, and a vacuum source. Meanwhile, a variety of off-the-shelf equipment can be acquired to advance the process in many areas.

Low Worker Exposure
In most cases, RTM materials can be used with minimal chemical exposure to workers and the environment. Many high-performance resin systems are stable and release only low-volatility materials. Since RTM is processed within a closed system, workers are exposed to the resin only when loading the dispensing equipment.

Bushings and Inserts can be Molded In
Bushings and inserts can be incorporated into the preform and injected in place to eliminate some higher-level assembly. Special considerations, however, pertain to the design and fabrication of the mold die (for example, the value added must be compared to the tool cost).

ADVANTAGES AND LIMITATIONS
The following list summarizes some of the fundamental advantages to this process.

1. Complex shapes (detail integration).
2. Low-part variability (product of the mold).
3. Good surface finish.
4. 55–70% fiber/resin ratio control.
5. Eliminates autoclave cycle.
6. Low material costs.
7. Minimal training.
8. Low-capital investment costs.
10. Bushings and inserts can be molded in.

Some of the limitations to RTM include:
1. Higher tool cost.
2. Design changes can be costly (tooling).
3. Cost of advanced preforming architecture is prohibitive.
4. Custom resin systems are needed.
5. Tool handling challenges (size and weight of tools).

For a long time, resin transfer molding has been used for applications suitable to consumer markets. However, in the last decade, through the development of high-strength resin systems and more advanced pumping systems, this process has advanced to new levels. These recent developments have promoted this technology as a practical manufacturing option for high-strength composite designs. The following sections will offer detailed insight to the benefits, applications, and methods that are currently used in the aerospace industry.

Given the many advantages mentioned earlier, perhaps the real value of RTM lies in the ability to combine several parts into one standard part. Standardization means that the process variables are defined, documented and fixed to minimize operator-sensitive parameters. An RTM standardized process will provide low part variability with high repeatability that decreases rework and scrap. These items must be satisfied to capitalize on the value of RTM.

Part Selection Criteria
To design and fabricate parts using the RTM process, one must evaluate the part requirements based on the following:

• Parts require high-strength, continuous-fiber reinforcement with 55–70% fiber loading.
• Parts are complex in nature with designed-in flanges, stiffeners, inserts, etc.
• Part tolerance requirements typically range from ±0.010–0.030 in. (0.005–0.016 mm).
• Part thickness ranges from 0.040–5.0 in. (1–127 mm).
• Surface finishes of 0.0001 in. (0.003 mm) root mean square (RMS) maximum variation or better are well within typical machining parameters.

Cost
Cost is another significant characteristic that must be clearly evaluated. As with all closed-cavity molds, the nonrecurring (or tooling) cost is high. This cost, of course, will fluctuate depending on the types of materials used and the tool complexity. Recurring costs are usually small enough to offset the nonrecurring costs even with reasonably low-volume production runs.

Cost savings that reflect a quality fit-up and low-part variability on higher assemblies are often difficult to quantify. Customizing details to fit properly is expensive. Therefore, higher assembly costs are reduced by using parts manufactured by RTM since the parts consistently fit correctly.

Higher tool cost. Because of the high quality of the mold and its inherent complexity, tooling is expensive. Parts with complex configurations will have costly multipiece breakdown tooling.

Design changes can be costly. Design changes are costly when complex multipiece molds are modified. Even a simple design change can result in extensive rework or tool remake.

Costs of advanced preforming architecture. The use of advanced preforming architecture can be prohibitive due to slow, labor-intensive processes.

Custom Resin Systems
The resins must meet design and process parameters that may be difficult to combine. For example, design criteria such as mechanical test values or flammability values must be compatible with the process criteria such as pot life, viscosity, worker exposure, cure time, etc. Resin tougheners in general cannot be added because the preform acts as a prime filter, entrapping these materials at the point of induction.

Tool Handling Challenges
One of the benefits of RTM is its ability to manufacture large parts. However, this can also be a major limitation because the tools are large and very heavy. Large and massive molds have special handling needs that can include cranes, trunnions, and fork lifts.

PREFORM SELECTION AND FABRICATION
Design Criteria
Some of the most common materials used to fabricate preforms are fiberglass, carbon, aramid, and ceramic fibers. These materials can be used separately or combined into a variety of hybrids to meet specific performance needs. Since these materials have been used in composite manufacturing for many years, they offer enhanced design flexibility.

There are several ways to form the reinforcements to a desired shape. Preform fabrication methods include braiding, knitting, weaving, filament winding, and stitching. Each of these methods is quite different and must be individually evaluated for specific design characteristics. Woven and filament-wound preforms typically require a binding agent to maintain consolidation and configuration. Binding agents work best if they are a derivative of the neat resin system. In some situations it is necessary to use a binder that is dissimilar. If this is the case, the binder can migrate, consolidating during injection in an uncontrolled manner and reducing the strength of the base resin system.

Preform material, fiber content, and orientation have a significant influence on the mechanical properties. With most preform styles, the fiber orientation will change through areas of transition, especially on complex part configurations. For example, fiber orientation and volume on a typical 2D braided preform in the shape of an hourglass will change as the fiber makes the transition from the small diameter to the large diameter (see Fig. 14-41). At the same time, fiber volume will decrease as the fiber makes the transition from the small diameter to the large diameter.

In structural applications, these characteristics make it difficult to design for specific load requirements. Depending on the application, test programs will often be needed to validate the mechanical properties.

Consolidated preforms. All preforms should be consolidated before they are loaded into the mold. Consolidated preforms ensure appropriate fiber orientation and volume. Fiber orientation and distortion in the RTM process must be understood from two aspects. The first deals with positioning, forming, and consolidating dry fibers. Unlike preimpregnated reinforcements, dry fibers are unstable and are easily distorted. Binders help to stabilize the fibers during their handling and positioning. During the forming and consolidation process, the preform becomes stable. Once the preform is consolidated, it can be handled, assembled, and located in the mold with limited distortion. The second aspect deals with the ability to hold and lock the correct fiber orientation during resin injection. When the preform is closed in the mold, it is further consolidated by the closing pressure. The preform’s high fiber content locks the fibers tightly in place, preventing fiber movement.

Preform consolidation can be achieved with different techniques which include stitching and using binders. The stitching technique is straightforward. Any of an assortment of threads—graphite, aramid, polyester, polyamide, or other material—can be used to sew preforms together and consolidate the fibers, as in the textile industry.
Powders, liquids, and veils. Binders, or tackifiers, are applied to the fibers with and without tack. Binders are available in powders, liquids, and veils.

Powders are usually preapplied to broad goods by a shaker or aerosol and set to the material with heat. Powdered binders can be locally applied during preforming, but pose environmental concerns that require special handling.

Liquid binders can also be preapplied to broad goods by aerosol or dipping techniques. In most instances, liquid binders are easier to use locally but should be used in a spray booth or other suitably vented system.

Another option is to apply the binder in a veil form. The veil is perhaps the easiest form of binder to use locally. The veil material is layered with the broad goods and set by heat without special handling equipment.

During the formation and consolidation of the preform, each of the three forms of binder require additional heating to melt and seat the desired shape. The consolidation process involves several methods. These methods include using match dies, diaphragm drape forming (Fig. 14-42), and tensioning (unique to filament winding).

A common approach to preforming is to lay up broad goods ply by ply. Compared to prepregs, dry broad goods are easier to lay up. Prepregs require a great deal of time to work the material into contours and radii. It is not critical for preforms to be hand-worked into tight conforming areas because the fibers will be held in position by the mold. The important aspects to forming and consolidating preforms are preventing ply pinching between the mold halves and ensuring proper location or indexing. Braiding and filament winding can be good options to consider when there is a desire to move away from hand lay up. These methods help to reduce the consolidation cycle and trimming requirements. Many preforming methods utilize automation to reduce variability.

Cost. Next to the cost of the mold die tool, the cost of the preforming operation is most critical to the cost-competitiveness of the RTM process. Constructing preforms usually accounts for more time than any other operation in the process in terms of recurring hours. The design of the part must complement both the method of preforming and the fiber architecture in a symbiotic relationship. The success of this relationship will ensure that recurring costs are minimal.

**TOOL SELECTION AND DESIGN**

**Design Criteria**

The quality of the mold is most critical to the RTM process. Surface finish and dimensional control are reflected products of the mold. In other words, the time and money spent to make high-quality molds will yield high-quality parts.

In the design of the mold die, the following features should be given special attention.

Resin ports. Resin is introduced into the mold through ports that vary in size, location, and number. Resin port variables depend on the mold configuration and the characteristics of the resin matrix. The design of these ports must make allowances for tool cleanup and preparation. Both of those tasks are accomplished with draft angles incorporated into the ports.

Reservoirs. The resin flows through the resin port into the reservoir. Ideally the reservoir runs the full length of the preform. The purpose of the reservoir is to allow an even flow of resin across a large area of the preform at a constant pressure.

Indexing. Aside from aligning mold halves, indexes are essential in providing accurate positioning of internal and breakdown mandrels of complex shapes. Though index pins are often used, surface indexes like dovetails and shelves are also used. Floating internal mandrels usually result in varied part thicknesses and uncontrolled fiber/resin ratios.

Mold cavity. The mold cavity thickness is critical to control the fiber/resin ratio. The appropriate thickness band is determined by the low- and high-fiber loading requirement. Consequently, thin parts are more susceptible to fiber loading deviations and require molds built to tighter tolerances (see Fig. 14-43).
Mold seals. In the RTM process, seals serve two functions: (1) to maintain vacuum integrity and (2) to contain the resin within the mold cavity. Failure of the seal in most cases will produce poor quality parts and resin seepage. Resin seepage leads to difficulties in part removal and tool cleanup.

Materials
There are many different tool materials available for fabricating molds. The material selection decision must take into account the mold requirements, which are subject to a number of factors. These include size, heating method, cure temperature, coefficient of thermal expansion, lead time, chemical resistance, processing pressures, closure methods, dimensional stability, and cost. For the majority of production applications, tool steels will satisfactorily meet the criteria mentioned earlier.

Heating Criteria
There are many methods of heating a mold. The most elementary method is standard oven heating. Standard ovens require small access doors for process hardware. They also require the use of bolt-together molds.

Electrical heating. The most common source of heat is electricity. Electrical heating methods use elements that are placed inside the mold. The number and size of the elements are chosen in accordance with a thermal analysis. This type of heating can be adapted to either bolt-together molds or press-loaded molds. Two of its limiting factors are possible hot spots and difficulties with element replacement. Also, to reduce cycle time, cooling capabilities can be incorporated into the mold along with the elements, although additional passageways through the mold must be built in.

Oil heating. Oil heating is another viable option. This method uses a network of connecting passageways internal to the mold. Subsequently, oil is pumped through the passageways. Controlling the temperature of the fluid provides means for both heating and cooling. The size and number of passageways is determined by using a thermal profile. The passageways can be machined, drilled, or cast into location. The oil heating method provides reliable, consistent heating and cooling and can be incorporated into all types of molds. A concern with this heating system is contamination. Complete isolation of the oil from the mold cavity must be maintained.

Other heating methods. Other methods of heating may be considered, such as a press with heated platens, forced circulated air, and induction.

Other Considerations
Mold parting lines. The design of the mold should locate the parting lines in a location that will minimize the possibility of ply pinch. Sharp angles must be avoided when developing the parting lines. Sharp angles are prone to damage and abrasive wear requiring rework.

Jackscrews and pullers. Surface tension between the mold and the part can prevent the part from releasing. Therefore, mechanical advantage is helpful in separating mold halves and extruding internal mandrels.

Breakdown segments. Complex configurations require multipiece breakdown segments. These segments must also have negative draft allowances for easy removal.

Sensors. Thermocouples must be used to verify the cure cycle. In most cases, thermocouples are positioned in the mold and not in the part. The number and location of thermocouples used should be based on a thermal analysis of the mold. The analysis should identify cold zones where thermocouples will be placed.

Once the mold is made, a thermal profile must be made to establish the dwell time for a specified temperature. The profile will provide a correlation between resin cure and the mold temperature. Other instruments such as pressure transducers, dielectric sensors, and ultrasonic sensors are also used to collect processing data and control parameters.

RESIN SELECTION AND REQUIREMENTS
In selection of a resin system, the first step is to clearly define the performance conditions for the product, such as the range of operating temperatures, thermal cycles, and mechanical properties. To ensure the proper resin selection, the resin properties must be evaluated based on the performance conditions. A wide variety of RTM resin systems are available, along with many others that are in the development stage. Some of the generic resin systems include: epoxies, cyanate esters, vinyl esters, polyester, and bis-maleimides (BMI).

Processing Requirements
The list of resin characteristics serves as the base to define the resin transfer process parameters. Resins that are suitable for the RTM process have low viscosity, extended pot life, low volatile content, low-exothermic temperatures, and a semirapid gel.

Safety
Safety concerns carry a high priority. Worker exposure and environmental impact must be low. Resin manufacturers have developed (and continue to develop) resin systems that are friendly to workers and the environment. However, resin materials usually have special guidelines for handling. These guidelines are contained in the material safety data sheets (MSDS) published by each manufacturer. Before any material is introduced to a lab or factory area, the MSDS must be provided to the user. The user has the responsibility to train workers and adapt the surroundings according to the guidelines of the MSDS.

Resins are available in a variety of formulations, including one-and two-part systems. Cleanup of noncross-linked formulations requires solvents. Therefore, solvent cleanup must be considered in resin system selection. Often, resins can be pumped directly from their shipping containers and require minimal solvent cleanup. Solvents are discouraged because they increase both worker exposure and the need for hazardous waste disposal.

RESIN DELIVERY SYSTEMS
Resin delivery systems available on the market have a wide range of capabilities and cost. The pump mechanism may be powered by a pneumatic, hydraulic, gear drive system, or a combination of these. A positive displacement pump is preferred when the part configuration is large and/or complex. This type of pump provides constant pressure and continuous resin flow. With it, the injection cycle can be controlled and optimized.

The most elementary pumping system is a pneumatic pressure pot. This type of system has produced many successful RTM parts. However, it is limited by the degree of control it allows over the rate and pressure of the resin flow front. On the other hand, advanced resin delivery systems provide positive displacement combined with computer control of critical variables of the resin injection operation that are otherwise operator-sensitive.

The resin type being used influences the selection of a resin delivery system. For example, a two-part resin needs a pump that offers metering, mixing, and delivering. A one-part system does not require mixing, so it needs delivery only.
Many systems offer enhanced features that improve the process. For example, a delivery system may maintain a predetermined hydrostatic resin pressure, and adjust and display heat for control of viscosity, resin flow rate, and volume. These systems are generally simple to set up and operate, and are easy to clean and maintain.

**PROCESSING FUNDAMENTALS**

This section offers fundamental guidelines to the RTM process (see Fig. 14-44). There are many variables that influence the mechanics of the process; these guidelines are based on the following:

1. Fiber loading for structural applications is 55–65%.
2. Hard vacuum assistance provides better resin flow for complete ply wet-out.
3. Resin viscosity < 500 cP allows lower injection pressure.
4. Preconsolidated preform is complete, ready for mold loading.
5. Mold is integrally heated to reduce cycle time and mold handling.
6. Resin is previously degassed to minimize porosity and void content.
7. Hydrostatic pressure is held after resin injection to lower porosity content.
8. Injection pressure is less than 100 psi (690 kPa) to allow a slow-moving flow front with minimal fiber distortion.

**Tool Preparations and Plumbing**

Like all composite and plastic processing methods, proper tool preparation is essential. Tools must be clean and free of all dirt, grease, residual resin, debris, and any other contaminants. All mold die details and features that include holes, bolts, end plates, seal grooves, and so on, must be coated with a suitable release agent. It is also recommended that the seals be cleaned and wiped off with a light application of release agent prior to being nested in location.

Inlet and exit lines are a required means of delivering the resin to and from the mold. The inlet and exit lines are made from various types of plumbing materials. These lines often incorporate inline valves, gages, and sensors to monitor and standardize the injection process. It is important to verify that the materials and fittings used for these lines are rated appropriately for the temperatures and pressures required by the resin system. Some lines can be as simple as a piece of nylon tubing. Other lines need compression and pipe fittings, and high-pressure and high-temperature tubing.

**Tool and Preform Loading**

After the mold has been prepared and the preform formed, consolidated, and trimmed, the preform is ready to be placed in the mold cavity. The preform should be carefully positioned in the mold with indexed locators. Once the preform has been set in place, the parting planes must be inspected for possible ply mislocation or obstruction that will cause ply pinch and mold closure interference. The seals and their mating surfaces should also be inspected for any type of obstruction prior to closing the mold. Even dirt and other small particles on the seals and seal surfaces can easily cause vacuum leaks. In a production environment it is recommended that the preform loading and mold closure be done in a clean environment free of potential contaminants.

**Vacuum Leak-down Test**

After the tool has been closed and the plumbing attached, the system must be checked for vacuum integrity. This is commonly done with a vacuum source and a vacuum gage at the resin trap. Shutoff valves can isolate the plumbing for the entire system. After applying high vacuum, allow the system to stand static for up to five minutes to verify the level of vacuum stability. The vacuum assists the resin flow through complex shapes having minimal porosity.

![Fig. 14-44 RTM equipment.](image-url)
CHAPTER 14

RESIN TRANSFER MOLDING

Heating
The mold should be heated to a specific temperature level to optimize the resin-injection process. The ideal temperature will provide minimum resin viscosity and maximize the time until the resin reaches its pot life. To allow the resin to flow freely into the vacuum trap, the exit line may need to be heated. In this case, an additional heat source such as an electric heat blanket is sufficient. The need for a heated vent line depends on specific resin characteristics and the ability to maintain flow through the lines.

Resin Injection and Cure
Ideally, the resin injection procedure creates a constant-flow front, with complete fiber wet-out on a microscopic level, and achieves total mold cavity fill. A recommended way to create a constant-flow front is to use an injection system that maintains positive displacement at low pressures. Sustaining a low resin viscosity throughout the injection cycle helps to control the pumping pressure. Therefore, it is imperative to understand the resin matrix characteristics and to exploit them as necessary. Another aid to achieving total fiber wet-out and mold fill is to conclude the injection cycle with appropriate hydrostatic pressure. The hydrostatic pressure should be maintained until the resin matrix is well within its gel phase. The level of hydrostatic pressure is governed by the type of resin system, mold design, and supporting equipment. As a general rule, higher pressures within the safe limits of the system will result in higher-quality parts.

The cure cycle begins when the cavity is completely filled at constant hydrostatic pressure and the mold is at cure temperature.

Part Removal
If a mold incorporates draft angles, jackscrews and other mechanical parts, parts are readily removed. However, the coefficient of thermal expansion between dissimilar materials can also influence the ability to remove parts from their molds. Parts are routinely removed (or loosened) from the mold at elevated temperatures to compensate for differences in CTE, as well as to improve tool turnaround time. Consequently, additional safety precautions are required.

Cycle Time Reduction
Presses. RTM manufacturers often use bolt-together molds. Presses, however, can be economically effective to reduce cycle time. Using a press can reduce cycle time in a number of ways. First, presses are ideal for maintaining mold closure during injection and cure. Second, presses decrease the tool thickness requirement, which allows easier and lower-cost handling of the mold. Third, a press allows quicker access to the mold cavity for faster tool turnaround.

Computer-supervised system. Another way to further reduce cycle time is to standardize the injection process. The means to standardize the injection procedure is to use a system that offers computer control and feedback. A system supervised by a computer allows the operator to program and set key processing parameters, such as resin flow rate, resin volume, injection temperatures, cure temperatures, pressures, and vacuum. Once the system is established and programmed, the injection cycle is simple and repeatable. The operator connects the injection system to the inlet of the mold and initiates the program. The computer controls the entire process: from the beginning until the end when the part is cured.

Postcure. Some resin systems need extended cure time, which adds to the cycle time. With specific resin systems, however, the mold turnaround time can be improved. This is achieved by removing a part from the mold when it has only partially cured and placing it in an oven to complete the cure. In most cases, these parts are placed in the oven unsupported so the mold is free to be reloaded and processed.

PROCESS IMPROVEMENTS AND DATA COLLECTION
General process improvements can be identified by collecting process data. Gathering data can be as simple as recording information on a process work sheet or incorporating a computer program. Again, key processing parameters such as flow rates, flow volumes, temperatures, pressures, and vacuum can be monitored by placing gages and sensors throughout the process. This information can be applied to statistical process control (SPC) methods to identify areas to be developed and improved.

TROUBLESHOOTING
Troubleshooting problems and solutions for RTM are listed below.

Preform
Ply orientation distortion.
• Minimize ply handling—integrate automated methods (that is, ply cutters, pick-and-place, drape formers).
• Stabilize material with a binder.

Poor consolidation.
• Increase the percent of binder.
• Use a well-fitted vacuum bag when vacuum compaction is applicable.
• Apply or increase heat during compaction.

Loft occurs during demolding of preform.
• Apply or increase heat to provide sufficient melt of the binder. Allow the preform and binder to cool prior to demolding.

Injection Process
No resin observed at the vents or vacuum trap.
• Heat or increase temperature on the exit line.
• Extend resin gel time by lowering the mold temperature.
• Increase injection pressure.

Resin seepage along parting planes.
• Decrease the injection pressure.
• Reduce the hydrostatic pressure.
• Check for foreign object or damage to the seal.
• Increase the mold clamping pressure.

Vacuum leaks.
• Clean or replace worn seals.
• Tighten plumbing fittings.
• Isolate the vacuum pot and check for leaks.
• Check for proper mold clamping pressure.

RTM Part
Ply migration.
• Verify the reinforcement volume—the volume may be too low.
• Reduce the resin injection pressure.
• Lower the resin viscosity.
SAFETY AND MAINTENANCE
Because it should accompany every manufacturing process, safety is always an important issue. RTM should incorporate the items below:

- Proper ventilation of resin volatiles, solvents, and release agents.
- Respiratory protection from dry fibers.
- Hazardous waste procedures for uncured resins, solvents, and graphite fibers.
- Thermal protection for hot molds, heated lines (for example, oil, resins, vents), resin plumbing, heat blankets.
- Safe procedures for mold handling, lifting, transporting, and storage.
- Use low injection pressures.
- Properly deaerate resin system.
- Use high vacuum assistance at the vent lines. Note: do not exceed the resin degas vacuum.
- Apply hydrostatic pressure after resin injection.
- Check seals for vacuum integrity.
- Check the resin pump for air infiltration.
- Check for moisture and/or other contaminants.

Resin richness.
- Increase fiber volume.
- Check molds for matched radii.
- Verify preform construction.

Poor fiber wet-out.
- Reduce resin viscosity.
- Reduce resin pump rate.
- Verify or reduce fiber volume.
- Apply or increase hydrostatic pressure.
- Apply or increase vacuum.
- Move or add resin port locations.

Ply pinch.
- Verify proper preform trim.
- Provide better ply consolidation methods.
- Provide accurate preform indexing methods.

- Comprehension training procedures (for example, use of safety glasses, foot protection).

SUMMARY

Design for Manufacturing

To capitalize on the benefits of RTM, products must be designed specifically for the process. A common element in successful RTM programs is the cooperative effort of many individuals from various organizations working together. Because of process advances, and because the part configurations are more complex, the challenge is to skillfully evaluate risk with respect to cost and delivery. The benefits of the team concept ensure quality product designs that are functional, manufacturable, and cost-effective. Dynamic cross-functional communication not only creates a quality design, but allows parallel processing to reduce the time to deliver products.

Another area where team effort excels is identifying, analyzing, and reducing risk. A team of supporting organizations will identify potential risk areas as early as possible. By identifying problems early in the program, team members can work out solutions in a more timely manner and reduce the effect on cost and product delivery. At the same time, areas may be identified that require further development. If any development work is required to support the program, the team can reevaluate the situation at an early stage and put into place the right response and commitment to satisfy the customer.

New Developments and Applications

Though RTM has been around for many decades, its use has grown considerably in recent years. RTM is expected to move forward in the future, with ongoing efforts to expand its application in aerospace. The process in general is a cost-performance approach to composite manufacturing. However, there are a number of areas that need to be explored to enhance the process even further. When the decision is made to implement the process in a production environment, the details become challenging. The challenge is to gain greater control and processibility at a lower cost. Opportunities for improvement include simpler preform fabrication and assembly methods, higher performance resin systems at a lower cost, low-cost durable mold dies, turnkey computer-controlled equipment, and lower-cost, accurate flow-modeling software.

References


REFERENCES

The following organizations provided supporting information for this chapter: Amoco Chemical Company, Chicago, IL; Bristol Division, MMMG, Bristol, VA; The Budd Company, Madison Heights, MI; DuPont Polymers, Wilmington, DE; Kemlite Company, Joliet, IL; Occidental Chemical Corporation, North Tonawanda, NY; Owens Corning, Toledo, OH; Quazite, Division of MMMG, Lenoir City, TN; Resinoid Engineering Corporation, Skokie, IL; USDA Forest Products Laboratory, Madison, WI; Xerxes Corporation, Solon, OH.

Bibliography


Low Profile Fillers for Automotive BMC and SMC,” Reinforced Plastics, V. 38, No. 6, (1994).


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BIBLIOGRAPHY


DIP MOLDING

THE PROCESS

Plastic dip molding fills a part of the total molding category that is dominated by injection and blow molding. The process is adaptable both in its material and design capabilities and is generally restricted to the production of polyvinyl chloride (PVC) moldings. However, it offers advantages such as modest tooling cost and the ability to produce small or large quantities in complex or simple shapes without size restriction. Because of modest tooling costs, fast prototypes are produced within a matter of days. Small product lots become economical with the process, and a wide range of colors and finishes are available. Post operations (punching, printing, and decorating) are also available.

SELECTION CRITERIA

Because the plastic dip molding process has the capability of modifying the raw material to change the physical and chemical properties of the end product, it is possible to produce a wide range of moldings to suit various needs. The principal selection criteria when comparing PVC dip molding to other processes is whether or not the end product requires PVC. If indeed it does, and if the product allows a fairly consistent wall thickness, it undoubtedly is a suitable candidate for the dip molding process. Conversely, if the finished product must resist solvents and have accurate external dimensions and variable (but specified) wall thickness throughout, it is not a candidate for dip molding.

GENERAL DESCRIPTION OF THE PROCESS

The process of PVC dip molding involves heating a metal tool shaped to the internal dimensions of the required molding, and immersing it in a tank of cold liquid PVC (plastisol). The tool is removed from the dip tank, carrying with it a coating of plastisol that has adhered to it. The coated tool is then placed in an oven for curing, after which the molding is cooled and removed from the tool as a finished product.

MATERIALS

Though some other materials are used for special applications, PVC by and large is the only material used in large production by the dip molding process. Plastisols are PVC resins suspended in a blend of plasticizers combined with heat stabilizers to prevent breakdown during curing and pigments to suit the end requirement. A variety of mixers can be used to create the plastisol, limited only by the requirement that there be enough movement in the liquid to blend the resin and plasticizer without producing a rise in temperature. The component parts of the mix are combined in a mixer, a vacuum is applied to ensure that all air is removed during mixing and the mix is pigmented to the desired color. After several tests of viscosity, specific gravity, and hardness, the plastisol is ready for the dip molding process.

METAL TOOLS

The metal tools, which are usually made of aluminum, are fabricated in one of three ways: from a solid block by conventional machining techniques, from a wooden pattern used to produce a cast aluminum shape that is subsequently finished by hand, or from sheet aluminum used to fabricate the desired shape. When finished, the tools are mounted on a frame to carry them through the process.

PROCESS SUMMARY

A tool release agent is applied for PVC part removal at the end of the process. Then a preheat stage follows. At this time, the tool is heated in a temperature-controlled oven and subsequently placed on a vertical motion rack that lowers the tool into the plastisol at a preset speed and depth. The heat of the tool causes the plastisol adjacent to the tool to increase its viscosity and hence adhere to the tool. The extent to which this wall thickness increases on the tool is controlled by three main factors: the heat and thermal capacity of the tool, the length of time the tool is left in contact with the plastisol, and the specific formulation of the plastisol. At the end of this dwell period, the tool is slowly withdrawn to control any unwanted drips or runs on the outside of the molding. The fusion of the PVC is then completed in a closely monitored curing oven where the full chemical and physical properties of the PVC are produced. Following the curing cycle, the parts are transferred to a cooling water tank and held normally between 50–60°F (10–15.5°C) where the form is cooled to room temperature and subsequently stripped from the tool. Following the molding and cooling processes, other processes are done as necessary such as trimming, punching, printing, or decorating.

Coating a tool, and subsequently stripping it, produces a molding with internal dimensions and shape identical to the external dimensions of the tool. Because there is no shrinkage during the process,
extremely accurate internal dimensions are produced with “free-flow” dimensions on the exterior surface. These external dimensions can be controlled with the latest and most sophisticated manufacturing technology.

APPLICATIONS

PVC dip moldings are used principally as protective covers for various applications where accurate internal dimensions are required but where external dimensions are usually more free. The current applications in mass production typically include a wide range of protective end caps and closures, handle bar grips and sleeves, bellows of various shapes and sizes, and protective boots and seals. In the automobile industry, PVC is used in seat belt covers, gear shift bellows, and battery terminal covers. Moreover, because the plastisol can be formulated to strict medical requirements, there is a wide range of applications in the medical field, including such well-known items as stethoscope tubes.

ADVANTAGES

The dip molding process has distinct advantages when compared to injection and blow molding:

1. Low tooling costs, usually less than 10% of those required for the other two processes.
2. Short lead time: it is not unusual to produce prototypes within two to three days and in full production within seven to ten days. As a comparison, injection and blow molding require many weeks to reach the production stage.
3. Efficient low-production runs. Because of the low tooling costs, small quantities and prototypes are made available quickly and economically. With injection and blow molding it is not possible to mold anything at all until the finished tool is produced first.
4. Flexibility. If difficulties are encountered during the prototype stage, the low-cost prototype tool is easily changed to produce the next prototype for appraisal.
5. Variability. The ability to modify the formulation of the plastisol provides various surface finishes, ranging from a high gloss to satin and grainy leather type textures without any additional tooling expense.
6. The ability to mold extremely complex shapes with severe undercut which is impossible by either the injection or blow molding process.
7. Product size diversity. Because size is only limited by the size of the tool and the subsequent size of the oven and dip tanks required to process that tool, it is possible to manufacture dip moldings in sizes much larger than is possible with injection or blow molding. Currently, dip moldings are produced in sizes of more than 3 ft (0.9 m) in diameter and 5 ft (1.5 m) long, with complex shapes and wall thicknesses in excess of 0.5 in (12.7 mm). Molding an item of this size by either of the other processes is impossible.

LIMITATIONS

The main limitations of the plastic dip molding process compared to injection molding and blow molding are:

1. An inability to give accurate external dimensions.
2. An inability to give accurate variable and varied wall thicknesses throughout a molding.
3. A process limitation to the use of PVC only, whereas the other processes can use a wide range of other plastics.
4. Higher cost in certain applications. Where large quantities of certain types of PVC moldings are required, multi-impression tooling and automatic injection molding machines produce a lower cost item than is possible with the plastic dip molding technique. The main contributor to the higher cost is that the plastisol material itself is more expensive than the injection molding grades of a similar material.
5. Reduced durability. Vinyl products do not hold up well when exposed to extremely high temperatures. Even the high durometer grades become very supple at temperatures of 130˚ F (54˚ C). However, if supported and well-stabilized, these vinyls can perform quite satisfactorily at temperatures above 250˚ F (121˚ C) for a limited period of time.

WHEN TO USE THIS PROCESS

Consider dip molding when fast prototypes and small quantities of custom moldings are required for specific applications or where the size of the molding required is not economically produced by any other process. At the other end of the scale, with the latest dip molding equipment, very large quantities of simple moldings such as end caps and grips are produced at speeds much greater than those available by the other two processes, and consequently at a lower cost. Though plastic dip molding overlaps injection and blow molding, and in some cases can manufacture moldings that are impossible or uneconomical by the other two processes, there are many applications where the other two processes would far outperform the plastic dip molding process in terms of both economics and specification.

PRODUCTION EQUIPMENT

Though dip molding equipment has developed in many different directions over the years, modern, automatic, and computer-controlled highly productive plastic dip molding equipment has become available from one or two specialized companies. There are numerous process parameters pertaining to the dip molding process. The most common are: temperature, dip length, tool clearance, tool spacing, oven flow, and cycle times.

Figure 15-1 shows a manual layout and the process steps needed for dip molding.
OPERATING PARAMETERS

Tool and oven temperatures are extremely important to the dip molding process. Tool temperature refers to the temperature of the aluminum tool mounted on the frame. The size and shape of this tool dictates the amount of preheat needed. On average, heated tool temperature is 325–400˚ F (163–204˚ C).

Oven Temperatures

Oven temperatures are relevant to the preheat and curing stages. The preheat oven is normally set at 600–650˚ F (315–343˚ C) with resulting tool temperatures ranging between 325 and 400˚ F (163 and 204˚ C). Cure temperatures are slightly less, depending on product wall thickness and tool spacing. It is important to retain a certain level of heat in the tool between the preheat and the curing stages because the heat required for curing the molding comes from both the tool and the oven. Tooling clearances and form spacing are closely related parameters because they refer to the number of forms that can be arranged on a tooling or jig frame. Although the number of forms depends largely on the size of the part, the key objective is to allow optimal spacing to accommodate proper airflow during preheat and curing.

Dip Length

The dip length parameter refers to the part length made by the particular piece of equipment and is determined by the size of the dipping tanks and oven. Another parameter is durability. Vinyl products do not hold up well when exposed to extremely high temperatures. However, this problem is resolved if the vinyls are supported and well-stabilized.

Oven airflow is a critical parameter. Whether electrical or gas fired, uniform heating is the desired result. With uniform heating, consistent wall thicknesses and optimal cure times can be achieved. Without it, it is nearly impossible to obtain consistent wall thickness and rapid cure.

Cycle Time

The final parameter, cycle time, refers to the length of time tools remain in each stage of the process sequence. This is critical in that if the tools remain in one stage of the process sequence too long or are moved on too quickly, quality will suffer. Dip molding is a science. Once specifications and parameters for each part are established, parts are manufactured using the same process parameters time after time.

MACHINE CONTROLS

Figures 15-2 and 15-3 show a computer-controlled plastic dip molding machine designed to produce moldings up to 24 in. (61 cm) long at high speed with a single operator. The production system is designed to process 40 frames of moldings per hour. The system will process fewer frames, 25 to 30 per hour, of larger moldings. The number of frames per hour is a function of the
MACHINE CONTROLS

Fig. 15-2 Side view of automated dip molding equipment. (Courtesy Molding & Coating Technologies, Inc.)
Fig. 15-3 Top view of automated dip molding equipment. (Courtesy Molding & Coating Technologies, Inc.)
MACHINE CONTROLS

CHAPTER 15

preheat, PVC dip, and strip times. Frames enter and exit the system at the strip station location. Five different frames on the system, or any combination of similar or different frames, may be processed simultaneously. The preheat and cure ovens are capable of holding up to two carrier frames each in process. The PVC dip, quench dip, strip station, and release agent dip locations will hold up to one frame each.

ORDER OF OPERATIONS

The manufacture of parts is done by processing 24 × 24 in. (61 × 61 cm) frames carrying tools through the following sequence of operations:

1. A carrier frame is loaded into the system by the operator. Initially, the frame is loaded from a rolling cart into the system entry station. Once the frame is loaded, the operator presses the start button. The system identifies the frame and begins the automated sequence.
2. The release agent dip mechanism dips, dwells, and withdraws the molds from the release agent tank.
3. Upon completion of the release agent dip, the preheat oven entry door opens, the preheat oven loading device moves the carrier frame into the oven, the oven entry door closes, and the preheat cycle begins.

After the first carrier frame has been moved into the preheat oven, as many as four additional frames may be entered into the system by the operator for a maximum of five carrier frames in the system at one time. The operator is then available to strip the parts.
4. Upon completion of the preheat cycle, the preheat oven exit door opens and the carrier frame is removed from the preheat oven by the oven unload device and moved into the PVC dip mechanism.
5. The dip mechanism moves the frame to the specified tank, then dips, dwells, and withdraws the tools from the tank to achieve the desired length and wall thickness.
6. Upon completion of the dip, the cure oven entry door is opened and the cure oven loading device loads the carrier frame into the cure oven. The oven entry door closes and the cure cycle begins.
7. Upon completion of the cure cycle, the cure oven exit door opens and the carrier frame is removed from the cure oven by the oven unload device and moved into the cooling dip mechanism. The cooling dip is executed.
8. Upon completion of the cooling cycle, the carrier frame moves to the strip station and is stripped by the operator.

At the conclusion of the strip, the operator presses the continue button to continue the next cycle. Once again, this sequence is repeated as all five frames cycle through the system (see Figs. 15-2 and 15-3).

ADVANTAGES OF AUTOMATED DIP MOLDING SYSTEMS

Automated dip molding provides the following advantages:

- **Productivity.** High productivity is the direct result of the high velocity convection ovens for preheat and cure.
- **Quality.** Improved quality results from accurate temperature, motion, and material control. Accurate temperature control is achieved by microprocessor controls and high-velocity airflow created by pressurizing air in a plenum, providing velocity, accuracy, and uniformity. Accuracy of ± 2˚F (±1˚C) is typical.

Accurate motion control is achieved by a PLC-directed servo motor. Dip accuracy of 0.005 in. (0.127 mm) is typical. The PLC-stored dip profiles maintain accuracy and consistency for every tool.

- **Material control is achieved through agitation and level control systems. Air bubbles, particulate matter, and stratification problems are eliminated.**
- **Flexibility.** Increased flexibility is achieved through carrier frame encoding that matches each carrier frame in process with the corresponding profile to precisely control every aspect of the molding process. Five different parts may be manufactured on the system at one time.

SPECIFICATIONS

- **Parts:** The parts are typically protective end caps, enclosures, sleeves, grips, and other custom moldings using a variety of colors and temperature grades of plastisol.
- **Diameters:** The part diameters range from 0.06–20.5 in. (1.6–52 cm). The maximum part diameter of 20.5 in. (52 cm) is limited by the size of the carrier frame.
- **Lengths:** The part lengths range up to 24 in. (61 cm).

PROCESS CYCLE TIME

The process objective is to provide a dip molding system to process carrier frames carrying tools through the following integrated sequence of operations to manufacture the molding.

- **Release Agent Dip.** About 20 seconds are required for this step. The dip requires an adjustable depth with an accuracy of ±0.100 in. (±2.54 mm).
- **Preheat.** Up to three minutes at 250–500˚F (121–260˚C) with an accuracy of ±2˚F (±1˚C) to achieve any desired tool temperature between 200 and 400˚F (93 and 187˚C).
- **PVC Dip.** Up to three minutes. Three dip locations provided with a maximum part dip length of 24 in. (61 cm) and accuracy of ±0.005 in. (±0.127 mm). A total of 10 programmable steps of up, down, and dwell are available to create straight-sided or tapered parts.
- **Quench Dip.** Up to two minutes with an accuracy of ±0.100 in. (±2.54 mm).
- **Strip.** About 15 to 90 seconds at station. Operator controlled, manual air stripping.
- **Cure.** Up to three minutes at 250–500˚F (121–260˚C) with an accuracy of ±2˚F (±1˚C).

- **Tanks:** Six quick change tanks and three tank bases with agitation and level control. Of the six tanks, three are in process and three are in storage.
AUXILIARY EQUIPMENT

Most of the equipment required for a plastic dip molding production unit is contained in the dip molding machine itself: temperature control devices for the plastisol in the tanks on an automatic basis and accurate tool temperature control mechanisms in the oven during the preheat stage and for the moldings during the curing cycle. In addition to actual production equipment, there are auxiliary pieces of machinery and tools for the mixing, production, and secondary operation stages of the dip molding process.

For the mixing stage, a compounding machine is needed to blend the liquids, resins, and additives. De-aeration equipment is needed to remove air and moisture from the mixture. Equipment to accurately add colors and scales is necessary as well. Finally, storage tanks or drums are needed to contain these materials.

Once the material is mixed, various tests must be conducted on each batch of material before it is forwarded to the production floor. Tests such as durometer, specific gravity, and viscosity checks are performed as are burn, tensile strength, and elongation checks.

Other auxiliary items include heating and stripping equipment. Heating equipment is occasionally required to heat the vinyl for ease of processing. Stripping requires hoses and automatic or semi-automatic devices to remove parts from the forms. Some dip molding jobs also require flip carts that flip the jig 90 degrees for easier stripping.

Secondary equipment includes such things as dies to cut holes or slots, and punch presses to make various-sized holes in the finished parts.

Printing equipment is needed to print company names, logos, or instructions on the end product. The most common form of printing is silk screening, done with single or multistation printers. This option is best suited for flat parts. Pad printing works best when printing on an irregular surface. With this method of printing, the image is transferred from an etched plate to the finished part. The third option is roll printing which allows printing around the circumference of a part. The inks used are vinyl formulations and after curing under heat lights, the image is permanently bonded to the part.

Auxiliary equipment is used after the molding is produced and stripped from the mold. For example, some auxiliary equipment is used for the automatic sorting of the various parts manufactured on the machine at the same time. A standard modern machine is capable of producing five different types of moldings at the same time in up to three different colors and/or grades of PVC. Therefore, these items require a process to separate moldings coming in and out of the machine. One way of accomplishing this is to have a pneumatic conveying of each set of moldings stripped from any individual frame into a separate collection area where they are automatically inspected, weighed, and packed. The other main area where auxiliary equipment and special tools will come into play is in the finishing process. This again would range from automatic trimming units to trim off the ends to other equipment suitable for punching and embossing.

Significant advances have been made in standard pad transfer and silk screen printing equipment to give exceptionally fine printing on the dip molding surfaces.

CYCLE TIME AND COST ESTIMATION

With the flexibility and power of modern automatic plastic dip molding equipment, cycle time estimation is now a simple process. The machine described earlier in the chapter is designed to process 40 frames per hour, which means that every 1½ minutes, a full frame of tools ready for stripping is presented at the strip station. The ability to control all parameters enables a wide range of products, including various wall thicknesses, processed within this 1½-minute indexing time. To estimate the cost of the dip molding, bear in mind the factors mentioned. A general cost per hour is calculated for the machine which is then recovered by the 40 frames processed within the hour of working. This completed, it is now a matter of calculating, depending on the overall diameter of the tools employed, how many of these tools will fit into the frame, and hence by dividing that number into the processing cost per frame—a unit cost per molding for processing is derived. Add to this the cost of raw material and the time spent on any ancillary operations such as trimming, punching, printing, etc. This cost estimating method can be reduced to a fairly simple formula whose main factors are the weight of raw material, the overall diameter of the tool, and the time spent on any post-finishing operations.

MATERIAL REQUIREMENTS

The plastic dip molding process in PVC plastisol depends entirely upon the availability of the material known as plastisol and its ability to change from a liquid to a solid in a chemical reaction. This reaction occurs by the application of heat which increases the plastisol’s viscosity. The material is then used to coat a heated tool that gives the part its final form.

Plastisol is a mixture of PVC polymer, a finely divided white powder, mixed into a selection of plasticizers. The choice of these plasticizers and the proportion of each that is put into the mixture determines the physical and chemical properties of the PVC moldings produced by the process. For example, if high-temperature applications are required, plasticizers are chosen that perform well at high temperatures. Conversely, if low-temperature flexibility is a major requirement, different plasticizers are chosen to ensure flexibility at low temperatures (–40˚ F [–40˚ C]). If resistance to oils and solvents is required, other plasticizers are used to incorporate these properties. In addition, the hardness of the finished molding (which may range from 35 Shore-A to 96 Shore-A) is
dependent upon the selection and proportion of plasticizers. For some applications, it is necessary to produce moldings that are foamed PVC; this is obtained by adding chemical foaming agents to the initial formulation.

At the time of mixing the polymers and plasticizers and other smaller proportions of heat stabilizers, pigments, etc., a fairly vigorous chemical reaction takes place in which the viscosity of the mix increases quite rapidly. After a few hours and as long as temperature is maintained below 100˚ F (37˚ C), this viscosity will tend to even out. At this stage, the plastisol may be stored (for a considerable period of time) as long as temperatures are kept below 100˚ F (37˚ C). The viscosity is further increased during the molding process when a hot tool is introduced into the plastisol. The additional heat causes the local thickening and hence the clinging to the tool that upon withdrawal is finally cured in the curing oven to give the full physical and chemical properties of the desired molding. Table 15-1 is a typical specification sheet for the physical and chemical end properties for plastic dip molded components. By using the table, the molder can formulate and manufacture the necessary plastisol to reach target figures given in the specification.

### DESIGN CONSIDERATIONS

Because of the flexibility of the process, the compounding of the raw material, and the ever-improving facilities developed by the dip molding process industry, it is difficult to make firm statements about design considerations. However, consider the following questions at the design stage:

1. Is the application for the molding and the environment suitable for a PVC molding? If the answer is no, then consider other processes because it is very difficult to mold materials other than PVC plastisol by the plastic dip molding technique. Examples of unsuitable environments are: constant operating temperatures in excess of 239˚ F (115˚ C), areas of high-solvent immersion (the solvent will extract the plasticizer from the molding and, when the molding dries out, becomes rigid and brittle), and environmental temperatures below –45˚ F (–43˚ C) the plasticizer will thicken and cause the molding to stiffen.

2. Can the molding be designed with a fairly even wall thickness or must it have accurate and variable wall thickness from part to part of the molding together with accurate external dimensions? If accurate external dimensions or variable and accurate wall thickness throughout the molding are required, the plastic dip molding process is not likely to meet the specification as only a male tool is used without the corresponding female tool as is the case in injection molding.

3. Is the application for a flexible part such as a bellows? If so, what is the maximum size when fully compressed and the maximum size when fully extended?

Another factor to consider in the early design stage is the estimated volume required for the part, as this will help to determine tooling required. Also, such questions as whether printing or secondary operations such as punching holes, etc., will be required. Factors such as appearance and finish should be addressed in the design stage.

One of the big advantages of the dip molding process is that it will produce moldings with an absolutely perfect flash-free exterior surface. There are no mold part lines or injection pressure points as neither of the factors creating such things are present in the process.

The next stage is to produce the design of the finished molding. Usually, the dip molding company can be relied on if it is given the main dimensions of the inside of the molding and parameters such as elongation and compression of bellows. On many occasions, it is better to produce a prototype and, following the necessary testing and trials, produce final product drawings from the prototype.

### TOLERANCES

Because of the wide range of durometers (hardnesses) produced by dip molding—from the very soft to the almost rigid—tolerances will vary depending on the durometer of the finished molding; however, as a general guide, the following holds fairly true.

- Length tolerances will be ±0.060 in. (1.5 mm)
- Wall thickness ±0.010 in. (0.254 mm)
- Drip length from 0.0–0.060 in. (0.0–1.5 mm)
- Variance in durometer ±5˚ Shore-A

---

**TABLE 15-1**

<table>
<thead>
<tr>
<th>Properties</th>
<th>ASTM Test Method No.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durometer Hardness</td>
<td>ASTMD-676</td>
<td>75 ±5 Shore-A</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>ASTMD-412</td>
<td>2000 psi (13.7 MPa)</td>
</tr>
<tr>
<td>Tear Strength</td>
<td>ASTMD-1004</td>
<td>280 psi (1.9 MPa)</td>
</tr>
<tr>
<td>Elongation</td>
<td>ASTM-412</td>
<td>400%</td>
</tr>
<tr>
<td>Dielectric Strength</td>
<td>ASTMD-149</td>
<td>650 V/mil (26 V/micron)</td>
</tr>
<tr>
<td>Maximum Operating Temperature</td>
<td></td>
<td>240˚ F (115˚ C)</td>
</tr>
<tr>
<td>Low-Temperature Flexiblity</td>
<td></td>
<td>–20˚ F (–29˚ C)</td>
</tr>
<tr>
<td>Flammability</td>
<td>FMVSS #302</td>
<td>Self Extinguishing Flame Resistant</td>
</tr>
<tr>
<td>Color</td>
<td></td>
<td>Red</td>
</tr>
</tbody>
</table>
TROUBLESHOOTING

SURFACE IMPERFECTIONS IN THE FINISHED DIP MOLDED PART

- Plastisol contamination in the dip tank due to high humidity, foreign bodies, or airborne contamination—keep all tanks covered completely when not in use. The design of the dip tank and its circulating system should ensure that constant viscosity of the plastisol is maintained and that any foreign matter is filtered out.
- Surface imperfections caused by material damage—change stir speed or technique, screen material near the stir shaft, adjust tank volumes, or increase the viscosity of the mixture by employing a thixotropy agent that prevents material separation.

BELL TOPPING

- Bell topping, a flaring-out effect seen at the open end of a round or square part that causes the partially cured molding to droop off the tool—decrease the tool temperature to an appropriate level, increase the distance between the forms, or recommend to the customer a lower wall gage.

MOISTURE OR AIR

- Moisture or air appearing in the material—add an additive that disperses in the material and reacts with any liquid present, or remove the material from the dip tank and de-aerate.

MATERIAL PICKUP

- Correct amount of material does not stay on the form in the allotted amount of time—heat the material, add thickeners, or increase the dip times.

DRIP

- Excess drip on the closed end of the part—change the design at the end of the tool from a taper to a radius, adjust withdrawal speed, increase the viscosity by adding thickeners, or increase heat which will cause the material to gel faster.

MAINTENANCE

The plastic dip molding process is relatively simple and with the advent of computer-controlled machines, maintenance of the machines is fairly inexpensive. Machine suppliers will give full maintenance procedures with their equipment.

There are two types of maintenance that should be performed on dip molding equipment: preventive and daily or routine. For preventive maintenance, the best strategy is to have a program in which machines are scheduled for downtime every three months, or quarterly, from the time the machine has been put into production.

Based on a quarterly preventive maintenance (PM) program, one should start with a dynamic PM in which a maintenance technician observes the machine in operation. Feedback is also acquired from machine operators to find out how the equipment is running. From this information, a maintenance schedule is made for the dip units.

During these scheduled downtimes, the maintenance technician checks and repairs the equipment. The examination includes the heating of ovens, electrical and pneumatic valves, limit switches, ball screws, DC and AC motors, and conveyers. If problems are discovered during any of these scheduled downtimes and cannot be handled during the allotted time frame, additional downtime must be arranged.

As for daily or routine maintenance, bearings, ball screws, and conveyer chains are oiled and greased. Blower belts are checked for wear or cracking, and the mechanical function of the equipment is observed for failure.

SAFETY

Modern production for the plastic dip molding process is fully equipped with built-in safety equipment to ensure the safety of the operator during production which frequently runs on a 24-hour per day basis. Pay attention to the safety of the operator during post-finishing operations, with particular attention to those machines using cutters to trim or punch the dip molding. Generally speaking, the safety procedures adopted in a normal manufacturing plant in association with the regulations laid down by OSHA are sufficient to ensure the safety of the operator during the plastic dip molding process. On the machine, safety gates and switches are installed so no one can get into the transfer unit on which the jig frame moves. If the gate happens to open, there are switches that stop the machine cycle automatically to prevent damage or injury. There are also safety switches on the unit to protect the machine and keep it from operating when something is malfunctioning. Emergency pause and start buttons are also installed. These are pressed if the entire machine needs to be shut down for any reason.

Dip molding operators, often called dippers, must wear safety glasses and special dipping gloves. The gloves must be able to withstand the heat from the jig frames...ordinary safety gloves are not sufficient. Protective sleeves are also given to dippers to use when stripping parts from the forms. Often, this step involves reaching underneath the frame, which could cause burns to the forearm.

As with most industrial settings, dippers wear earplugs to reduce the noise from the machinery and air hoses. Steel-toed shoes are also required in the event of a jig falling.
SAFETY

Some jig carts are made so that they can flip 90 degrees to allow for easier stripping. If this is the case, the operator must know if the cart is securely locked before stripping begins. This will prevent possible injury from jig movement.

Compressed air is also used when stripping most parts from forms. Operators need to be aware that compressed air is driven at a high velocity and can cause serious damage if used improperly.

IMPROVEMENTS AND NEW DEVELOPMENTS

Three main areas of the process afford continuous improvement and development opportunities: formulations, machine design and controls, and finishing.

FORMULATION

The development of PVC plastisol and new and improved grades of PVC resin, in conjunction with new types of plasticizer and additives, are enabling the formulation of PVC plastisol. These plastisols when produced as dip moldings will create a PVC molding with qualities superior to those available today. It is unlikely that further improvements can be made in high-temperature resistance, due to the inherent temperature restriction of the base PVC. Areas where improvement will be made are increases in durometers, greater resistance to oils and solvents, and improvements in low-temperature flexibility.

Work is currently under way to enable the use of materials other than PVC for the plastic dip molding operation. Under investigation are finely divided thermoplastic powders such as polyethylene and polyvinylacetate, and other materials including the polyurethanes and silicones. All of these will considerably increase the market for the plastic dip molding process.

MACHINE DESIGN AND CONTROLS

Another primary area of development is the improvement in machine design. While the latest machines have highly sophisticated computer controls and extremely efficient high-speed heat transfer ovens, work remains in areas ranging from automatic tool stripping, to creating a variety of different shapes and sizes of molding during the production cycle. When this is accomplished, greater efficiencies will accrue by converting a manual operator to an automatic one.

FINISHING

Finally, development work continues in the finishing of the molding after it is removed from the machine. These finishing operations include such tasks as trimming, punching, printing, postforming, inspection, counting, packing, etc.
FINISHING, FABRICATION AND ASSEMBLY

PREPARATION AND FINISHING

After the part is made, secondary operations are usually required to complete the final product. This includes machining, buffing, and fabrication processes.

MACHINING PLASTICS

Standard machining operations, such as sawing, drilling, turning, and milling, transform the basic shapes of plastics into usable parts. Machining plastics is an economical means of prototyping complex shapes, and low- to medium-production-run parts, as well as secondary operations on molded or formed parts. In addition, some engineering plastics are particularly suited for production-length runs on automatic screw machines. Machining is sometimes chosen over injection molding, even in high-volume production runs that require extremely tight tolerances or zero draft angles.

There are several key differences in machining plastics and metals to obtain high-quality finished parts. Plastic thermal expansion is up to ten times greater than that of metals. Heat loss with plastics is much slower than with metals. Plastics are also more elastic and have lower operating temperatures than metals. Speeds and feeds are adjusted to account for these differences and to avoid melting, tearing, and out-of-tolerance finished parts. Conventional woodworking and metalworking machinery easily provides the desired results. In fact, machining plastics is easier than working with machinable brass or aluminum alloys.

Tooling

Many tools for plastics are similar to those used for machining and finishing metal or wood products. High-speed tools are acceptable for short runs, but tungsten carbide or diamond bit tools are recommended for long runs. Tools are diamond lapped to eliminate nicks and burrs, a major cause of chipping and frictional heat build-up. Stellite or carbide-tipped tools can help reduce resharpening frequency. Cutting edges previously used on metals are reground and honed before cutting any plastic. Thermostats and composites are more abrasive to cutting tools and require diamond-tipped tooling to achieve success.

Adequate cutting tool clearance is essential. Dull tools and/or improper clearance angles cause difficulty because plastic is resilient and elastic. Either problem causes the part to compress, expand outward, and rub against the tool, creating friction and heat.

Measurements must be taken with care. Compression can result in inconsistent measurement, because dimensional measurements can change for up to 24 hours after machining is completed. Optical comparators are useful where other measuring instruments may exert excessive pressure on the part. Heat localization causes expansion in the affected area and can result in overcuts and undercuts, or in drilling a tapered hole. It is best to check dimensions at the expected service temperature; however, temperature compensation suffices if this is not practical.

Some plastics machine easier and faster than others and can hold tighter tolerances due to their physical and mechanical properties. Generally, a high melting point, inherent lubricity, good hardness, and rigidity improve machinability.

Coolants

Thermoplastics may need a coolant to reduce frictional heat and gumming while machining. Heat generated from the machining operation does not dissipate through the workpiece; therefore, the surface finish is affected when temperatures reach the softening point. Excessive heat build-up can also dull the tool. The first choice for cooling is clean, compressed air, since no part contamination occurs and chip removal is improved. Mist spray, water-soluble oil, or light cutting oils are also recommended as coolants in high-speed and automatic operations. A small amount of liquid soap added to water makes an inexpensive but effective coolant. The coolant must be selected with care, as some liquids may craze, crack, or dissolve the plastic.

Sawing

A large number of saws are used to cut plastics. Coping saws, hacksaws, handsaws, and saber saws are used for short-run cutting. Bandsaw blades should have skip-tooth design. The wide gullet in this type of blade allows ample space for plastic chip removal from the kerf. The teeth should have zero rake and some set for optimal performance. Bandsaw blades can be reversed to achieve a zero or negative rake.

The contributors of this chapter are: Scott Bruner, Cadillac Plastic & Chemical Company; Barry David, Associate Professor, Millersville University; Carmen J. Giannandrea, President, Sonic Ease, Inc.; Ted Malinowsky, R & D Director, Norwood Coated Products; Pierre Pottier, President, Laramy Products Company, Inc.; Brian Sheehan, Technical Writer, HGG Laserfare, Inc.; Mike Topping, Market Development Manager, Ashland Chemical, Inc.

The reviewer of this chapter is: Ed Dennison, Accro-Seal, A Kalplas Co.
Circular saw blades should have plenty of set or be hollow ground, to prevent binding in the kerf. The rake angle is zero or slightly negative, and the blade should have a deep, well rounded gullet. The back clearance is about 30°. The preferred number of teeth per inch (millimeter) varies with the thickness and type of material. At least 10 teeth/in. (4 teeth/cm) are used for cutting thin materials. Fewer teeth are needed for cutting plastics greater than 0.25 in. (6.4 mm) thick.

When an extra-fine edge is desired, backing up the material is recommended to reduce chipping, fraying, and delamination of composites. Table 16-1 suggests the number of teeth per inch (mm) for various speeds and material thicknesses. Table 16-2 shows problems and causes for cutting off.

**Drilling**

Standard metal or woodworking drills are used with some success, but special drills designed for plastics produce the best results. Holes drilled in thermoplastics and some thermosets are 0.002–0.004 in. (0.05–0.10 mm) undersized, due to the resilient nature of the material. To offset this, a similarly oversized drill is used.

When drilling plastics, all drills, either twist or half round, should have deep, highly polished flutes (desirable for good chip removal). Very sharp, high-speed drills with a high helix angle (ground to a 70–120° point) and a lip clearance of 9–15° produce the best results. Drill design should specify the web of conventional or narrower dimensions (0.063 in. [1.6 mm]). Rake and point angles are listed in Table 16-3, while the rake angle on the cutting edge is generally zero or several degrees negative. Drill characteristics are shown in Fig. 16-1.

Cutting speeds are affected by the tool geometry, lubricant or coolant, type of plastic, and feed and depth of cut. The cutting speed of most plastic is given in surface feet per minute (fpm) or meters per second (m/sec). These refer to the distance the cutting edge of the drill travels over the time period when measured on the circumference of the cutting tool. The following formula is used to determine surface meters per second:

\[
m/sec = \pi D \times \text{rpm}
\]

and

\[
\text{rev/sec} = \frac{\text{m/sec}}{(\pi D)}
\]

where:

- \(m/sec\) = surface meters per second
- \(\pi\) = 3.14
- \(D\) = diameter of cutting tool in meters
- \(\text{rpm}\) = revolutions per minute
- \(\text{rev/sec}\) = revolutions per second

As a general rule, plastics have a cutting speed of 200 fpm (1 m/sec). Table 16-4 lists recommended speeds for thermoplastics and thermosets by drill size.

The rate at which the drill or cutting tool enters the material is crucial. The distance that the tool is forced into the material each revolution is termed the feed. Feed is measured in inches or mils.

**TABLE 16-1**

<table>
<thead>
<tr>
<th>Material</th>
<th>&lt;0.5 in. - Precision</th>
<th>0.5 - 1 in. Precision</th>
<th>1 - 3 in. - Buttress</th>
<th>3 in. - Buttress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pitch teeth/in.</td>
<td>Band Speed ft/min</td>
<td>Pitch teeth/in.</td>
<td>Band Speed ft/min</td>
</tr>
<tr>
<td>Acetal</td>
<td>10-14</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>2500</td>
<td>2000</td>
<td>1500</td>
</tr>
<tr>
<td>Cast Acrylic</td>
<td>10-14</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>3500</td>
<td>3000</td>
<td>2500</td>
</tr>
<tr>
<td>Nylon (Polyamide)</td>
<td>10-14</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>2500</td>
<td>2000</td>
<td>1500</td>
</tr>
<tr>
<td>PEEK</td>
<td>8-14</td>
<td>6-8</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>3500</td>
<td>3000</td>
<td>2500</td>
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<tr>
<td>PET</td>
<td>10-14</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5000</td>
<td>4300</td>
<td>3500</td>
<td>3000</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>10-14</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>3500</td>
<td>3000</td>
<td>2500</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>8-14</td>
<td>6-8</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4000</td>
<td>3500</td>
<td>3000</td>
<td>2500</td>
</tr>
<tr>
<td>PTFE</td>
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<td>6</td>
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<td>3</td>
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<tr>
<td></td>
<td>3000</td>
<td>2500</td>
<td>2000</td>
<td>1500</td>
</tr>
<tr>
<td>PPS</td>
<td>8-14</td>
<td>6-8</td>
<td>3</td>
<td>3</td>
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<tr>
<td></td>
<td>5000</td>
<td>4300</td>
<td>3500</td>
<td>3000</td>
</tr>
<tr>
<td>Torlon™ (Polyamide)</td>
<td>8-14</td>
<td>6-8</td>
<td>3</td>
<td>3</td>
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<tr>
<td></td>
<td>5000</td>
<td>4300</td>
<td>3500</td>
<td>3000</td>
</tr>
<tr>
<td>Ultem™ (Polyetherimide)</td>
<td>8-14</td>
<td>6-8</td>
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<tr>
<td></td>
<td>4000</td>
<td>3500</td>
<td>3000</td>
<td>2500</td>
</tr>
</tbody>
</table>
limeters. Drill feed ranges from 0.001–0.003 in. (0.025–0.08 mm) for most plastics, depending on the thickness of the material. Drilling feeds of plastics based on nominal hole diameters are listed in Table 16-5.

Forward speed is generally held at 0.005–0.009 in./rev (0.13–0.23 mm/rev). Results of both drilling and reaming are improved if compressed air, water-soluble oil, or mist spray is used to lubricate and cool the material. Drilling with an in-out motion can help to dissipate the heat into the coolant. Depending on the size of the drilled hole, speeds of 500–6000 rpm are recommended. When drilling a series of small holes, a pin is inserted in each hole to prevent distortion. For holes in thin sections, circle cutters, which are drills that cut the circumference and eject a round thin plug of material, are

<table>
<thead>
<tr>
<th>Problem</th>
<th>Common Causes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melted Surface</td>
<td>1. Tool dull</td>
</tr>
<tr>
<td></td>
<td>2. Insufficient side clearance</td>
</tr>
<tr>
<td></td>
<td>3. Insufficient coolant supply</td>
</tr>
<tr>
<td>Rough Finish</td>
<td>1. Feed too heavy</td>
</tr>
<tr>
<td></td>
<td>2. Tool improperly sharpened</td>
</tr>
<tr>
<td></td>
<td>3. Cutting edge not honed</td>
</tr>
<tr>
<td>Spiral Marks</td>
<td>1. Tool rubs during its retreat (use same fall on cam as rise)</td>
</tr>
<tr>
<td></td>
<td>2. Burr on point of tool</td>
</tr>
<tr>
<td>Concave or Convex Surfaces</td>
<td>1. Point angle too great</td>
</tr>
<tr>
<td></td>
<td>2. Tool not perpendicular to spindle</td>
</tr>
<tr>
<td></td>
<td>3. Tool deflecting (use negative rake)</td>
</tr>
<tr>
<td></td>
<td>4. Feed too heavy</td>
</tr>
<tr>
<td></td>
<td>5. Tool mounted above or below center</td>
</tr>
<tr>
<td>Nibs or Burrs at Cut-off Point</td>
<td>1. Point angle not great enough</td>
</tr>
<tr>
<td></td>
<td>2. Tool dull or not honed</td>
</tr>
<tr>
<td></td>
<td>3. Feed too heavy</td>
</tr>
<tr>
<td>Burrs on Outside Diameter</td>
<td>1. No chamfer before cut-off</td>
</tr>
<tr>
<td></td>
<td>2. Tool dull</td>
</tr>
</tbody>
</table>

(Courtesy Polymer Corporation)
often preferred for production. It is normal practice to drill a 0.5 in. (12.7 mm) diameter hole at about 700 rpm with a 0.005–0.01 in./rev (0.13–0.25 mm/rev) feed rate. Hand feeding should be avoided because an uneven feed may cause the drill to grab.

Most plastics are reamed with hand or collar reamers to produce holes with good finish and accurate dimensions. Expansion-type reamers and standard 0.001–0.002 in. (0.025–0.051 mm) oversize speed stub machine reamers are also used. Helical flute reamers are recommended if there is an interruption in the inside diameter. Cuts made with a fixed reamer are often undersized unless at least 0.005 in. (0.13 mm) is removed by the final reaming. With a 0.01–0.02 in./rev (0.25–0.51 mm/rev) feed rate and a 0.005–0.01 in. (0.13–0.25 mm) deep cut, reamer speeds of 250–450 fpm are recommended.

Reaming Teflon™ (PTFE) is not generally recommended. The operation causes the material to compress, especially if the reamer is not exceptionally sharp. Also, PTFE’s elasticity causes holes to “fall in,” creating undersized holes. If necessary, special reamers with a primary relief (clearance) angle can produce accurate holes. The use of an oversized reamer can correct undersized holes. When hole diameter permits, a single-point boring tool is recommended to finish the hole to close tolerance. Table 16-6 lists troubleshooting suggestions for drilling.

### Tapping and Threading

General machine shop tools and methods are used for tapping and threading. Taps are finish ground and have highly polished flutes to avoid overheating the material. Lubricants are used as a coolant and to aid in clearing chips from the hole.

Due to the elastic nature of most plastics, oversized taps are used. These taps are designated as follows:

- **H1**: Basic size to basic + 0.012 mm.
- **H2**: Basic + 0.012 mm to basic + 0.025 mm.
- **H3**: Basic + 0.025 mm to basic + 0.038 mm.
- **H4**: Basic + 0.038 mm to basic + 0.050 mm.

The cutting speed for machine tapping should not exceed 9.8 in./sec (0.25 m/sec). The tap is backed out often to clear chips. Normally, no more than 75% of the full thread is cut into the plastic. Acme and ISO metric are the preferred threads, and sharp V threads are not recommended. The following ISO metric thread designation is defined:

### TABLE 16-4
**Recommended Speeds for Thermoplastics and Thermosets by Drill Size**

<table>
<thead>
<tr>
<th>Drill Size</th>
<th>Thermoplastics Speed r/s</th>
<th>Thermosets Speed r/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>#32 and smaller</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>#17-31</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>#1-16</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>A-C</td>
<td>40</td>
<td>28</td>
</tr>
<tr>
<td>D-O</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>P-Z</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>1.5 mm</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>3 mm</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>5 mm</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>6 mm</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>8 mm</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>9.5 mm</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>11 mm</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>12.5 mm</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

### TABLE 16-5
**Nominal Hole Diameter**

<table>
<thead>
<tr>
<th>Material</th>
<th>Feed in./Revolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetal</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>Cast Acrylic</td>
<td>0.002-0.005 0.003-0.010 0.005-0.012 0.008-0.015 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>PEEK</td>
<td>0.002-0.005 0.002-0.005 0.002-0.005 0.004-0.008 0.004-0.008 0.008-0.012 0.008-0.012 0.008-0.012</td>
</tr>
<tr>
<td>PET</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>Polyolefins</td>
<td>0.008** 0.008** 0.008** 0.008** 0.008*** 0.008*** 0.008*** 0.015****</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>Teflon</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>PPS</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>Torlon</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
<tr>
<td>Ultem</td>
<td>0.007-0.015 0.007-0.015 0.007-0.015 0.015-0.025 0.015-0.025 0.020-0.050 0.020-0.050 0.20-0.050</td>
</tr>
</tbody>
</table>

* All dimensions are inches. Convert to metrics by multiplying diameter times 25.4. Results are in millimeters (mm).

** at 250 rpm, 60° point angle, 15-20° clearance

*** at 250 rpm, 120° point angle, 12-15° clearance

**** at 330 rpm, 140° point angle, 12-15° clearance

---

16-4

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M6 \times 1.00 - 5g6g \quad (3)

where:

- \( M6 \) = metric thread designation
- \( 1.00 \) = pitch
- \( 5g \) = pitch diameter tolerance symbol
  (5 = tolerance grade, \( g \) = tolerance position)
- \( 6g \) = crest diameter tolerance symbol
  (6 = tolerance grade, \( g \) = tolerance position)

For threading thermosets, the percentage of thread is based on the diameters in small sizes and pitch in larger sizes. The following formula is used to determine the percentage of thread:

\[
D = T - n \times 2d \quad (4)
\]

where:

- \( D \) = drill diameter
- \( T \) = outside diameter of thread or tap
- \( n \) = percentage of thread depth desired (expressed as a decimal)
- \( d \) = depth of thread

**Milling, Turning, Routing and Planing**

Carbide and diamond-tipped cutting tools are recommended for thermoplastics in these operations. Surface speeds of 300–500 ft/min (1.5–2.5 m/sec) with feeds of 0.005–0.02 in./rev (0.13–0.51 mm/rev) produce the best results. The tool should have a negative back rake and front clearance. High-speed routing may be used for slotting or gate removal on injection-molded parts. Table 16-7 and Fig. 16-2 show the design of the turning cutting tool. Table 16-8 shows speeds and feeds of a turning operation for various materials.

Tables 16-9 and 16-10 list recommended speeds and feeds for end milling-slotting and face milling, respectively. Table 16-11 shows problems and common causes for turning and boring.

Climb cutting gives a good machined finish on most thermoplastics. In climb milling, the work moves in the same direction as the rotating cutter (see Fig. 16-3). The feed rate on a multiple-edge milling cutter may be expressed in millimeters of cut per cutting edge per second, or in inches of cut per cutting edge per minute. The mill machine feed is expressed in millimeters of table movement per second rather than millimeters per spindle rotation. The following formula is used to calculate the feed in inches per minute or millimeters per second:

\[
\text{mm/sec} = \frac{t \times \text{fpt} \times \text{rev/sec}}{2} \quad (5)
\]

and

\[
\text{in./min} = \frac{t \times \text{fpt} / \text{rpm}}{2} \quad (6)
\]

where:

- \( \text{mm/sec} \) = feed in millimeters
- \( t \) = number of teeth
- \( \text{fpt} \) = feed, in./tooth (mm/tooth)
- \( \text{rev/sec} \) = revolutions per second
- \( \text{rpm} \) = revolutions per minute

**Thermosets Differ from Thermoplastics**

Machining thermosets does not involve the problem of melting from high-speed frictional heat. However, the material has an abrasive interaction with the tool. Diamond-tipped tools are used for optimal surface finish and long tool life. Higher speeds improve the machined finish of thermosets, but the increased speed reduces tool life. When thermosets are machined, powder rather than chips is emitted. This powder is easily removed with a vacuum system. To prevent grabbing and binding, tools should have a zero rake.
Chip Formation

Chip formation is a process that is common to all operations involving a conventional machining action using single or multipoint cutting tools. Chips are generated as the cutting tool penetrates the workpiece and lifts the excess material away as it moves along the work. The tool moves at a given velocity through the work with a cutting action force and feed force. The tool moves into the work with a depth of cut as these forces compress the material ahead of the tool. The area under compression is in a state of plastic deformation, and within this area is the shear zone. Material can fail in the shear zone at an area referred to as the shear plane. This plane typically occurs at approximately a 45˚ angle to the surface. The material moves up and over the cutting tool and breaks off the base material. As the chip is generated, material deformation occurs in the chip and in the base material cutting tool area.

Three types of chips are created during the machining process. The type of chip depends on the material that is cut, speed of cut, rate of feed, depth of cut, tool geometry, and type of cutting tool.

A Type 1, or segmented chip is formed when brittle material is cut or when considerable friction exists between the tool and work. Materials that are hard or have a high resistance to compression and deformation usually produce segmented chips when machined. Machining these materials typically results in exceptional surface finishes. However, tool life is reduced, and the resultant rounding of the cutting edge causes additional pressure on the tool and excess friction. In addition, a dull tool causes a coarse surface finish on the work. Segmented chips can be formed on softer materials by reducing the cutting speed and increasing the feed. Chip breakers are also added to aid the formation of segmented chips.

The Type 2, or continuous chip is formed when easily machinable materials are cut. The chip is formed like a ribbon flowing along the cutting tool. The chip has a smooth surface on the bottom (cutting tool) side and a rounded surface on the top portion.

### TABLE 16-7
Geometry of Turning Cutting Tool

<table>
<thead>
<tr>
<th>Material</th>
<th>Side Relief Angle, Degrees</th>
<th>End Relief Angle, Degrees</th>
<th>Back Rake Angle, Degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetal</td>
<td>4-6</td>
<td>4-6</td>
<td>0-5</td>
</tr>
<tr>
<td>Acrylic</td>
<td>5-10</td>
<td>5-10</td>
<td>10-20</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>3</td>
<td>3</td>
<td>0-5</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>5-20</td>
<td>0.5-10</td>
<td>0-10</td>
</tr>
<tr>
<td>Nylon</td>
<td>5-20</td>
<td>15-25</td>
<td>neg 5-0</td>
</tr>
<tr>
<td>PFTE</td>
<td>5-20</td>
<td>0.5-10</td>
<td>0-10</td>
</tr>
</tbody>
</table>

Fig. 16-2 Turning cutting tool features.
Unlike the segmented chip that curls and breaks off, the continuous chips wind around the tool.

A Type 3 chip, a continuous chip with a built-up edge, is formed when heat and pressure cause the cut material to compress and adhere to the edge of the tool. The chips build up on the work and result in increased friction between the tool and work as temperature increases. The higher temperatures reduce tool life and may distort the work material. The Type 3 chip is an unwanted situation that is controlled through proper cutting speeds, cutting fluids, and tool geometry.

BUFFING PLASTICS

The following description will discuss thermosetting plastics, thermoplastics, and plastic laminates.

Thermosetting Plastics

These materials are readily buffed with low-grease compounds on muslin buffs, operating from 2000 to 5000 surface feet per minute (sfm) (610 to 1525 m/min) for coloring, and from 3000 to 6000 sfm (914 to 1829 m/min) for cutting down. Headed polishing wheels or belts in suitable grit sizes are used to cut molding gates or flash lines. The buff should be full disc, either loose or sewed, depending on the shape of the part. Tripoli is suitable for many jobs, but unfused aluminum oxide powders are recommended for fine luster.

Thermoplastics

These materials are more difficult to buff than thermosetting plastics because they can melt and flow under the heat developed by buffing. Cutting molding gates or flash lines is done carefully, either by a wet belt to prevent overheating or by a soft buff and fine white silica or tripoli in grease binders. Further refinement and blending to the surrounding color may require careful experimentation to discover the right combination of buff and compound. Here the experience of the compound manufacturer is invaluable. Speeds are normally low and the pressure is light when buffing thermoplastics. Buffing speeds are ordinarily between 1000 and 4000 sfm (305 and 1219 m/min).

Plastic Laminates

As far as the surface is concerned, plastic laminates may be handled in accordance with the previous suggestions, depending

<table>
<thead>
<tr>
<th>Material</th>
<th>Speed ft/min</th>
<th>Feed in./tooth</th>
<th>Diameter (in.)</th>
<th>Depth of Cut (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25 in./0.250</td>
<td>0.50 in./0.250</td>
<td>0.75 in./0.250</td>
<td>1 in. 2 in./0.250</td>
</tr>
<tr>
<td>Acetal</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>Cast Acrylic</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>Nylon</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>PEEK</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>PET</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>Polyolefins</td>
<td>8000*</td>
<td>8000*</td>
<td>8000*</td>
<td>8000*</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>PFTE</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>PPS</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>Torlon™</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.008</td>
</tr>
<tr>
<td>Ultem™</td>
<td>270-450</td>
<td>270-450</td>
<td>270-450</td>
<td>300-500</td>
</tr>
<tr>
<td></td>
<td>0.002</td>
<td>0.003</td>
<td>0.003</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Note: Either high positive or high shear geometry cutter bodies are recommended.
* Speed (rpm), and feed (in./min)
CUTTING WITH LASERS

As modern manufacturing develops new and better materials, such as plastics and composites that provide design options not previously available with conventional materials (that is, metals), nonconventional machining methods are often used for processing. In many cases, laser machining is an efficient and cost effective means to that end. A carbon dioxide laser (light amplification by stimulated emission of radiation) can deliver powerful radiation at
a wavelength of 0.6299 in. (16 mm). A laser is used to make intricate holes and complex patterns in plastics. The laser power can be controlled to merely etch the plastic surface or to vaporize and melt it. Holes and cuts made by a laser have a slight taper, but the cuts are clean with a finished appearance. Laser cuts are more precise, and tolerances are held more closely than those made with conventional machining operations. There is no physical contact between the plastic and the laser equipment; therefore no chips are produced. Laser cutting produces a residue of fine dust that is easily removed by vacuum systems. Most plastics can be laser machined. However, some laminar composites can heat up, bubble, and char.

Basics of Laser Processing

A simple analogy to laser processing is burning a leaf with the aid of a magnifying glass. The lens focuses sunlight to a small point, thereby concentrating the energy and burning the leaf.

The major difference between this analogy and the use of lasers is the quality of light that is concentrated. While the sun emits energy over a wide electromagnetic spectrum range, the laser’s energy is concentrated at a specific wavelength.

The word laser is an acronym that indicates light amplification by stimulated emission of radiation. That is the description of the process that produces the beam. A material, referred to as the “lasing medium,” is electrically stimulated to release photons. The emitted photon wavelength depends on the lasing medium’s composition (see Fig. 16-4).

Industrial lasers are dominated by two types, Nd:YAG and CO₂. The names are derived from the lasing medium. The beam produced by the Nd:YAG process results from stimulating a man-made crystal of neodymium yttrium aluminum garnet. The CO₂ is a gas-powered laser whose lasing medium is carbon dioxide gas (see Fig. 16-5). The wavelengths produced by each are 0.042 in. (1.07 mm) and 0.417 in. (10.6 mm), respectively. Because of the thermal absorption properties of many plastics, the CO₂ process is a better choice for these applications.

Laser Processing of Plastics

Advantages. One of the first industrial applications for the CO₂ laser was to pierce holes in baby bottle nipples. Lasers, as well as synthetic material processing, have matured significantly since their industrial infancy 25 years ago. This is primarily because of the ease with which the laser is coupled to automated machining. With proper optics and multiaxis CNC positioning equipment, the modern laser can perform amazing 3D machining (see Fig. 16-6).

The fact that the laser beam can be optically manipulated via robotics is another of its advantages. With 5- and 6-axis machining capabilities, the laser can cut and drill features into a molded part. Furthermore, the laser beam, unlike a drill bit or saw blade, is a tool that does not require changing and does not wear out.

Contemporary machines have the ability to control all axes simultaneously. Some of the more advanced systems can hold tol-
erances closer than 0.005 in. (0.13 mm) while operating at speeds of up to 3000 in./min (76 m/min).

Modern CNC equipment also includes functions that allow integration between a computer and the cutting operations. For example, many advanced systems can run software to produce parts on odd-shaped pieces of scrap material.

Lasers are superior to conventional plastic machining for two reasons. The first of these is speed. A 300-W CO2 laser can slice through a 0.125 in. (3.18 mm) thick PVC at 140 in./sec (3556 mm/sec). The same laser can cut through a similar-thickness piece of acrylic at 72 in./sec (1829 mm/sec). The second advantage is a reduction in secondary operations. Because the laser vaporizes material rather than chopping away in the manner of conventional cutting or drilling, there are no adverse effects around the edges (that is, fraying or molten build-up). In most cases, especially with thermoplastics, the cut or drilled edge is left smooth, as if it were fire polished. Often the only secondary operation is to wipe away the soot from the vaporized material.

Drilling. There are two laser-drilling strategies. One is burst drilling, where the laser simply punches holes in the material, and is analogous to a sewing machine needle without thread (see Fig. 16-7). The other strategy is trepanning, where the laser cuts a circle in the material.

An early and successful example of laser drilling was the production of aerosol spray nozzles, which require varying hole sizes. However, it is difficult to make adjustments while in production. By drilling, there are no adverse effects around the edges (that is, fraying or molten build-up). In most cases, especially with thermoplastics, the cut or drilled edge is left smooth, as if it were fire polished. Often the only secondary operation is to wipe away the soot from the vaporized material.

Drilling. There are two laser-drilling strategies. One is burst drilling, where the laser simply punches holes in the material, and is analogous to a sewing machine needle without thread (see Fig. 16-7). The other strategy is trepanning, where the laser cuts a circle in the material.

An early and successful example of laser drilling was the production of aerosol spray nozzles, which require varying hole sizes. However, it is difficult to make adjustments while in production. By using the laser as a secondary process, a 0.06 in. (1.5 mm) diameter hole can be changed to a 0.1 in. (2.5 mm) hole with a simple program change, change in focal point, or power adjustment.

A more recent marriage between plastics and laser processing is the production of laminar flow panels for the aerospace industry. These panels are designed to reduce drag and increase lift on aircraft wings. High-strength, low-weight plastics are an obvious choice for these designs. Laser-drilled holes typically cause little, if any, damage to the surrounding material. As a result, natural wear and tear is minimized at the outset.

Another advantage of using this method is the speed and accuracy with which the laser drills holes. Modern systems can perform burst-drilling tasks on the fly. By adjusting the laser’s pulse rate, the frequency and duration of the laser shutter’s opening and closing, and the rate of travel, a properly equipped workstation can accurately, quickly, and efficiently produce a laminar flow pattern.

Cutting. Modern laser systems with four or more axes promise a bright future for laser processing of premolded plastic objects. Ring and helical removal, transitional milling techniques, and other finishing processes are performed by contemporary CNC positioning equipment.

Because there is no physical contact with the processed part, it is possible to cut and drill off-normal to the surface. Holes are drilled and patterns can be cut at angles or on curves without fear of the tool slipping and gouging the part. The same tool (the laser beam) cuts all patterns and drills all holes, and there is no need to change bits or blades. All changes are simple positioning or parameter adjustments that are made by the CNC controller while the work is in process.

Lasers are also useful for selective material removal, such as wire stripping. Conventional methods can often bend, break, or otherwise damage the strand beneath the coating. One example of this is a double strand of coated 0.009 in. (0.23 mm) wire, used as a sensor in the automotive industry. The coating is a mere 0.001 in. (0.038 mm) thick. Using a low-power CO2 engraving laser, the coating is successfully removed without damage to the underlying copper wire.

Disadvantages. A serious concern about cutting plastic with lasers is the safety factor. Some plastics, especially polycarbonates, release toxic gases when vaporized. For these materials, it is necessary to either completely enclose the workstation or install a vacuum hose in close proximity to the cutting area to ensure adequate ventilation.

Another disadvantage to laser processing is that the beam begins to diverge soon after the focal point. This results in energy dissipation that is proportional to the divergence area. The farther away from the focal point, the higher the loss in efficiency and quality. Because of this, materials with thicknesses in excess of 0.375 in. (9.5 mm) are usually not chosen for laser processing with systems under 1500 watts.

Stereolithography

An advantageous coupling of the laser process and plastics is for purposes of rapid prototyping, particularly stereolithography. This is a modeling process that involves curing layers of plastic with a laser beam. The process begins with a computer-aided design (CAD) program which slices a prototype design in layers. Each of these layers is in turn translated into x- and y-axis movements and fed into a CNC controller, which is connected to a specialized laser workstation (see Fig. 16-8).

The workstation includes a CNC-driven servomotor beam-positioning mirror, a low-power, visible-light laser system, and a liquid plastic container (a polymer acrylate thermostet photocurable resin) that has a movable platform. The platform is raised toward the top of the vat containing the liquid plastic, just below the surface of the resin. The laser then traces the path in the shape of the first or bottom slice from the CAD program, curing the resin. Next, the platform is lowered slightly, and the next slice is cured to the first. The process is repeated until the model is complete (see Fig. 16-9). The laser completes the plastic cure from 60–90%. The final curing takes place in a light oven.

A similar process uses a laser to sinter mixtures of powders containing polyvinyl chloride, nylon, and polycarbonates. The laser
fuses each successive layer, with the unaffected material left behind to act as support for the unfinished layers. This process is used for applications that range from engine block design to brain surgery.

Assembly methods include high-temperature air welding, ultrasonic welding, electromagnetic welding, and fasteners.

![Fig. 16-8 Stereolithography laser system.](image)

![Fig. 16-9 Cone created with stereolithography.](image)

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**ASSEMBLY**

**PLASTIC WELDS**

High-temperature air welding in this section will include a discussion of equipment, accessories, basic rules and techniques, types of welds, special considerations, and inspection. The welding of plastics is similar to the welding of metals. Both methods use a heat source, welding rods, and give similar types of finished welds such as butt welds, fillet welds, and lap joints. Joints are beveled or otherwise prepared in much the same manner as for metal welding, and the joints are similarly evaluated for strength. Due to differences in the physical characteristics of each material, however, there are notable differences between welding thermoplastics and welding metals.

When welding metal, the rod and the parent material are made molten and puddled into a joint that hardens into a weld as it cools. Unlike metals that have a sharply defined point at which they become molten, thermoplastics have a varying, but fairly wide, range between the temperature at which they soften and the temperature at which they char and burn (in the case of PVC, for example), or melt (in the case of the polyolefins and others). Unlike metals, thermoplastics are poor heat conductors and are therefore difficult to heat uniformly. Because of this, the surface of a plastic welding rod or of the parent material chars or burns before the material below the surface becomes fully softened. The decomposition time at welding temperature is shorter than the time required to completely soften many thermoplastics for fusion welding. The plastics welder, therefore, must work within a much smaller and more accurate temperature range than the person welding metals.

Because the plastic welding rod does not become completely molten and appears much the same before and after welding, a plastic weld may appear incomplete to one accustomed to metal welding. The explanation is simple: since only the outer surface of the rod has become molten and the inner core has remained hard, the welder is able to exert pressure on the rod, forcing it into the joint to create a permanent bond. When heat is removed, the rod reverts to its original form. Thus, even though a strong permanent bond is obtained, the appearance of the welding rod is much the same as before the weld was made, except for molten flow patterns on either side of the weld bead.

Technically speaking, all thermoplastics are weldable. Their weldability is governed only by the extent of their melting range; those with the widest melting range are easiest to weld. Today’s most widely used industrial thermoplastics are PVC, high-density polyethylene, and polypropylene.

The following essentials improve plastic welds:

- Correct temperature.
- Correct pressure.
- Correct angle.
- Correct speed.

**Plastic Welding Equipment**

Modern plastic welding torches are electrically heated but can be divided into two broad categories. The first is the group of torches intended for in-shop use, and they are connected to a...
source of compressed air or a container of inert gas, preferably nitrogen. (Note: never connect a plastic welding torch to a flammable gas source or to oxygen.) These shop torches are available with several combinations of controls and accessories.

The second category is the group of plastic welding torches designed for field use, where compressed air is not readily available. These are of two types: a unit consisting of a standard shop torch but with a portable electric air compressor built into the carrying case; and a self-contained unit, where a small motor built into the handle runs a fan and passes a stream of ambient air over the element. These units are lightweight and fairly economical, but due to their design, are bulky to use.

All torches heat the air by means of electric heating elements located in the torch barrel, and therefore all units require electricity. The temperature range of the torch varies according to the wattage of the element in the unit at the time, but given the range of elements from 250–750 W, the total heat range is from 350–1100˚ F (177–593˚ C).

**Accessories for Plastic Welding Torches**

Several accessories are used with plastic welding torches.

**Round tip.** This, the most basic tip in plastic welding, is usually provided with the torch. It is used for hand welding of plastics, which is mostly for small or confined work, or when the weld has an intricate configuration.

**Tacking tip.** This tip is used for tacking two thermoplastic parts together. The primary advantage of tacking prior to welding is that a neater and stronger weld is obtained. Tacking also eliminates entrapped air. (Note: never weld without tacking.)

**Speed-welding tip.** Speed tips come with feed tubes of various sizes and shapes to accommodate different welding rods. These tips have two tubes feeding hot air from the barrel. The lower one preheats the sheet while the upper one, to which the feed tube for the rod is welded, preheats the rod and heats it at the weld point. These tips allow welding speeds of about four times that of hand welding. They are ideal for long, straight, flat welds and are suitable for welding pipes of at least 4 in. (102 mm) in diameter.

**Autoseal tip.** This tip is used for welding both flat and corner flexible strip. It imparts pressure to the strip by means of a shoe and preheats both the strip and the base material, thus increasing the welding rate.

**Gas and power control unit.** This unit, commonly known as a nitrogen saver, reduces the use of costly inert gas by automatically switching from nitrogen to compressed air when the torch is not in use and is resting in its bracket. It also has a pressure-sensitive switch that shuts off power to the unit if either the nitrogen or compressed air pressure drops below a certain point. This prevents burning out elements.

**Related Equipment and Accessories**

There are a number of contact-welding tools, also known as fusion-welding tools. The principle is that the two pieces that are joined are pressed against a heated tool until the edges start to melt. The tool is withdrawn and the edges pressed together. The tool is usually PTFE coated to prevent sticking. The heated tool is not coated but accepts a variety of coated dies in pairs (one male and one female) of various metric or IPS sizes. The pipe end is inserted in the female die, while the fitting is slipped over the male die. When the inner surface of the fitting and the outer surface of the pipe are starting to melt, they are removed from the tool, and the pipe is quickly pressed into the fitting. This is mostly used with polyethylene and polypropylene pipes.

There are also tools designed to heat plastic sheets so they can be bent at angles. One such tool consists of two bars regulated by one control so that both are always at the same temperature. The control is set to obtain the proper softening temperature for the material that is bent. The sheet is inserted between the bars for a period determined by the thickness of the sheet and then removed and bent at a different station. It is held at the desired degree of bend until the sheet has cooled enough to hold the bend.

Another system has only one bar managed by a similar control. Attached on the bar is an extruded aluminum “sword” with a 90˚ edge. The sword is placed on the desired bend line and allowed to melt through two-thirds to three-quarters of the material. At this time, the sword is removed, the sheet is bent, and the two molten edges fuse. This method makes a near-perfect right-angle bend with a radius but is only suitable for polyethylene and polypropylene. The bar method works on all thermoplastics, but it makes a bend with a radius that is three times the thickness of the sheet.

Spark testers are useful in testing for leaks. They consist of a portable transformer, which takes standard 110-V current and transforms it to high-voltage, low-amperage current emerging from a probe. If a grounded conductive material is placed behind the weld and the probe is passed on the outside, a blue haze is visible if the weld is whole. If, however, a bright spark is seen going through the material, there is a “holiday” in the weld at the point where the spark was generated.

A welding rod is also considered an accessory. It is always of the same material as the material that is welded. Welding rods for most common plastics are readily available, but rods for the less-common plastics are often difficult to find.

**Basic Rules for Welding Plastics**

There are several rules that facilitate welding plastics:

- If using compressed air, a clean air supply is essential. Moisture in the air short-circuits and burns out the torch heating element. Oil in the air line can contaminate the weld and eventually ruin the element. If using nitrogen, “dry” nitrogen is required.

- Air or nitrogen is run through the torch before turning on electricity. Air is also run through for 5 minutes after turning the power off. This cools the element and prolongs its life.

- Only three-wire grounded systems are used.

- The temperature of the welding gas is determined by the element size used and, within that element’s range, by the flow of air over the element. The lower the pressure, the higher the temperature used. The normal operating pressure range of an element is 2.5–3.5 psi (17–24 kPa). If higher or lower pressures are needed to obtain the correct temperature, the element is changed. The operating temperature is determined with a thermometer held about 0.25 in. (6.4 mm) from the end of the welding tip.

- The torch is never grasped by the barrel or the tip even if it appears that it is not actuated.

- The instructions that come with a particular brand of torch must be read before using it for the first time.

**WELDING PLASTICS**

Although general procedures for welding plastics are similar to welding metals, subtle differences are apparent. Since the quality of the finished weld is directly proportional to the welder’s skill, the beginner should first become familiar with thermoplastics and their properties.
Types of Welds

Although welding procedures differ, the same basic types of welds are used by metal and plastic welders. Some of the more common plastic welds are described below.

Butt welds, edge welds, and corner welds. To prepare material to weld butt joints (butt welds), edge welds, and certain types of corner welds, the edges of both pieces are beveled using a saw, jointer, sander, or block plane. A feather edge is not required, but a 0.03 in. (0.8 mm) flat should be retained. The two pieces, when placed together, should now have a “V” groove with a 60˚ angle. Most shops operate at 50–55˚ to reduce the number of passes.

To create a good bond in the finished weld, the two joined surfaces must be free of all dirt, dust, oil, moisture, and loose particles. Solvents are not used to clean beveled edges since they can soften the edges, causing a poor weld.

The two pieces are then placed together. If the pieces will be tacked, a root gap of 0.016–0.031 in. (0.41–0.79 mm) is retained between the pieces. A root gap is not retained when using the tacking tip for the tacking operation.

Lap welds. Lap welding requires little preliminary preparation, since the joined pieces are placed on top of each other. As with the welds previously described, surfaces are clean and free of all dirt, dust, oil, moisture, and loose particles. To hold pieces firmly for welding, “C” clamps are used or a tack weld is applied.

Fillet welds. Fillet welds and lap fillet welds require little preliminary preparation. The joined pieces are clean and free of dirt. Jointed pieces are held securely by using clamps, blocks, tack welds, or by hand. When making fillet welds with one or both edges beveled, a root gap of 0.016–0.031 in. (0.41–0.79 mm) is required if a tacking tip is not used.

Rosette welds. Rosette welds are similar to lap welds. Little preliminary preparation is required other than cleaning and drilling the holes to the desired size and position. A hand or electric drill is used for this purpose.

Before back-welding cemented joints, the cement is allowed to cure for at least six hours. All cement residue is removed with a knife, sandpaper, emery cloth, wire brush, or router before welding.

Tacking

Just as in metal welding, tacking is a method of superficially joining pieces to hold them in position for final welding. With plastic welding, this is accomplished either by using a small-diameter rod or a tacking tip on the operator’s torch.

Rod tack welding is similar to hand welding except that the use of a smaller welding or tacking rod allows greater welding speed.

The tacking tip is a pointed shoe that is attached to the welding torch and heated with gas from the torch. By applying pressure on this pointed tip, material softened by the heat is fused. Advantages of the tacking tip are primarily its speed and neatness. Use of the tacking tip also eliminates a potential source of weakness in completed welds caused by rod tacks left in place. Most importantly, jigs and clamps are not necessary, and one hand is free to hold the work together.

The pointed tacking tip is held at an angle of approximately 80˚ and placed directly on the tacked joint. Then, as if it were a pencil, the operator slowly draws a line along the joint.

When welded pieces are large or unwieldy, short tacks are often made at strategic points, such as corners, at regular intervals. These short tacks help to hold the pieces in place. With the partially tacked pieces in the proper position, the tacking tip is drawn around the entire joint, creating a continuous seal. The resultant tack holds large pieces of material sufficiently so they can be handled and moved without coming apart. If the welder wishes to reposition the pieces, the tack weld can be broken and remade.

The welder is now ready to make a completed weld. Since the pieces are held in place by the tack weld, no jigs or clamps are necessary, and the operator has both hands free.

Remember that tacking produces only a superficial weld with little strength. It is not considered a completed weld.

Hand Welding

In welding plastics, materials are fused by a proper combination of heat and pressure. With the conventional hand-welding method, this combination is achieved by applying pressure to the welding rod with one hand while, at the same time, applying heat to the rod and base material with hot gas from the welding torch. Successful welds require that both pressure and heat are kept constant and in proper balance. Excessive pressure on the rod can stretch the bead and produce unsatisfactory results. Too much heat chars, melts, or distorts the material.

Preparation for welding. With the torch ready for welding (tip inserted and welding gas and current turned on), the temperature is checked by holding the bulb of a thermometer 0.25 in. (6.4 mm) from the end of the tip. When welding PVC, the correct temperature is easily determined by holding the tip 0.25 in. (6.4 mm) from the material and slowly counting off four seconds. At the count of four, the material should show a faint yellowish tinge, and the temperature is adjusted accordingly.

The proper filler rod is selected. Using a sharp knife or cutting pliers, the filler rod is cut to the desired length (slightly longer than the length of the intended weld) at an angle of 60˚. This provides a thin wedge, which is easily heated and facilitates starting the weld.

Starting the weld. While holding the torch with the tip 0.25–0.75 in. (6.4–19.1 mm) from the welded material, the starting area on the base material and rod is preheated until it appears shiny and becomes tacky. The rod is held at a 90˚ angle (for polyethylene and fluorocarbons, the angle is 45˚) to the base material and moved up and down slightly so that it barely touches it. When heated sufficiently, the rod sticks to the base material. To maintain the correct balance of heat, the torch is now moved in a vertical fanning or weaving motion to heat both the rod and base material equally. At the same time, the rod is pressed into the material with a slight downward pressure (approximately 3 lb [1.4 kg]). When a molten wave becomes evident where the rod meets the base material, the rod should bend and begin to move forward. The overheated rod becomes rubbery and makes the application of even pressure virtually impossible; overheated base material chars or melts, causing an unsatisfactory bond.

When welding plastics, a good start is essential. Welds most frequently fail at the starting point. For this reason, starting points on multiple-bead welds are staggered whenever possible.

Once the weld is started, the torch should continue to fan from the rod to the base material with approximately two full oscillations per second. Because the welding rod has less bulk than the base material, it heats more rapidly. To compensate for this bulk difference, the arc of the fanning motion is concentrated on the base material. Differently, the arc of the fanning motion is concentrated on the base material approximately 60% of the time when using 0.125 in. (3.2 mm) rod and approximately 40% of the time when using 0.156 in. (4.0 mm) rod. The fanning motion should heat 0.5 in. (12.7 mm) of the welding rod and 0.375 in. (9.5 mm) forward of the rod on the base material. Average welding speed is 4–6 in./min (102–152 mm/min).

Correct angle of the welding rod. When welding PVC, the rod is held at an angle of 90˚ to the base material. Although greater welding speed can be obtained by leaning the rod past the perpendicular (away from the direction of welding), the resultant stretch-
ing of the rod produces checks and cracks in the finished weld upon cooling. To exert sufficient pressure on polyethylene rod, it is fed into the weld bed at a 45° angle to the direction of the weld, with the upper part of the rod looping away from the direction of the weld. For fillet welds, the rod is held so that it bisects the angle between the two welded surfaces. In most cases, this is a 45° angle. It is essential to preheat all surfaces that are joined. When butt welding PVC pipe, the welding rod should always point toward the center of the pipe to prevent stretched welds.

Feeding the rod. In the welding process, the rod is eventually used up, and the welder must renew his grip on the rod. Unless this is performed carefully, the sudden release of pressure may cause the rod to lift from the weld bed, causing air to become trapped under the weld, resulting in a weak weld. To eliminate this possibility, the fourth and fifth fingers are placed on either side of the rod to maintain pressure while repositioning the thumb and forefinger. If this movement is too difficult, the third or fourth finger is placed on top of the already deposited bead (it is cool since only the bottom surface is exposed to heat), and the rod is held down while repositioning the thumb and forefinger. Normal pressure can then be resumed. When using the latter method, the torch is turned away from the working area to eliminate the danger of burning fingers.

Finishing the weld. When a weld is terminated, all forward motion is stopped, and a quick application of heat is directed at the intersection of the rod and the base material. Heat is removed, and downward pressure is maintained on the rod for several seconds. The rod is allowed to cool for several seconds to prevent any possibility of the bead pulling from its bed. Downward pressure is then released, and the rod is twisted with the fingers until it breaks. If a continuation weld is made, the deposited bead is terminated by cutting at an angle of 30° with a sharp knife or cutting pliers after allowing the rod to cool for several seconds under pressure. When joining one rod to another in a continuation weld, cut the new rod at a 60° angle. Heat the new rod surface, and weld on the angle of the old rod so that joined pieces appear as one. Welds are never spilled by overlapping side by side. When terminating welds, as in the case of pipe welding, weld is always lapped on top (not beside) of itself for a distance of 0.375–0.50 in. (9.5–12.7 mm).

When welding PVC, a good finished weld appears comparatively uniform with no brown or black discoloration. If insufficient heat is applied, the rod appears in its original form and is easily pulled away from the base material. Small flow lines or waves on either side of the bead are evident on a satisfactory weld. In the case of polyethylene, polypropylene, and chlorinated polyethylene, an overheated weld produces a flat bead with oversized flow lines. Polyethylene and polypropylene do not char or discolor when overheated but become transparent, much like hot candle wax.

When welding heavy material sections, multiple beads are welded in the joint, one on top of the other. Caution must be exercised when running these multiple beads so that the mass does not become overheated and produce a bad weld. When back-welding a cemented pipe, all cement at the joints is removed. When welding pipe, the 90° angle is maintained at all times between the rod and the base material. To decrease the number of welding runs when laying multiple beads, a large-diameter rod (0.156–0.188 in. [4.0–4.8 mm]) is used. As a general rule, a minimal number of beads is used. The finished weld should always overlap the beveled edge of the base material.

**Speed Welding**

High-speed welding incorporates the basic methods used in hand welding. Its primary difference lies in the use of a specially designed high-speed tip, which enables the welder to produce more uniform welds and work faster. As with hand welding, constant heat and pressure are maintained.

**Principles.** The increased rate of welding in high-speed welding is made possible by preheating both the welding rod and the base material before the fusion point. The rod is preheated as it passes through a tube in the speed-welding tip. The base material is preheated by hot air passing through a vent in the tip ahead of the fusion point. A pointed shoe on the end of the tip supplies pressure on the rod and eliminates the need for the operator to apply pressure. At the same time, it smooths out the rod, giving a more uniform appearance to the finished weld.

**Advantages.** In high-speed welding, the conventional two-handed welding method becomes a faster and more uniform one-handed operation. Once started, the rod is fed automatically into the preheating tube as the welder is pulled along the joint. High-speed tips are designed to provide the constant balance of heat and pressure necessary for a satisfactory weld. Average welding speeds are about 40 in./min (1016 mm/min) for PVC and 24–30 in./min (610–762 mm/min) for polypropylene.

Starting the weld. With the high-speed torch held like a dagger and the hose on the outside of the wrist, the tip is brought over the starting point about 3 in. (76 mm) from the material so the hot air does not affect the material. The welding rod is inserted into the preheating tube, and the pointed shoe of the tip is immediately placed on the material at the starting point. The welder is held perpendicular to the material, and the rod is pushed through until it stops against the material at the starting point. If necessary, the torch is lifted slightly to allow the rod to pass under the shoe. Keeping a slight pressure on the rod with the left hand and only the weight of the torch on the shoe, the torch is pulled slowly toward the operator. The weld is now started. Once the rod is inserted in the preheating tube, the remaining steps in the procedure must follow in rapid sequence to prevent scorching or melting of the rod.

**Continuing the weld.** In the beginning of travel, the rod is helped along by pushing it into the tube with slight pressure. Once the weld is properly started, the torch is brought to a 45° angle, and the rod feeds automatically without further help. As the torch moves along, visual inspection indicates the weld quality. When welding PVC, brown or charred rod edges indicate a poor weld caused by welding too slowly. If the rod has been softened by overheating, it stretches, breaks, or flattens out. When welding polyethylene or polypropylene too slowly, the rod flattens out, and the transparent flow lines on each side of the bead appear oversized. Absence of flow lines indicates insufficient pressure or an excessive welding rate.

The angle between the torch and the base material determines the welding rate. Since the preheater hole in the speed tip precedes the shoe, the angle that the welder makes with the welded material determines how close the hole is to the base material and how much preheating is occurring. As a result, the torch is held at a 90° angle when starting the weld and at a 45° angle thereafter. When a visual inspection of the weld indicates an excessive welding rate, the torch is returned to the 90° angle temporarily to slow the welding rate. It is then gradually moved to the desired angle for the proper welding speed. The welder is held so that the preheater hole and the shoe are always in line with the direction of the weld, so that only the material in front of the shoe is preheated. A heat pattern on the base material indicates the area that is preheated. The rod is always welding in the center of that pattern.

**Finishing the weld.** Once started, speed welding is maintained at a fairly constant pace. The torch cannot be held still. To stop
welding before the rod is used up, the torch is brought back past the 90˚ angle, and the rod is cut off with the end of the shoe. Stopping the weld before the rod is used up is also accomplished by pulling the speed tip off the remaining rod. When cutting the rod with the shoe, the remaining rod must be removed promptly from the preheater tube. Rod that is not removed promptly chars or melts, clogging the tube and requiring cleanout. This is accomplished by inserting a new rod in the tube.

A good speed weld in a “V” joint has a slightly higher crown than the normal hand weld and more uniformity. It should appear smooth and shiny, with a slight bead on each side. For best results and faster welding speeds, the shoe on the speed tip is cleaned occasionally with a wire brush to remove any residue that might cling to it and create drag on the rod.

Work limitations. The modern high-speed plastic welding torch is designed primarily to meet the needs of production-type welding. Since increased speeds are necessary to procure good welds, the high-speed welding torch is not suited for small, intricate work. At first, the position in which the welder is held may seem clumsy and difficult. However, practice and experience soon enable the operator to successfully complete all welds made with a hand welder, such as but, “V”, corner, and lap joint welds. Speed welds are made on circular as well as flat work, and on all outside welding of hoods and ducts. In addition, inside welds on tanks can be speed welded unless the working space is too small to manipulate the torch.

Welding Flexible Thermoplastics and Tank-lining Materials

In addition to many structural applications, thermoplastics are used extensively for lining nonplastic structures and vessels. Thermoplastics used as lining materials are gradually replacing previous lining with lead, brick, tar, rubber, or glass. The fabrication of thermoplastics for complete structures and vessels is necessarily restricted due to strength requirements and costs. However, their use as a noncorrosive lining material has opened many new fields. Using special adhesives, thermoplastic linings are applied to metal, wood, or concrete. The lining seams are welded with strip or round rod, providing a continuous leakproof surface. The end product provides both maximum protection against corrosion and the necessary rigidity. These are advantages that the materials by themselves could not provide.

More recently, new types of lining materials have become popular. These are known as geomembranes and can be of woven synthetic, or in some cases, relatively thin flexible polyethylene. The latter is used primarily for lining landfills and is always welded to prevent leaks.

Types of lining materials. Thermoplastics used for welded liners fall into three categories: rigid, flexible, and a combination of both. The rigid-type linings use either a thin “foil” of thermoplastic sheet that is cemented to a vessel and then welded, or a self-supporting thermoplastic container, which is welded to fit the lined vessel, and upon completion, dropped inside. This “drop in” liner may be bolted to the vessel. Outlets are welded in after the liner is in place. Rigid strip or round rod is used for welding.

Plasticized PVC sheet that is 0.094–0.250 in. (2.4–6.4 mm) thick is used for flexible linings. This sheet is cemented to the inside of a vessel, and the seams are welded with flexible flat or contoured corner strip. A PVC sheet, which is a combination of rigid and flexible laminated sheets, is the third type of thermoplastic lining available. The flexible side is cemented to the vessel, and the rigid side is exposed to the corrosive liquids. All welding is done on the rigid inner side of the sheet with either rigid strip or round rod.

The thin, flexible PTFE materials belong to the first category. The fact that they are difficult to bond, difficult to weld, and very expensive has restricted their use, but in high temperatures and high-corrosion applications, there is no substitute for them.

All three types of linings are used extensively in plating and storage tanks, vats, sewerage systems, pipelines, and ventilating systems. The techniques for welding with rigid round rod were previously outlined.

Types of welds. There are four basic types of strip welds in lining work: butt strip weld, corner strip weld, outside corner strip weld, and lap weld. These welds are made with strips extruded from material similar to the sheet.

Butt strip weld. This weld joins strips on flat surfaces using a flat strip 0.625–1.0 in. (15.9–25.4 mm) wide and 0.094 in. (2.4 mm) thick with beveled sides. The sheets are not beveled on the butted edges unless a root weld with round plasticized rod is used. Such a root weld lends strength to the joint and ensures complete leak tightness. Welding is done with a flat tip and strip feeder.

Corner strip weld. This type of weld joins sheets where they meet on inside corners. Corner strip is from 0.625–1.0 in. (15.9–25.4 mm) wide on top and from 0.25–0.50 in. (6.4–12.7 mm) wide on bottom. These strips vary in thickness from 0.375 in. (9.5 mm) and up, and the sides are shaped at a 45˚ angle with the top of the strip. Welding is done with a “V” tip and strip feeder.

Outside corner strip weld. This weld joins sheets that come together on outside corners, as in lining the outside of a tank. Each leg of the strip is 0.50 in. (12.7 mm) wide and 0.094 in. (2.4 mm) thick. Welding is done with a “V” tip only.

Lap weld and lap strip weld. The lap weld joins sheets on a flat surface without the use of a strip. The meeting surfaces of the joint are heated using a round or flat tip. When these surfaces become tacky, they are pressed together with a roller, causing a weld. This type of weld is not recommended for tank work, since it leaves an air pocket under the uppermost sheet; this can cause swelling when heated. The lap strip weld is a better method of lap welding and is often used for joining inner liners of pipe sections. The two meeting surfaces are cemented and sealed by welding a 1.0 in. (25.4 mm) wide step-shaped strip. Welding is done with a flat tip with a shaped roller.

Preparing surfaces for lining. Metal. Metal surfaces are sandblasted or grit blasted to remove rust, scale, coating, grease, and moisture. Weld spatter is removed and rough welds ground smooth. After blasting, all surfaces are primed.

Concrete. Concrete surfaces must be clean, dry, and free of loose particles and foreign matter. All lined surfaces are etched with hydrochloric acid solution and washed down with water. The surface is then dried thoroughly before applying adhesives. The finished surface is roughened to support good adhesion.

Welding Flexible Thermoplastics

Plasticized PVC sheet. The sheet is cleaned with an approved solvent to remove all dust and grease. Sheets are preheated to 100˚ F (38˚ C) before welding. The starting end of corner strips is scarfed at a 30˚ angle on the bottom. Welding strips, which are rigid PVC, are either tacked or cemented in place and then back-welded. Refer to manufacturers for application instructions.

FEP fluorocarbon. Bonding to metal is achieved with special adhesives or by heat pressing without the use of adhesives. The material is heated to approximately 550˚ F (288˚ C) and pressed...
on the metal at 500–2000 psi (3.4–13.8 MPa). Preparation for welding and strip must include positive ventilation away from the work area, since toxic fumes are emitted when the material is brought to the melting point.

Welding procedures for plasticized PVC. When hand welding flat and corner strips, the flat strip is taken with the free hand. With a slight amount of pressure directed toward the base material, the strip is held perpendicular to the joint. A fanning motion is begun with the flat tip so that the strip and base material are heated equally. While the materials begin to flow at the fusion point, the sides of the strip, and along the joint of the base material, the welding tip is held 0.25–0.50 in. (6.4–12.7 mm) from the work.

Hand welding of plasticized corner strip is similar to the method described with the flat strip except that a “V” tip is used in place of the flat tip. The “V” tip produces a heat pattern that conforms to the shape of the corner strip and base material. The fanning motion of the welder is once again used while the strip is pressed into the corner at a 45˚ angle. Visual inspection of the weld as it progresses should reveal flowing material along the sides of the strip and at the fusion point.

Hand welding of both flat and corner plasticized strip is facilitated by the use of a strip feeder, which passes the strip through a hollow handle and under a roller. The use of this tool allows more uniform pressure on the welding strip, resulting in a more consistent weld. In addition, the strip feeder removes the operator’s hand from the heat source.

Semiautomatic welding of plasticized vinyl joint strips. At the start of the weld, the torch is held vertically or at a 90˚ angle to the work. The end of the tip is placed approximately 0.50 in. (12.7 mm) beyond the starting point on the base material. Triangular or flat strip is fed into the depression behind and under the roller used in the tip. The strip is immediately pushed down until it rests against the base material.

With the torch still at a 90˚ angle to the work, it is lifted slightly until the shoe rests on the top side of the strip. The strip is then pressed down with the end of the tip, and a quick tamping motion is started while feeding the strip by hand. The tamping motion is continued, and at the same time, the shoe or tip is “walked” along the strip for about 2 in. (51 mm). Tamping prevents overheating the strip and base material and consequent stretching or tearing of the strip by pulling the torch along when the strip is too soft.

As the strip begins to feel solid under the shoe, the tamping motion is discontinued, and the angle of the torch is lowered to the base material. The torch is now drawn over the joint at a controlled rate. Proper welding rates are 18–24 in./min (457–610 mm/min). A proper seal shows material flow on both sides of the strip.

Once the welding operation is started, it may be continued with one hand, and the forward motion of the torch automatically feeds the strip through the tip. When the operator sees the proper sealing, constant pressure and rate of welding is maintained. If the operation is slowed, the torch is once again brought to a 90˚ angle with the base material, and a tamping motion resumed. With experience, starts can be made directly in the corner of a tank. By splicing the strip that has been applied and the applied piece, a satisfactory joint is always made.

The sheet or strip material should not blister or burn, since this yields an unsound weld. Welds cannot be properly repaired by reheating the weld and exerting pressure on the strip. A faulty weld must be cut away, cleaned, and rewelded.

Welding flexible-rigid laminated PVC sheet. Butt joints are used whenever possible. Where space allows, a 0.75 in. (19.1 mm)-wide rigid butt strip is welded over the joint using a flat welding tip. The welded strip is then back-welded with a rigid round rod. If space does not permit using this method, the joint is skived to an angle of 60˚ and welded with three passes of rigid round rod.

Corner joints are sealed using a rigid extruded angle. The angle piece is first tacked in place using a tacking tip or a 0.094 in. (2.39 mm) rod intermittently along the edges of the angle. These edges are then back-welded with a rigid round rod. The angle strip is bent in the corners of the tank by cutting a 90˚ angle section in one leg of the strip, heating and bending the angle, and welding the seam.

Fluorocarbons. Although fluorocarbons are not yet widely used as lining materials, their high heat distortion point and chemical inertness make them ideal tank lining materials. FEP and PFA sheets are butt welded using the techniques originally developed to weld chlorinated polyether tank lining materials, even though it is now seldom used as a liner.

Hand welding flat and corner strip. The procedure for welding PFTE flat and corner strip by the conventional hand method is similar to that described for flexible PVC. The flow of hot gas is about one-half that used for PVC to prevent splashing of the molten PFTE. Welding temperatures are 600–650˚ F (316–343˚ C). A satisfactory weld is achieved only when the underside of the strip and the top surface of the sheet are molten. As the weld progresses, a bead of molten material is visible at the intersection of the strip and the sheet. The use of a roller to provide pressure on the strip is recommended for producing uniform welds.

Speed welding flat and corner strip. For sealing a PFTE strip to sheet lining, the strip is held in place with a tacking tip and, using a round rod, both edges of the strip are speed welded. Procedures are similar to those outlined for welding combination flexible-rigid linings.

Semiautomatic strip welding. The rigid tip makes semiautomatic welding possible with both PFTE flat and corner strip. A roller is used in place of a shoe to eliminate excess drag on the strip. Hot gas is introduced into the feeding chamber to soften the strip and make it pliable. A flat roller is used for flat strip, and a slightly contoured roller is used for the corner strip. These rollers are interchangeable on the same basic tip. The feeding chamber and brackets for the rollers may be detached from the lower part of the assembly, and the latter part can be used as a conventional flat tip. Welding with the rigid tip is greatly facilitated if the PFTE strip is preheated to about 350˚ F (177˚ C). This is particularly true with a corner strip that has a larger cross section than the flat strip and is stiff when cold.

To start a weld in a corner or against the side of a tank, the strip is inserted into the feed-roller assembly, and the weld is begun as with a flat tip. For the first 0.50 in. (12.7 mm), the strip pressure is supplied by hand until a roller is brought to bear on top of the strip. The torch is now held at a 45˚ angle with the base material, and the full width of the roller is kept in contact with the strip. Welding should proceed at a rate that produces flow on both sides of the strip. To finish a weld in a corner or against the side of a tank, the tip is replaced with a flat tip, and the weld is finished by hand.

When welding bottom corners in a tank, starts are made in the corners and spliced halfway between the corners. Strips are cut on an angle at each start and spliced to allow neat overlapping. Splices are overlapped 0.5–0.75 in. (12.7–19.1 mm).

Weld testing. The most efficient method of testing welds is by means of a high-frequency spark tester operating at more than 8000 V. In cases where wood and concrete are lined, a grounded-
The wire system is used so that wires are inserted between the butted sheets. The welds are made directly over the wires with no detrimental effect on the joint. The liner is then spark tested.

Visual inspection of the welds should reveal flow lines along both sides of the welded strip. Where these lines are not apparent, attempts are made to pry the strip loose from the sheet with a knife. Practice welds are tested by attempting to peel the strip from the sheet. The weld can also be cut for visual inspection.

Repair. Repairs are made on punctured, torn, or faulty linings by cutting away the faulty section and cementing or welding a new section. Burned or cold welds require cutting and rewelding.

**Instructions for Welding Individual Materials**

The welding techniques outlined in the preceding sections apply to all weldable thermoplastics. Each type of thermoplastic, however, has individual physical and chemical properties that influence both the welding process and the finished product. Factors such as chemical resistance, recommended working temperature, impact resistance, coefficient of thermal expansion, structural rigidity, and notch sensitivity must be considered before selecting material. Information and recommendations on special applications are available from material manufacturers. General information for welding the more common thermoplastics is shown in Table 16-12.

Polyvinyl chloride. Three factors influence the welding of PVC: the type of PVC used (normal or high-impact), the amount of plasticizer present in the material, and the quality of the welding rod.

There are two types of rigid (unplasticized) PVC available: Type I (normal impact) and Type II (high impact). Type II PVC is modified with rubber to increase its impact resistance. However, welding temperatures and rates are lower than those used for Type I to avoid scorching.

Plasticizers are liquids or compounds added during extrusion to make the thermoplastic more flexible. Plasticizers are not used in rigid PVC pipe, fittings, or sheet, but are used in some welding rods to improve the welding quality. Under normal conditions, a 10% plasticized rod gives better performance and strength. The proper extrusion of the welding rod is important since voids and air pockets affect the ultimate strength of a weld. In addition, welding rod stresses are detected by a slight movement of the rod when placed in an oven. Always inspect the rod for lumpiness, voids, and stress before welding.

Polyethylene. Several factors should be considered when welding polyethylene. Although there is a wide variance in composition, there are two types available for industrial purposes: regular or branched polyethylene, and linear or high-density polyethylene. The linear type is a more rigid, higher-temperature material. Both types have a tendency to degrade in sunlight and oxidize in air. This degradation, due to ultraviolet rays, is easily solved by adding carbon black in the extrusion process of polyethylene for use in outdoor applications.

Oxidation is a factor when welding polyethylene. Nitrogen is used as the welding gas to eliminate oxidation at higher temperatures and to achieve maximum strength. Immediately upon extrusion, very slight oxidation occurs on the material surface. This very thin film is sufficient to affect the final welded product. For this reason, best results are obtained by welding immediately after extrusion.

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**TABLE 16-12**

<table>
<thead>
<tr>
<th>PVC Type I</th>
<th>PVC Type II</th>
<th>PVC Plasticized</th>
<th>Polyethylene Regular</th>
<th>Polyethylene Linear</th>
<th>Polypropylene</th>
<th>Chlorinated Polyether</th>
<th>FEP Fluorocarbon</th>
<th>Acrylic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding gas</td>
<td>Air</td>
<td>Air</td>
<td>Air</td>
<td>Inert</td>
<td>Inert</td>
<td>Inert</td>
<td>Air</td>
<td>Air</td>
</tr>
<tr>
<td>Butt-weld strength-%</td>
<td>75–90</td>
<td>75–90</td>
<td>75–90</td>
<td>80–95</td>
<td>50–80</td>
<td>65–90</td>
<td>65–90</td>
<td>80–95</td>
</tr>
<tr>
<td>Maximum continuous service temperature (^\circ\ F (^\circ\ C))</td>
<td>160 ((71))</td>
<td>145 ((63))</td>
<td>150 ((66))</td>
<td>140 ((60))</td>
<td>210 ((99))</td>
<td>230 ((110))</td>
<td>250 ((121))</td>
<td>250 ((121))</td>
</tr>
<tr>
<td>Bending and forming temperature (^\circ\ F (^\circ\ C))</td>
<td>250 ((121))</td>
<td>250 ((121))</td>
<td>100 ((38))</td>
<td>245 ((118))</td>
<td>270 ((132))</td>
<td>300 ((149))</td>
<td>350 ((177))</td>
<td>550 ((288))</td>
</tr>
<tr>
<td>Cementable</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>0.91</td>
<td>0.95</td>
<td>0.90</td>
<td>1.4</td>
<td>2.15</td>
</tr>
<tr>
<td>Support combustion</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Odor under flame</td>
<td>HCL</td>
<td>HCL</td>
<td>HCL</td>
<td>Wax</td>
<td>Wax</td>
<td>Wax</td>
<td>Sweet chlorine</td>
<td>Pungent</td>
</tr>
<tr>
<td>Color**</td>
<td>Grey</td>
<td>Light grey</td>
<td>Black</td>
<td>Translucent or black</td>
<td>White or black</td>
<td>Cream to amber</td>
<td>Olive drab</td>
<td>Bluish translucent</td>
</tr>
</tbody>
</table>

* Measured 0.25 in. (6 mm) from welding tip.
** These are most commonly used colors, and are subject to change. For complete details refer to specifications of individual plastic manufacturers.
cutting the material and by removing the oxidized film from the rod with fine sandpaper or scraping with a knife.

The welding rod and base material must be of the same composition, since this affects the weld bond. Polyethylene welding differs from that of PVC due to more flexibility of the rod or the sharper melting point of polyethylene. Large-size rods are used wherever possible, and the weld is inspected for air inclusions, poor tolerance, and stress.

The term stress cracking, often included in discussions about polyethylene, refers to crazing, cracking, or splitting of the material under certain conditions of chemical environment, heat, or stress. Stress cracking results from welding materials of slightly different composition, welding at improper temperatures, and subjecting materials to undue stress or chemical attack. Stress cracking is also caused by oxidation. Proper welding rates avoid stress: 5 in./min (127 mm/min) for hand weld and approximately 30 in./min (762 mm/min) for speed welding. Maximum weld strength is achieved 10 hours after the weld is completed.

Polypropylene. A higher-temperature material quite similar to linear polyethylene for welding procedures, polypropylene is susceptible to stress cracking and oxidation and requires the use of nitrogen to obtain maximum strength. Some splash of molten plastic occurs when welding this material, but this does not affect the weld and is eliminated by throttling the airflow.

FEP fluorocarbon. One of the newer thermoplastics, fluorinated ethylene-propylene resin (FEP) is a derivative of Teflon™ and has the highest heat distortion point yet developed. The general techniques for welding are the same as those for regular polyethylene. It is susceptible to stress cracking but does not oxidize in the presence of air. Gases evolved at temperatures above 400˚ F (204˚ C) are highly toxic and are eliminated by adequate ventilation.

Acrylic—Plexiglas™. This was one of the first thermoplastics welded when the Germans, during World War II, used the process to mend bullet holes in airplane canopies. Acrylic requires high temperature, a slightly plasticized rod, and compressed air for welding. Welding procedures are the same as those for PVC. Acrylic is susceptible to stress cracking and can froth and blow during welding. The flow lines on a finished weld usually show air inclusion. Most acrylies are welded to themselves or to PVC using PVC rod. This makes them ideal for see-through applications, such as dry boxes, when clear PVC is not available. PVC welding techniques are used in all cases. With both acrylics and PVC, extreme care avoids charring the material. Welding is accomplished with air heated at 400–450 F (204–232˚ C) for PVC rod; 500–550˚ F (260–288˚ C) is used for acrylic rod. The rod is normally held at a 90˚ angle to the weld seam with a pressure of 2–3 psi (14–21 kPa) exerted on it.

High-temperature PVC. Chlorinated PVC (CPVC) is best welded by hand to obtain maximum strengths of 80–100%. Since a high temperature is required to melt CPVC (300˚ F [149˚ C]), a rod-feeding device is recommended to maintain a constant 3 psi (21 kPa) rod pressure without undue discomfort to the fingers from heat.

On typical sheet and pipe seams, the edges are cleaned and beveled prior to tack welding. The finish weld is accomplished with 600–650˚ F (316–343˚ C) air temperature at the tip and 3–4 psi (21–28 kPa) gas pressure. The 90˚ welding angle is maintained. When welding, the rod softens, and a slight bulge occurs just above the weld. The rod cannot melt further; the operator should prevent scorching of the rod or the work through excessive heat.

ABS. Acrylonitrile-butadiene-styrene (ABS) has excellent forming properties for most applications. ABS is available in normal and high-temperature types, and either can be hand or speed welded. Conventional ABS is welded with air or inert gas at 350–400˚ F (177–204˚ C); high-temperature ABS requires 500–550˚ F (260–288˚ C).

Shaped rod. Highly successful welding is accomplished with triangular and oval cross-sectional-shaped rod. These rods permit a complete weld in fewer passes and have a smoother, more finished appearance than conventional rod welds. Most rod shapes are tailored for large or small seams. Special speed tips are designed to accommodate the various cross-sections of shaped rod.

Triangular rod. Triangular rod is designed to fit a beveled seam and deliver a flat, finished weld in a single pass. It is smooth, strong, and neat in appearance. Although welding speed is slower, the seam is finished in a fraction of the time required by multiple passes with small-diameter round rod.

Oval rod. This cross-section reduces the number of passes required to fill a weld seam and produces a smooth-crowned weld of much neater appearance. Several round-rod beads may be deposited in the weld root before applying the oval rod.

General Considerations.

Stretching and distortion. Regardless of a welder’s skill and technique, some stretching of the welding rod occurs. Unless stretching exceeds 15%, the strength and stability of the completed weld are unaffected. As previously pointed out, excessive stretching occurs when the welding rod is leaned away from the direction of welding. In speed welding, stretching is caused by excessive pressure placed on the rod or by plastic residue on the shoe and in the preheating tube. When a thermoplastic rod is heated sufficiently to form a weld, it becomes soft and can stretch. Upon cooling, it contracts considerably. When this happens, stresses caused by stretching produce cracks and checks across the weld face. A simple method of determining the amount of stretch in a completed weld is to measure the rod length before and after welding.

Thermoplastics, when heated, tend to revert to their original shape. In multilayer welds, deposited beads are reheated in the process of laying new beads one on another. For this reason, stretching in multilayer welds must be held to a minimum, since checks and cracks caused by stretching create voids in the finished weld and cannot be detected by visual inspection. When making multilayer welds, ample time should be allowed for each weld pass to cool before proceeding with additional welds. To save time and give added strength to multilayer welds, the operator alternates from one side of the groove to the other. In addition to rod stretching, welding can also cause distortion of the base material. This is particularly true when multilayer single “V” butt welds are made.

As in metal welding, sudden heating and eventual cooling cause considerable expansion and contraction in the welded materials. Unlike metals, however, thermoplastics are poor heat conductors, and stresses created by alternate heating and cooling are confined to a smaller area. This concentration of heat combined with an expansion coefficient eight times that of steel creates great stresses in the welded plastic material. Weld shrinkage upon cooling is greater near the crown than at the root. For this reason, when welding sheets, material is offset before welding to compensate for the distortion created by single “V” and fillet welds. Also, it is advisable to preheat the general welded area so that the sheet can better absorb the stresses caused by welding. Because of the absence of misdirected and wasted heat in speed welding, less distortion is imparted to the base material than with hand welding. The use of triangular welding rod in place of multilayer welds with a round welding rod also decreases the amount of distortion, since one weld replaces several.
Dressing and repairing welds. Contrary to metal welding procedures, it is not good practice to dress plastic welds unless a flat surface is required. Weld strength is reduced as much as 25% when the crown is removed, and careless sanding or grinding frequently makes notches in the weld, creating weaknesses. This is particularly true of the more notch-sensitive materials, such as PVC. If dressing is necessary on a completed weld, it is done with a file or rotary sander.

Welds that appear burned or charred or that lack cohesion with the base material are removed and a new weld made. Rewelding faulty welds does not remove the original weakness; a faulty weld is, therefore, completely removed with a knife, rasp, router, or sandpaper, and the joint welded anew. Poor starts and cold welds are removed easily by reheating and cutting with a knife.

Welding threaded and socket-cemented pipe fittings. Plastic pipes and fittings are joined by three methods: threading, welding, and solvent cementing. To assure maximum strength and leak tightness, combinations of these methods are often used. Information regarding threading and cementing of pipes and fittings can be obtained from material suppliers. Only the welding and back-welding of fittings are covered here.

Threaded fittings are welded only to repair leaks, since the sole advantage of threading is to provide a pipe system that may be dismantled and its components reused. Since only heavy-wall (Schedule 80) pipe is threaded, this method is recommended only for temporary installations. Before a threaded joint is back-welded, the exposed threads in the weld area adjacent to the fitting are removed with a file to provide smooth surfaces for welding. A full-fillet weld is recommended when back-welding threaded fittings. A slight drip leak can be repaired with a single weld using a 0.125 in. (3.18 mm) rod. More serious leaks require three welds (five welds in the case of pipes more than 2 in. [51 mm] in diameter).

Cemented fittings can be back-welded to repair a leaking joint and to ensure against further leaks. When repairing leaks, the fitting cannot be back-welded while it is leaking, since the moisture prevents a good bond. The weld surfaces are roughed with a file or sandpaper before welding. A single-bead weld repairs slight leaks; serious leaks require a full-fillet weld. Socket-type fittings allow rapid installation of a piping system and assure strong joints with thin-wall (Schedule A and 40) pipe as well as heavy-wall (Schedule 80 and 120) pipe. Once installed, the system cannot be dismantled and reused unless the pipe is cut adjacent to the fitting and new fittings are procured. Socket fittings can be cemented, cemented and back-welded, or completely welded.

Welding socket fittings to pipe without solvent cement takes approximately 25%. Welds that are less than 75% of the original strength are considered unsatisfactory.

Visual inspection. Regardless of the welded material, a good weld always shows flow lines or waves on both sides of the deposited bead. These waves indicate the welding surface of the rod was heated sufficiently to allow the materials to flow, and enough pressure was exerted on the rod to force the viscous material out of the weld bed, permitting bonding of the softened plastic parts.

Visual examination of multilayer welds is accomplished by cutting across the axis of the weld and polishing the cross section. Close inspection reveals any faults such as voids, scorching, and notching.

Weld testing. Procedures for testing plastic materials are established by the American Society for Testing Materials and the Society of the Plastics Industry, as well as by individual plastics fabricators. These are divided into three categories: destructive, nondestructive, and chemical. Methods used for mechanical or destructive weld testing are tensile testing, bending, removal of rod, burst testing, and impact testing. These methods can be used immediately after welds are completed or after a 24-hour curing period.

Tensile test. Used primarily to evaluate butt welds on rigid sheet, this method, outlined by the Society of the Plastics Industry, is as follows. Using a 0.188 in. (4.8 mm) sheet, prepare a specimen approximately 8 × 6 in. (203 × 152 mm). Cut the specimen in half, each 4 × 6 in. (102 × 152 mm), and bevel both pieces to a double “V” by sanding one 6 in. (152 mm) side of each piece to a 30˚ angle, leaving a 0.016 in. (0.41 mm) flat surface on the apex of each bevel. Clean the beveled surfaces thoroughly, and clamp the test specimen securely to a bench, leaving a 0.016 in. (0.41 mm) space between the flattened apexes. Adjust the welding torch to the correct temperature, and apply two or three beads on each side of the specimen, using a small-diameter rod for root welding and a larger rod to complete the weld. Cut at least five specimens, approximately 0.5 in. (13 mm) wide, and pull each in the tensile tester at a rate of 0.025 in./min (0.64 mm/min). Calculate the percentage welding value as follows:

\[ WV = \frac{S_b \times 100}{S_t} \]  \hspace{1cm} (7)

where:

- \( WV \) = welding value
- \( S_b \) = breaking strength of weld
- \( S_t \) = original tensile strength of material

Bending test. Prepare the specimen as described for the tensile test. While still hot, bend it in half along the weld axis. The bead should cohere to the beveled surface of the sheet. In a similar test, conducted 24 hours after welding, pull test specimen should not readily break when bent 90˚ by hand. Examine breaks to evaluate the base material. If the base material is broken, the weld is adequate.

Removal of the rod. A simple method for detecting ineffective bonding in a completed weld is to allow the rod to extend beyond the weld area. While the rod is still hot, grasp its free end and attempt to pull out the welded section. If properly welded, the filler rod will break before it pulls away from the base material. However, this method tests only the last 1–2 in. (25–51 mm) of the weld. To test the entire section, attempt to remove the deposited filler rod with a pair of pliers or a knife after the material has cooled. Break the weld loose with a hammer and screwdriver and examine. If properly bonded, fragments of the base material should cohere to the broken rod and vice versa. The use of colored rod facilitates weld inspection.
CHAPTER 16

ASSEMBLY

Burst test. The most effective method for testing pipe butt welds and fillet welds on fabricated fittings and couplings is to cap the open ends of the pipe and subject the weld to hydrostatic pressure from tap water. Tapered plugs can be welded for the test using edge or full-fillet welds.

Impact test. The final destructive test is that of subjecting the weld to a sudden impact, such as hitting it with a hammer. When broken, examine the weld for faulty bonding, voids, and scorching.

Nondestructive tests. Cracks, porosity, and lack of bonding are detected in welded containers by filling them with water and checking for leaks. Another common method is to apply air pressure to the inside of a capped container and immerse it in water. Bubbles of escaping air indicate a leak. A pipe system is checked by painting the joints with a soapy solution and then placing the capped system under air pressure. Bubbles indicate slow leaks. To locate fine porosity in welds, a high-frequency spark tester is used. Operating at 10,000–30,000 V, this instrument sends a shower of sparks over the surface of the plastic that is grounded with a metal backing. Porosity is indicated by a straight line of sparks passing through the weld to the grounded metal. This method is used for testing plasticized and rigid tank linings. Air inclusions and voids in natural color polyethylene and polypropylene welds are detected by using a bright light held at an oblique angle to the work. The most effective nondestructive method for testing welds is the use of an x-ray or fluoroscope machine, which can reveal voids and scouring in hidden welds on finished products.

Chemical tests. Welded test specimens are immersed in acetone for 2–4 hours. Faulty welds separate from the base material, and residual strains and stresses in the welded section are noted by swelling of the material. Delamination and disintegration indicate defective materials. After acetone immersion, welded beads are pried out and inspected for fusion. Good weld beads are difficult to pry loose.

Dye penetrant on a completed weld also serves as an inspection aid, since a good weld does not allow the penetrant to seep through. Where temperature and chemical attack approach the known limits of a material’s resistance, welded specimens are tested chemically. Butt and corner welds are immersed in the intended chemical environment and placed under stress while proposed temperatures are maintained. If stress, cracking, and weld separation are apparent, the material is unsatisfactory.

Failure of thermoplastic welds, when subjected to these tests, is caused by a lack of fusion between the bead and base material, voids or porosity, a lack of fusion between beads, or a lack of fusion between the lands of the base materials.

ULTRASONIC PLASTIC WELDING

This section will discuss ultrasonic applications, how it works, reasons to use this process, alternate methods, basic rules for use, decorative patterns, maintenance, pitfalls, safety, troubleshooting, and microprocessor control. Ultrasonic equipment was developed in the 1940s. With the introduction of more plastic as a replacement for metal, wood, cloth, rubber, and other materials, there is a continuous search for better methods of assembling products. Traditional techniques, such as glue, rivets, screws, and even sewing, do not satisfy the demands of modern manufacturers. The preparation of the products, the price of the components, and the cost of installation are often not acceptable. In most cases, the quality and aesthetics of hardware and glue are inferior to a proper ultrasonic application. Often the use of ultrasonics provides more than one function, for example, the assembly of two or more parts and obtaining a hermetic seal simultaneously.

Ultrasonic Applications

Ultrasonic plastic welding is used in all areas of industry. With the continuous growth of disposables, the medical industry makes substantial use of ultrasonic equipment. Medical devices, from simple components such as clamps, to filters and body part replacements, are made from plastic.

The automotive industry is another large ultrasonics user. Ultrasonics are used in decorative hood and side panel components, gas tank assemblies, instrument panels, sun visors, controls, seat belt buckles, valves, and other engine components.

Toy manufacturing relies heavily on ultrasonic welding to eliminate sharp, potentially dangerous components such as screws and metal hardware.

The garment industry uses ultrasonics for many applications that were once sewn, such as collar stays, filter materials, buttonholes, hook and loop, and the stitching and cutting of synthetic materials.

How Does it Work?

The term ultrasonics refers to the frequency range at which the equipment operates. Most equipment functions from 15–40 kHz; the two most prevalent are 20 and 40 kHz. Bonding is created by mechanical motion, not by the sound waves.

Three components. There are three basic components used in most sonic welding equipment: the generator, the transducer, and the horn or sonotrode. The generator takes the electrical current (120–240 V) and produces power up to 3000 watts. The power is channeled to a device called a convertor or transducer. The transducer converts the electrical energy to mechanical energy. This mechanical motion can be 15,000, 20,000, or 40,000 cycles/second (see Fig. 16-10).

The transducer is coupled to a device commonly called a horn (or a sonotrode in Europe). The horn, made of metal and tuned to operate at the appropriate frequency, moves much like a miniature jackhammer. This mechanical motion, from 15 to 400 Hz, when applied against plastic, causes it to move in harmony. This jackhammer effect bonds the two plastic parts, colliding at 15,000–40,000 cycles/second. The process produces friction at the interface of the two parts, creating heat. This heat melts the plastic and produces a bond.

The power supply generator is the heart of the system. It provides the electrical power at the required frequency and amplitude to the transducer. The generator takes the electrical power (120 V, 50/60 Hz in the United States) and converts it to 20,000 or 40,000 cycles/second.

Other components. There are other components associated with the generator. Many manufacturers put amplitude controls in their generators. These devices reduce the amplitude produced at the horn. In most cases, they also reduce the total power available. The amplitude control allows a reduction of amplitude without changing the booster size. By reducing the amplitude, an overlapped condition is reduced. This control also provides a more controlled cycle for parts that weld too quickly. The amplitude is not lowered when the weld requires more than 90% of the available power.

Test switch. Another element associated with the generator is the test switch. When activated, this switch allows the user to test the efficiency of the horn, booster, and transducer. The equipment is tested at the end of each work day.

On/off switch. The on/off switch controls the power to the generator. With some generators, turning on the switch initiates a self-test program. A weld cannot usually be accomplished while the self-test program is functioning. Some manufacturers have an operating switch that allows pneumatic activation of the press without energizing the sonics. This allows the user to check alignment.
and the mechanical stop under pressure. Other manufacturers have a heads-down switch on the press that serves the same function.

Power meter. A power meter or load meter is usually found in the generator. This meter may come in the form of a bar graph. It indicates what percentage of power available is being used during welding or testing. These meters are not capable of displaying very fast high peaks.

Protective devices. Fuses, circuit breakers, and other protective devices are usually found on or in the generator. These devices protect the major electronic generator components. If the circuit breaker or fuse continually trips, the unit requires servicing.

Most generators have fans for cooling the power supply. The air is usually brought in through an opening in the front of the unit and exited out the back. It is important not to block the air circulation. Most manufacturers have incorporated thermo switches into the unit’s heat sink. If the fan fails, the switch automatically shuts down the system.

Some older generators have a manual tuning control. The tuning device can be a slotted screw, knob, or pot. The intent is to closely match the resonant frequency of the system with the horn, booster, and transducer. The generator is usually tuned while in the test mode, and the meter reading is tuned to the lowest setting. Newer units have automatic frequency control (AFC), which automatically matches the resonant frequency.

One frequency. As previously noted, generators can produce frequencies from 15 through 40 kHz. However, generators are designed to function at one frequency only.

The higher frequencies (near 40 kHz) are used on more delicate applications, such as when welding parts having delicate electronic elements and when welding films. Very small components are also usually bonded at the higher frequency. The limitation of the higher frequency is that the maximum wattage is usually lower than the more popular 20-kHz units. Frequencies near 40 kHz are the second most popular frequency range.

The least popular 15-kHz systems are capable of operating larger horns. As the frequency becomes lower, the wavelength increases. Because a 15-kHz unit produces an audible frequency, the weld is usually done in a sound enclosure to protect the operator.

Overload light. The overload light is an important generator feature. The light illuminates when the system loads beyond its threshold setting. An overload can be caused by a cracked or out-of-tune horn, excessive pressure that stalls the horn, or high peak power surges. If the overload light comes on and the cause cannot be determined, the equipment must be shut down until repairs are made.

Timers. Most ultrasonic units have timers to control the bonding process. The sonic timer controls the length of the welding cycle. When this timer is activated, the transducer, booster, and horn vibrate. While the horn is vibrating, pressure is placed on the bonded parts. Some units also have a delay timer, which determines when the sonic cycle commences. A third timer is the hold timer, which keeps pressure on the components without vibrating. This pressure allows the melted plastic parts to solidify before they are released. Welders that do not have delay timers use other methods of starting the sonics.

Timer designs vary. Some use simple pots with less-than-accurate scales. In many cases, the scale increments vary from one end of the range to the other. Other manufacturers use digital readouts that allow users to accurately set the timer. With many older units, timer accuracy is questionable.

Some manufacturers do not have separate generators and presses. The generator is integrated into the press, hence the title “integrated welder.” These welders have the previously described controls mounted in the press generator unit.

The press. The press is the control center of the ultrasonic unit. The press usually houses many controls in addition to the pneumatic functions. The transducer, booster, and horn are mounted in the press. The power produced by the generator is delivered to the press. If it does not function correctly, or its controls malfunction, a quality weld is not achieved.

Two rules are paramount prior to making control parameter changes. First, the problem must be analyzed before making the
change. Second, if a parameter change is required, one control at a
time is changed.

The pneumatic section consists of an air cylinder and valve(s),
gage(s), and regulator(s). The air cylinder applies force to the prod-
uct and is attached to a carriage that contains the transducer, boos-
ter, and horn. The horn makes the physical contact with the product
that is sandwiched between it and the fixture. The pressure applied
has a direct relationship to the power delivered to the product.

Some manufacturers supply equipment that can deliver two
pressure settings. This allows the user to change from one setting to
another during the welding or holding cycle. For certain applica-
tions, a combination of pressure settings provides stronger welds.

Speed control valves. Most manufacturers have incorporated a
down-speed control valve in their ultrasonic equipment. This control
valve is an important element in the power delivery system. If the
press comes down fast, the peak power is high. However, if the head
comes down slowly, the peak power is generally lower, depending
upon the cycle time. In some cases, a weld must be accomplished
quickly because a prolonged weld cycle damages the parts. Although
a faster cycle can be accomplished with a fast down speed, these fast
speeds also increase the chance of overloading when using a high-
amplitude horn and booster combination. Applications such as
inserting and shear welding require a slow down speed.

Many older units do not have speed control valves on the press
front panel, so adjustments are made to the exhaust screws on the
solenoid valves on the inside of the unit. Still others use a dash-
pot-type control to soften the stroke.

Cushion cylinder. It is common to add a cushioning-type
cylinder to slow the down stroke; this cushion is normally used to
increase productivity. When a long, slow stroke is required to
reach a part, the slow speed adds considerable time to the overall
cycle. The cushion cylinder is used to brake the head just before
the horn touches the product. This produces the necessary control
while keeping the overall cycle time to a minimum.

Mechanical stops. Most equipment is supplied with mechanici-
cal stops. These components restrict the travel of the press head. A
mechanical stop is important when the overall dimension of a
welded part is critical. It is also necessary when reducing flash or
marking a part during welding.

Most older units use crude means of controlling the stops. Newer
equipment has more sophisticated controls, making it
much easier to set the stops.

Pretriggering. Pretriggering is the ability to start the ultra-
sonic vibration prior to the horn touching the parts. Pretriggering
is necessary for applications such as inserting, staking or swaging,
and shear welding. While some equipment has the pretrigger on
the press front panel, it is located internally in others. The pretrig-
erg switch either allows the switch to move in conjunction with
the stroke or uses a movable trip device that activates the switch.
Usually the stroke is slow when pretriggering is used.

As previously stated, pretriggering is required when driving an
insert ultrasonically. If the head comes down too fast, the insert
becomes press fit. Once the inserts are mechanically driven into
the part and the sonics are turned on, little or no flow occurs. The
insert does not vibrate in harmony with the horn when it is embed-
ded into the plastic.

When the sonics are pre-triggered, the sonic weld cycle is
extended to compensate for the time the horn is fired in air.

The end-of-weld switch performs the opposite function of the
pretrigger switch. Just as with the pretrigger switch, some are located
inside the unit, while others are on the front panel (see Fig. 16-11).

Transducers. The convertor or transducer is one of the three
components mounted in the press that produce the mechanical
motion necessary to produce the bond. There are two transducer
types: the magnetostrictive and the electrostrictive.

Magnetostrictive transducers. These units are made of per-
mannickel laminations brazed to a connector body; the body is usu-
ally made of Monel™. These laminations are placed into a mag-
netic field that induces mechanical motion. The magnetostrictive
converter is relatively inefficient but has a history of long life, espe-
sially for applications such as ultrasonic machining. Magneto-
strictive transducers are still used in the medical industry. Cataract removal, brain surgery, and heart surgery rely on these transducers.

Electrostrictive transducers. These transducers use piezoelectric ceramic wafers. These wafers, usually two or four, sandwich copper washers. Each wafer has a polarity that, when subjected to alternating voltage from the generator, vibrates at the same frequency as the signal. The disc alternately expands and contracts, creating the mechanical motion called amplitude.

Clarifying the definitions of amplitude and frequency is appropriate at this point. Frequency is the number of cycles per second at which the jackhammer works, and amplitude defines how hard the jackhammer strikes its intended object. As the horn vibrates, it expands and contracts. Amplitude, essentially the amount it expands, is usually expressed in thousandths of an inch or microns.

Most 20-kHz convertors or transducers produce mechanical motion on the order of 0.0008 in. (0.020 mm). This is usually insufficient motion to weld most plastics. For example, polystyrene, which is considered easy to weld, is usually welded at 0.0012–0.0025 in. (0.030–0.064 mm) motion. Therefore, the motion is amplified from the convertor. The two devices used to increase or reduce this motion are the booster and the horn.

Booster. The booster has two main functions. First, it clamps the booster, horn, and convertor in the press. The booster has a ring mounted at its nodal point, an area where no motion takes place. This ring is clamped by the press head and holds all three components. The second function of the booster is to modify the amplitude from the transducer. The mass of the booster above the mounting ring compared to the mass below the ring provides the amplification multiplier. For example, if the mass closest to the converter is larger than that closest to the horn, the booster increases the amplitude. Boosters are usually made from aluminum or titanium (see Fig. 16-12).

The ultrasonic press has been the focus of discussion to this point. This press represents the dominant method of ultrasonic
welding. However, sonics are also needed in positions that cannot be reached using a conventional press. A need also exists for correcting a poor weld. This is a role of the hand gun.

Hand gun. When using a hand gun, shown in Fig. 16-13, the operator acts as the press. The operator controls the down speed, pressure, and time. The converter becomes a handle that usually includes a switch for activating the sonics. Some units have timers, while others depend on operator skill to use the unit consistently.

The hand gun consists of a converter and horn. Boosters are normally not used. The 40-kHz hand gun is popular because it is smaller and lighter than its 20-kHz counterpart. Because boosters are not used, the amplitude is built into the horn. The size of the horn is usually limited by the operator’s ability to apply sufficient pressure to make the weld.

Common uses of the hand gun include spot welding, staking or swaging, and repair. The aesthetic quality of hand gun welds is normally not important. An automotive instrument panel is an example of a hand gun application; these panels are usually spot welded or staked. Multiple welds on instrument panels are usually made automatically; the hand gun is used to correct poorly welded areas.

Horn materials. The horn must vibrate at the proper frequency and expand and contract at its designed amplitude. The unit should also run efficiently. It must use little power to run in air, and the face of the horn must produce the required amplitude. It is common for a horn to run inefficiently in air at the proper frequency but produce no amplitude. This usually indicates that the mechanical motion is in the wrong direction.

There are four materials used to produce horns: aluminum, steel, Monel™ (copper-nickel alloy), and titanium. Each material has a specific use and limitation. Most horns are machined to one-half the wavelength of the particular material. However, horns are also made to any multiple of half-wavelengths. Longer horns are often used when half a wavelength is too short to reach the part.

Aluminum. Aluminum is a good acoustic material that machines easily. Small and large horns are produced from aluminum. Aluminum horns are normally limited to an amplitude of 0.0025 in. (0.064 mm).

Aluminum is safe but can wear fast in abrasive applications. It can also impart oxides on the material it contacts. Chrome plating or hard coating can increase horn life and eliminate the oxides.

Steel. This material is used for low-gain, high-force applications. Steel is a poor acoustic material because it easily becomes hot and does not tune as efficiently as other materials. Steel is an excellent material when driving metal inserts into plastic and in applications where the horn is used to sonically cut. For horns made of titanium or aluminum, tips can be made of steel, prolonging horn life. The tip is easily replaced without replacing the entire horn. Amplitudes of steel horns are also limited to 0.0025 in. (0.064 mm).

Monel™. Once a very popular material, it is seldom used today. This alloy has many of the same characteristics as aluminum. One advantage is that other materials can be brazed to it and used in applications restricted to 0.0025 in. (0.064 mm) amplitude. It is much more expensive than steel or aluminum.

Titanium. By far the most popular horn material, titanium can withstand amplitudes up to 0.006 in. (0.15 mm). However, titanium is not hard like steel or carbide. When used in an abrasive application, it wears rapidly. For this reason, high-gain titanium horns are not recommended for driving metal inserts.

Cylindrical horn. Cylindrical horns are the most popular. The basic design is a solid cylinder with straight sides. This horn has no amplitude gain. The amplitude developed by the converter and booster is what is seen on the horn face. When a cylindrical horn exceeds 4 in. (102 mm) in diameter, it usually requires slots. These slots are used to reduce superfluous resonance. The slots run with the grain of the material, and the grain should run from the booster to the output face. The slots run through the horn, stopping at least 0.50–0.63 in. (12.7–16.0 mm) from the output end and at least 0.5 in. (12.7 mm) from a threaded hole.

A second design is a tapered cylindrical horn. The sides, which taper from a larger diameter at the input end to a smaller diameter at the output end, are smooth and straight. This horn is sometimes referred to as a conical or linear horn. A tapered-cylinder horn creates more amplitude than the basic solid cylindrical horn but is usually not used above 0.002 in. (0.051 mm) of amplification.

Exponential cone horn. The exponential cone horn can produce greater amplitudes than a tapered or linear cone horn. With this horn, an exponential curve is started very close to the input end and runs to the output face. This design usually produces longer-resonant-length horns. The stresses are still minimal, since the cross-sectional change is gradual. This horn is normally not used to create high amplitudes because of the material needed and the amount of machining required to reach these higher amplitudes.

Catenoidal horn. Catenoidal horns are next in order of amplitude. The catenoidal shape usually starts near the nodal point. This horn produces more amplitude than the exponential horn having the same input and output diameters. However, the stresses are higher than the tapered exponential design.

Step cylinder. The step cylinder shares its popularity with the basic cylindrical horn. However, this horn produces the highest magnification of all the cylindrical horns having the same input and output dimensions. This horn also has the highest concentration of stresses and usually the shortest resonant frequency. The step cylinder horn has the sharpest transition from one diameter to another. The transition takes place at the nodal point using an appropriate radius. Step cylinders usually produce twice the amplitude of an exponential horn.

A similar design is the internal-step cylinder. When a solid output face is not required or it is not economical to build an externally-stepped cylindrical horn, an internal-step design is used. The change in mass above and below the nodal point takes place internally. This design allows production of large-diameter, high-gain horns.

Nodal plunger. A nodal plunger is a component added to a horn to prevent burning or blowout during welding. Cylindrical horns can cause the center of disc parts to burn or produce holes, especially when the part is center gated. The holes and burning are caused by the part diaphragming at 20,000–40,000 cycles/second. To prevent this diaphragming, the vibration is damped. A nodal plunger, which is a device mounted internally at the nodal point of the horn, prevents the part from diaphragming by exerting pressure against the center of the part during welding.

Blade horn. Rectangular or blade horns have limitations similar to those of round horns. It is easier to determine the amplification of a blade horn than that of a cylindrical horn.

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Fig. 16-13 Hand gun.
With rectangular horns, it is important to monitor the diagonal dimension. If this dimension approaches one-half wavelength or multiples of a wavelength, the horn may not operate efficiently. For example, a 3 × 4 in. (76 × 102 mm) rectangular horn is a poor design because its diagonal dimension is 5 in. (127 mm). This is close to half a wavelength.

Blade horns greater than 3.5 in. (89 mm) wide usually require slots to reduce superfluous resonance as with larger round horns. Replaceable tips are used when horn wear becomes a problem. Lower tip masses reduce the probability of failure. Titanium tips are recommended in most cases. Threaded tips that are used on horns with less than 0.0025 in. (0.064 mm) amplitude generally wear well. As the tip size increases, the horn amplitude is normally reduced. Tips can become hot and affect the horn’s frequency. External cooling is used if necessary. Several blade horn designs are shown in Fig. 16-14.

Fixtures. The ultrasonic process also requires holding the bonded components in position during welding. The element that holds the parts is called a fixture or nest. The fixture is designed to hold the components, and align and support the parts without absorbing the energy transmitted into the parts.

The nest may allow the product to move in harmony with the horn instead of out of phase. This type of nest reduces the horn’s efficiency. If the bottom of the part that is located in the fixture is marred during welding, this indicates that the part is moving in the fixture in harmony with the horn; the fixture design requires changing. The modification can be as simple as making a rigid nest soft or vice versa.

When a part has unusual contours, the fixture is usually cast; the fixture material may be rigid or soft. When soft material is cast, the material is supported on all sides. Fixtures are also used to control flash during welding. The fixture must come above the parting line of the two components. It should fit tightly enough to control the molten flash and push it back against the part, but not so tightly that it retards the sonic motion.

Why Use Ultrasonics?

When assembling a plastic product, ultrasonic assembly offers many advantages. For instance, screws, washers, and nuts used in mechanical assembly are expensive, sometimes more expensive than the plastic parts they assemble. The other advantage of using ultrasonics over hardware is that the plastic does not corrode. Well-designed plastic parts provide quality assembly faster and are aesthetically better than those assembled with fasteners. The ultrasonic technique also eliminates the need to store the hardware.

Alternative Methods

The following are alternative methods of joining plastics.

Spin welding. The spin-welding technique joins plastic by quickly spinning one of the parts to be joined. While spinning, this part is brought slowly onto the second (stationary) part, which is held securely in a fixture. As the two parts come together, melting occurs due to the heat generated by the spinning action. Spin welding is the preferred method when joining large circular parts or parts made from low-density material such as polypropylene or polyurethane. The cost of spin-welding equipment is generally higher than sonic equipment. The assembly of vacuum cleaner tanks is an example of a spin-welding application.

RF sealing. The radio frequency (RF) technique is popular for assembling plastic film and sheets; the most common frequency is 27.16 MHz. This equipment is large and uses dies, usually made of brass, to seal. The advantage of the radio frequency technique is that large, complicated shapes can be bonded and cut. If the bonded material has no backing or scrim, it can normally be sealed and cut using a technique called tear sealing. A tear seal is achieved when the bonded material is thinned in certain areas. The thinning is the result of the die design. After sealing, the scrap area is easily pulled away from the base material.

Radio frequency equipment is generally more expensive than ultrasonic equipment. However, it can seal much larger areas than
the equivalent-cost ultrasonic equipment. RF sealing is limited to a few materials and thicknesses. Vinyl, urethane, nylons, and PET films are good candidates for RF sealing.

Heat sealing. The heat-sealing technique is similar to RF sealing. The equipment is similar in design, and a die is also used. Heat sealing can provide a large seal on materials such as films. The disadvantage of heat sealing is that it is less controllable than RF or ultrasonic sealing.

Heat sealing is an economical alternative when bonding items such as plastic bags and some tubes. Heat can be used for metal insertion and swaging of molded parts.

There is an additional process that uses forced hot air to soften the product and chilled dies to form the material. This process is superior to the standard heat method; however, it is more expensive. This technique is used successfully in bonding automotive door panels, for example.

Vibration welding. Vibration welding uses a side-to-side motion to create a bond. One of the welded components is locked in place, while the second is rubbed back and forth across the first one. This action, like ultrasonics, produces friction, which in turn produces heat that melts the plastic. After the cycle is complete, the parts are aligned and held under pressure until the plastic solidifies.

Vibration welding produces excellent welds on large parts or multiple small parts. Some designs limit the use of this method because of the amount of side-to-side stroke necessary to produce a bond. Most vibration equipment moves on one axis.

This technique is used successfully where the part dimensions meet the required wall thickness. The equipment is large and expensive; therefore, relatively large production volumes are necessary to justify the cost.

Vibration welding is used in the automotive industry for assembling tail light assemblies and duct systems, and in bonding carpet to panel. The medical industry also uses vibration welding on items such as large vacuum containers.

Hot-plate welding. Hot-plate welding uses heat to bond a variety of products. The joined parts are held in fixtures, which align the parts and hold the product. A heated platen is placed between the two components, and the two parts in the fixtures close on the platen. Only the areas to be bonded make contact with the platen. After sufficient heat is introduced into the parts, the two fixtures open and the platen withdraws. After platen withdrawal, the two parts are brought together as the plastic is still molten. The parts flow together and are held in place until solidified.

When the bond is formed using hot-plate welding, a large amount of flash is usually produced. Excess material flows out of the joint area. Dies can be developed to remove this flash in the welder. In other cases, this excess material is removed in secondary operations.

This system is more expensive than that for ultrasonics. Items like plastic balls, bait boxes, and automotive components are bonded successfully with hot-plate welding.

Basic Rules for Ultrasonic Welding

There are several basic rules that govern ultrasonic welding methods.

Energy director versus shear joint. The energy director joint is the most popular one. The energy director bonds most amorphous and crystalline resins. However, when a hermetic bond is desired, additional care is required. Most amorphous resins provide a hermetic seal with an energy director joint. When considering the higher-melt-temperature amorphous resins, a shear joint produces a better hermetic seal. When hermetic seals are required in crystalline resins, a shear joint is always required.

The energy director consists of a sharp, triangular-shaped bead usually placed around the perimeter of the parts. A 90° angle is recommended for amorphous resins and a 60° angle for crystalline resins. Energy directors usually flash. Once flash is produced, it can only be eliminated by a secondary operation. This flash is a design consideration, and the joint design must be carefully selected. Joint designs can hide or restrict the flow of molten plastic. A tongue-and-groove or a stepped-joint design is recommended.

The molds are kept metal safe to minimize the joint size. Larger joints are made by removing mold material (see Fig. 16-15).

The shear joint is used when a hermetic seal is required, especially with crystalline resins. The shear joint is sometimes referred to as an interference joint, because the two parts have an interference fit. When sonics are applied, the interference bead melts the second part and produces a strong joint. It prevents crystalline materials from degrading due to air exposure during solidification. This type of joint takes a large amount of energy to weld because of the amount of material that is melted. The joint is designed so that both pieces are aligned prior to welding. One part usually lies in a cavity of the second part.

A shear joint weld procedure is different than that for an energy director. The horn must descend slowly, and the sonics are pretriggered. The most common mistake with a shear joint is bringing the horn down too fast. A high speed press fits the parts, and the sonics weld poorly if at all (see Fig. 16-16).

When incorporating a shear joint, an angle side may be used to align the two parts. However, this technique is not recommended. If strength is not required, a bead shear joint is used. A modification of a shear joint, this design is simpler to incorporate in the mold. Staking, heading, or refloving of plastic is the process of ultrasonically flowing plastic over and around objects for the purpose of joining two or more objects. The objects need not be plastic.

Staking or heading is normally used to bond two parts that were previously joined by hardware such as screws or rivets. This process is accomplished when the plastic part has a post that protrudes through the secondary part(s) that are assembled. A head is ultrasonically formed on the plastic part. The boss or post can be solid or hollow, and rectangular or triangular.

Staking posts. Staking solid posts is accomplished in various ways. One technique is to use a staking tip, which is designed with a concave cavity. In the center of the cavity is a pointed tip. This tip makes the first contact with the post and starts the flow outward. The flow is captured by the concave cavity, which works as a mold. When the material becomes solidified, it forms a doughnut-shaped head.

A standard staking tip is not recommended for glass-filled or other abrasive materials. Abrasive material rapidly wears the small point. A post containing excessive fill material may crumble under the sonics instead of flowing.

Mushroom and flat-face tips. Another method of staking is to use a button or mushroom tip. This tip is used with minimum-filled materials. The mushroom tip forms a head that is similar to a rivet head; the small point is omitted in a mushroom tip.

Another technique is to use a flat-face tip, which can be knurled or smooth. A knurled tip is used when appearance is not critical. A smooth tip can provide a flat head or can flow material flush, filling a counterbore or countersink cavity.

A hollow post is usually recommended for 0.156 in. (4.0 mm) diameter or larger posts. The tip used to weld a hollow post usually has a pilot, and rolls back the wall of the post. The result looks similar to a hollow rivet. Another advantage of a hollow post is that the weld can be broken to make repairs and then reassembled with a self-threading screw.
The staking operation. This operation is usually performed by the sonic head descending slowly. The sonics are pretriggered so that the melt starts immediately upon horn contact. The post height is calculated to fill the horn tip cavity. Just as with other sonic applications, excessive material is not an advantage. A stake works best when the post is well supported. Also, if the clearance between the post and hole is too large, material flows down the side of the post and into the hole. A good mechanical stop pro-
Spot welding. Spot welding is another technique of joining two similar materials that cannot incorporate a joint design. Sheet material, molded parts, and thermoformed parts are excellent candidates for spot welding.

The spot-welding tip pierces the top layer(s) and drives the molten plastic into the bottom layer. The tip leaves a doughnut-shaped ring similar to the staking tip. However, a deep cavity is left in the center of the doughnut. The side opposite the spot weld leaves no trace of a weld.

Using a spot weld produces a permanent, strong bond. The weld usually migrates beyond the area penetrated by the tip. Spot welds made in close proximity have produced hermetic seals. Just as with staking, spot welding can be accomplished by driving the material into a fixture containing a spot-welding tip (see Fig. 16-18).

Plunge and scan welding. Cutting and sealing can be accomplished using synthetic fabrics. This process is performed by plunge or scan welding.

In plunge welding, the press is cycled in the same manner as when bonding two rigid plastic pieces. The material is sandwiched between the horn and anvil. The anvil is usually made from hardened steel, and the horn is usually titanium. The anvil, unlike a cutting die, is not sharp. If two layers are cut simultaneously, they will bond along the cut edge. If one layer is cut, the cut edge is sealed.

In scan welding, either the vibrating horn passes over the material and anvil or the material and anvil pass under the horn. When straight-line cutting is performed, the anvil usually consists of a wheel. The wheel can cut and seal by parting the material ultrasoni-
Decorative Patterns

Ultrasonics are also used to emboss and decorate fabrics and films. By either plunge or scan welding, either the horn or anvil can contain an embossed pattern. The horn or anvil embosses much like a branding iron. When materials are clamped between them, they are fused in the areas that are compressed. It is recommended to engrave the anvil and not the horn; this provides longer life and is less expensive to fabricate.

A colorful decorative pattern is developed when one color of material is placed over a second color. When the right material is used, the color of the second material bleeds through the first, producing an interesting design.

The decorating technique may also serve functionally. For example, a simulated stitch or serpentine pattern may bond two or more materials as would a sewing machine. Patterns ultrasonically produced may allow the manufacturer to use a foam-in-place process after welding, since there are no stitch holes through which the foam can leak.

Degating. With the recent increase in the use of robotics for demolding parts, ultrasonic degating is a natural extension of the process. The concept is to vibrate the runner so that the parts move in an out-of-phase condition. The parts move back and forth and fatigue until the gate breaks. Ultrasonic degating is not normally successful with softer plastics. The part must also have sufficient weight to flex while the sonics are applied.

Gate size is important in successful degating. The horn makes contact with the runner while the parts hang in the air. Many short bursts of a sonic cycle work better than a single burst.

Adhesives. When adhesives are applied, they may cure too quickly. Most hot melts have a set-up time that is sometimes miscalculated, causing the adhesive to set up prior to total assembly. When this happens, ultrasonics are applied to the parts, causing the adhesives to remelt and reflow.

Parts can be precoated with heat-activated adhesives and ultrasonically assembled at a later time. Lamp shades and their ribbons use this process. String is also coated with adhesives and used as tear strips in packaging.

Solvent-bonded parts may be cured by ultrasonics. The ultrasonics reduce the solvent-bonding cure time and eliminate the need for clamps and storage areas.

Maintenance

Ultrasonic equipment requires minimum maintenance for long life. However, clean, dry air is required.

The horn is tested daily prior to starting production. If the reading is higher than normal, the connections between the horn and booster, and booster and convertor are examined. Burned or corroded joints are cleaned using a fine emery cloth.

The generator and press are opened every six months. After disconnecting the voltage line, dust and dirt are blown out of the generator and press. Loose or poor electrical connections are also repaired. The slide in the press, an important component, should operate smoothly. Grease or dirt that may accumulate is wiped off of any slide components. Tightness and bearing wear are also checked.

Pitfalls

Some materials, such as nylon, are hygroscopic. These materials absorb moisture easily. Moisture-laden materials require more weld time than dry materials. Hygroscopic materials are best welded at the molding press, where the material is dry and warm.

The temperature of the parts during welding can greatly affect the weld quality. A common mistake is to move parts from a cold storage area and bring them directly to the welder. These conditions can cause parts to craze or crack.

Materials such as talc, glass, and carbon are used in combination with various resins, to add stability to the molded parts. These fillers can aid in welding; however, they can also create problems. When welding parts with filler materials, the joint areas must be kept resin rich. A fill percentage of 15% or less is best. When filler material is near the material surface, excessive wear of the ultrasonic horn can be expected.

Coloring materials can affect part weldability. Lighter colors weld more easily than darker ones. Some additives used in coloring inhibit welding because they contain oils or releases. Dark colors may also mask defects in the material such as burned or contaminated material.

Regrinds can be used in materials that are ultrasonically welded. However, if the regrinds are not monitored closely, they will reduce the weld quality. The percentage used and the quality of the regrind determine the weld quality. The material degrades each time it is reprocessed.

Lubricants, oils, and release agents inhibit part weldability. Ultrasonic welding produces heat that is developed by friction.
Lubricants reduce friction, and therefore, they reduce the ability to bond. As little as one part per million (ppm) of lubricant can cause welding problems.

The lack of proper mold maintenance causes parts to weld inconsistently. Unnoticed pin wear produces tight joints. Flash is produced during welding, because worn molds allow molded components to touch during welding. Mold wear causes serious problems with shear welding.

There is a misconception that the ultrasonic welder produces its maximum wattage at every weld. All ultrasonic welders are on-demand systems. They produce wattage based on pressure, amplitude, and time. A variation in any of these parameters affects weld wattage.

A common mistake is to plug the ultrasonic welder into the same power supply as that used for the molding machine. When the molding machine is injecting plastic, a voltage drop usually occurs. When the welding cycle occurs in conjunction with the filling cycle, the voltage to the welder drops. If this drop is significant, it reduces the wattage and amplitude produced. On high-quality parts, this can mean the difference between acceptable parts and rejects.

Extension cords, multiple units on one circuit, or other equipment on the same circuit are common causes of voltage variations. Power peaks are equally as bad as voltage drops. In some cases, peak power can cause marginal-amplitude horns to crack.

Air pressure variations produce the same negative results as electrical power variations. As previously stated, air pressure is a main component used in producing a quality welded part.

All standard ultrasonic units are equipped with pressure regulators. These regulators ensure against overpressure. However, there are no safeguards when the pressure drops. The gage may read the correct pressure, but the air volume may be insufficient to keep the cylinder full. If the cylinder has not recovered, the force will diminish. This change affects the down speed, the total force on the part that affects the energy delivered.

Speed control valves and springs are integral parts of most welders. The speed control is used to control the head speed. Faster speeds deliver power more quickly into the part. Speed changes affect the weld result.

Springs are used in many welders to prevent the head from dropping rapidly in the case of an air line breakage. If the stroke length is changed, the force delivered to the part also changes. When the stroke is short, the spring produces little resistance, and as the stroke becomes longer, the resistance increases.

The amount of air pressure used to move the head is selected to deliver the proper power to the part. It is not selected based on head speed, which is determined by the speed control device.

Safety

Most ultrasonic welders are very safe. All modern standard presses use two-hand anti-tie-down switches.

Some ultrasonic equipment is used in areas where radio frequency welders are in use. The random radiation produced by this equipment can cause the ultrasonic welder to fire prematurely.

Noise produced by the sonic welders is usually harmless. Discomfort caused by squeal can be relieved by earplugs or headsets. When the sonic welder is positioned to function automatically, operators and personnel in the area require protection. The use of guards and safety gates is usually sufficient.

Troubleshooting

It is often difficult to determine the causes of poor welding, but certain rules always apply:

**Equipment works but not welding.** When two previously bonded parts are welded and the equipment functions properly, but parts have not flowed together. If there is melt in the joint area but no bond, this is an indication that mold release or other lubricants are present. A high concentration of filler material may also exist at the joint area.

**Not bonding.** When welding a shear joint, very little bond is made and there is no presence of mold release or lubricants. The down speed of the press should be checked to ensure that it is slow and that the sonics are pretriggered.

Excessive flash. Excessive flash at a joint area that previously welded correctly occurs when the weld cycle is too long, the welding pressure is excessive, or the head down speed requires increasing. One parameter is adjusted at a time.

**Internal component damage.** Internal components are damaged or bonded during welding. A reduction in cycle time or amplitude may eliminate this problem. If the welding operation is run on a 20-kHz machine, a 40-kHz unit may be required. Another solution is to change the internal parts to noncompatible materials. Lubricants or mold release may also be used on internal parts.

**Disc melts or holes produced.** When welding cylindrical parts, the center of the disc melts or holes blow through. An amplitude reduction may solve this problem. Additionally, the horn may be adapted with a nodal plunger.

**Insert not holding.** When an ultrasonic insert pulls out easily because the hole does not conform to the insert manufacturer’s specifications. The insert cannot be driven too fast or with a high-amplitude horn.

**Marks.** Marks appear on nest side of part. The fixture is made of the wrong material, and the part is moving in phase with the horn instead of out of phase. The nest may be made from a soft material; however, ensure that the material is retained within a metal housing.

**Microprocessor.**

Ultrasonic equipment manufacturers were aware of the shortcomings associated with conventional equipment. They searched for ways to improve the reliability of the welders. The solution was found in using a microprocessor and the more sophisticated devices that are only used with a microprocessor.

Each manufacturer provides basic controls, and some manufacturers have a variety of sophisticated controls available. Each user must determine which controls are necessary for his/her requirements.

Most microprocessor-based units allow the user to make a weld using various techniques. Nonmicroprocessor units use time to regulate the weld quality. With a microprocessor unit, welding is accomplished by energy, peak power, distance, or time. Although these are the primary parameters for welding, there are also secondary controls.

Many secondary parameters are monitored and controlled. Items such as total distance, weld distance, hold distance, energy, down speed time, total time, and peak power are some of the functions that are monitored. Electronic air regulators, pressure transducers, and linear encoders are optional features.

The microprocessor is a must for a precision manufacturer. The medical industry requires microprocessors that provide product history and validation.

The most misunderstood welding method when using the microprocessor is the weld-by-distance mode. There are two distance-welding modes. One, called absolute distance, measures the total distance the head travels to the weld completion. The second, the collapse distance mode, measures the distance from the start of the sonic cycle and terminates the cycle when a predetermined distance is reached.
When welding to an absolute distance, part-to-part variation is not considered. The weld terminates when the ultrasonic head has traveled a predetermined distance. This mode ensures that the overall part height remains consistent. The total distance that the part is driven beyond the predetermined length is determined by how molten the material gets during the welding cycle. A mechanical stop is used to ensure that this compression is controlled.

When welding in the collapsed mode, determining its dimension is often difficult. The most common mistake is to use the height of the energy director as the collapsed distance.

Most sonic equipment uses a trigger, pressure, or load cell-type switch to activate the ultrasonic cycle. Contact with the part is required to activate these switches. The amount of pressure that is exerted before activating the sonics varies among manufacturers. Also, the welded part influences when the sonics are activated. This contact compresses the parts prior to welding. As a result, at the start of the sonic cycle the energy director is already collapsed to a dimension less than the original height. Therefore, the total collapsed distance is less than the original energy director height.

When welding in the collapsed mode, trigger pressure and distance welded are determined empirically. However, in both the absolute and collapse distance mode, once a parameter is determined, it is accurately repeated. This assumes that the parts also remain consistent.

The microprocessor provides the industry with an excellent tool that provides more information in an understandable format. Most ultrasonic users who set up conventional welders can now demonstrate what is happening during the welding cycle. This allows the end user to analyze the data and make judgements based on this analysis.

**ELECTROMAGNETIC WELDING**

This section will describe the process of electromagnetic (EMA) bonding, general design considerations, work coil design, types of work coils, materials used, joint design, and design freedom allowed. EMA bonding of thermoplastics provides a simple, rapid, and reliable assembly technique to produce structural, hermetic, or high-pressure seals on most thermoplastic materials. It uses the principles of induction heating by developing fusion temperature at the abutting interface of welded parts.

The process is used to weld a thermoplastic, filled or unfilled, to itself or to certain dissimilar thermoplastics and nonthermoplastic materials (such as paper to thermoplastics). The EMA process can easily weld engineering, high-performance resins, and difficult-to-weld materials such as polyolefins and polyamides.

**Process**

Welding one thermoplastic part to another is achieved by inductively heating a ferromagnetically-filled thermoplastic medium layer at the joint interface to the fusion temperature of the abutting substrate. A chemical bond is obtained across this interface. The EMA medium layer consists of a thermoplastic matrix that is either the same as, or compatible to, the abutting substrate. This thermoplastic matrix incorporates a dispersion of fine-micron-sized ferromagnetic powders such as iron or stainless steel; heat losses develop from the filler concentration within the thermoplastic matrix of the medium preform. This occurs via eddy currents and hysteresis losses (see Fig. 16-19). The heat developed in the filler melts the thermoplastic matrix, which in turn locally melts the abutting substrate surface. The EMA material heats via induction, and fusion is achieved by conduction.

Four components comprise the process (Fig. 16-20). An induction generator converts 50–60-Hz electrical power to 3–8-MHz output frequency, with output power from 2–5 kW. Work coils are water-cooled copper inductors that develop the desired magnetic field intensity through the EMA material. Fixturing is used to hold parts.

![Fig. 16-19 Electromagnetic induction heating.](image1)

![Fig. 16-20 Electromagnetic welding process.](image2)
in place in the magnetic field. Finally, electromagnetic materials, essentially the key to the process, are typically supplied in the form of molded gaskets, extruded profile preforms, sheet, or as an integral part of the molded product via coinjection or insert molding.

**General Design Considerations**

The following design items are important when considering the electromagnetic process for an application:

- Material that is bonded—determines the thermoplastic matrix material used for the EMA preform.
- Environment for the end-use product— influences the filler type.
- Physical properties required (structural, hermetic, etc.)—suggest the preferred joint design.
- Geometry of the bond line—determines the work coil design and fixtures requirements.
- Coupling distance of the coil to the joint— inluences the filler particle size, power output and frequency, and resulting operating efficiency.
- Volume of units—determines the parts handling method: manual, semiautomatic, or fully automated.
- Size of part and joint length—determines the power output necessary.
- Speed— influenced by the filler type, filler particle size, coil type, cross-sectional dimension of the EMA material, power output, frequency output, part size, and joint configuration.

The two most important aspects that determine if a part can be fused via electromagnetic welding are work coil design and joint design. The other variables, such as power output, frequency, filler type and size, and polymer type, are controllable and tailored for each application.

**Work Coil Design**

A primary consideration for a successful electromagnetic bonding application is the design of the work coil. If fundamental coil design principles are adhered to, costly failures are eliminated and optimal operating efficiencies are achieved.

Work coils used in electromagnetic bonding are similar to those used in standard induction heating for annealing or heat treating metals at 200–500 kHz. In electromagnetic bonding of thermoplastics, higher frequencies, typically 3–8 MHz, are used. Because of these higher frequencies, coil design becomes important to reduce the tendency for overloading and arcing.

Sufficient power and frequency. Work coils are manufactured in a variety of types and styles, depending on the shape and size of the welded object and the bond area. The work coil design must follow certain principles to achieve maximum efficiency of the high-frequency generator. Rapid and reliable heating depends on (a) constructing a work coil that suits the application; and (b) the capacity or power output of the generator. That is, the generator must have sufficient power and frequency to heat the EMA material rapidly. If the part is shaped so that it can be surrounded by a work coil with a uniform coupling distance, then the application is a candidate for the electromagnetic bonding process. Most applications use a power output rating of 2–5 kW. Multiple work coils and generators can be used on a single application to increase speed.

Elevating EMA temperature. The induction coil quickly elevates the temperature of the EMA material, located at the bond interface, by passing high-frequency current through the coil that is inductively absorbed into this material. Heat develops in the EMA material via hysteresis and eddy current loss. The coil becomes the transformer’s primary circuit, with the EMA functioning as the secondary circuit. The EMA material is not a part of the closed electrical circuit, so the heat generation is solely through induction. The EMA material is typically nonconductive.

Heat is generated via energy losses within the EMA material; this results in a rapid temperature rise within the material. In ferrous powders such as iron or stainless steel, which have magnetic properties, these energy losses are a result of hysteresis and eddy currents up to the Curie point (where magnetic properties cease to exist). At this point, continued heating is created through eddy current losses only.

Since electromagnetic fields become exponentially more concentrated as the coupling distance to the coil is decreased, the bond line is located as close to the coil as possible to maximize the heat transferred into the EMA. The strength of the magnetic field varies inversely with the square of the distance between the EMA and the coil.

Figure 16-21 illustrates two single-turn coils, one exhibiting a close coupling distance and the second indicating a loose coupling distance. A coupling distance of 0.063 in. (1.6 mm) is satisfactory, but in some cases direct coil contact with the part, where the coil acts as a pressure medium, is preferable.

**Types of Work Coils**

Electromagnetic bonding work coils are available in single-turn, two-turn, hairpin, and split designs.

Single-turn coils. Due to the direction of the current and the resultant magnetic field on single-turn coils, a relatively weak
field intensity can develop at the end of the coil leads. However, this type of coil has the most design freedom. It requires less space and has fewer restrictions than other varieties. Whenever possible, a nonactive, water-cooled copper reflector is placed inside the coil. This increases the heating efficiency by concentrating the EMA field through the joint (Fig. 16-22). A reflector reduces cold spots at the leads, but if the part design permits, a two-turn coil eliminates this deficiency.

Two-turn coils. A variety of two-turn shapes are possible. The most common is a cylindrical or helical coil, shown in Fig. 16-23, which is used to weld round containers. A rectangular or square coil, or an irregularly shaped coil, is used to weld irregularly shaped items. For maximum efficiency, a reflector coil is again often placed inside the coil to concentrate the field within the joint area. This is especially the case for parts that are 6 in. (152 mm) in diameter and larger.

As a general rule, the length of a multiturn helical coil should not exceed three to four times its diameter. In designing helical copper tube coils where a restricting heat zone is desired, the coils are manufactured with an offset so that uniform heating is achieved.

Hairpin coils. Hairpin coils are actually single-turn coils squeezed together. This results in a coupling distance between the turns that is equivalent to the part thickness. The magnetic field is highly concentrated as the coupling distance is reduced. These coils can be formed into irregular shapes and are often used as dies within a press action that features movable and fixed platens. Hairpin coils are efficient for bonding long, flat sheets or perimeter seals of structural components with materials such as glass mat composites. Figure 16-24 illustrates a typical hairpin coil. Hairpins and helical designs are the most common types of coils.

Split coils. Split coils are used for easy removal of the part. Instead of using a single-turn coil and moving the part within it, the coil is split in half, and electrical contacts are made by actuating the split coils manually or with air cylinders. All coils are water cooled. Split coils are useful for large parts, such as pipe or conduit, or parts with limited access to the bond line, such as fittings with flanges. A split coil is illustrated in Fig. 16-25.

Materials Used to Construct Work Coils

Work coils are typically constructed from copper tubing, copper sheet stock, or machined blocks with brazed water cooling. Coils manufactured from tubing can be round, square, or rectangular and have 0.125 to 0.375 in. (3.2 to 9.5 mm) inside dimensions. The 0.125 in. (3.2 mm) dimension tubing is used sparingly, because it can constrict water flow and thus contribute to overheating. For short heat cycles and small parts (for which minimal heating should have little effect), this size must be considered.

Round copper tubing is used for many coil types; however, since coupling distance to the part is critical, square tubing is preferred.

Copper sheeting stock at 0.062 in. (1.6 mm) thickness is also used for applications up to 5 in. wide × 20 in. long (127 mm wide × 508 mm long) or 1 in. wide × 80 in. long (25.4 mm wide × 2.0 m long). The use of sheet stock permits large-surface-area sealing for irregular flat shapes.

Joint Design

There are many approaches to the proper joint; each depends on the application. One influencing factor is whether the part is injection molded, blow molded, extruded profile, or thermoformed. The most critical factors that determine joint design are the performance requirements. If a hermetic seal is required, a tongue-and-groove design is recommended. If a high-pressure hermetic seal is needed, a step joint or a tongue-and-groove joint designed to place the EMA material in shear is appropriate. If only a static-flow airtight seal or a structural weld is required, a flat-to-flat flange is sufficient. As long as there is sufficient room within the package limits, a tongue-and-groove joint, which places the EMA material in shear, is best. This type of joint provides the best sealing reliability and strength. If the EMA material is dispensed automatically via an extruder, a flat-to-
A groove joint is most appropriate. Typically, this type of application covers high-volume structural welds.

Since the EMA material that is located at the joint interface becomes molten when activated, it flows under pressure into the voids and irregular surfaces to produce reliable welds. Ideally, the molten flow is contained and subjected to an internal pressure against the abutting weld surface. The flow of the EMA material is compared to filling a cavity in injection molding. The following formula is used to determine the amount of material required to fill the joint:

\[ A_E = k A_v \]

where:

- \( A_E \) = cross-sectional area of the EMA material
- \( k \) = 0.02–1.07, a constant that depends on the joint interface pressure and the welded material
- \( A_v \) = cross-sectional area of the joint void

Figure 16-26 illustrates this ratio in joint configurations. Figure 16-27 illustrates several typical joints.

**Design Freedom**

The electromagnetic welding process offers many advantages over conventional bonding techniques. The process is used to weld highly filled thermoplastic materials, very large parts, 3D joint planes, and difficult-to-weld materials such as polyolefins.

The fillers and fibers in filled materials have replaced part of the thermoplastic matrix. This results in resin-poor areas, which present difficulties for most conventional welding techniques. When welding these filled resins, the thermoplastic matrix of the EMA material fulfills a dual purpose: it not only transports the fusion heat, but also provides the necessary additional resin to ensure polymer-to-polymer linkage.

The EMA process is used to weld very large bond lines (up to 20 in. [508 mm] in length) in one shot. The process is also capable of continuous-area web sealing of large thermoplastic sheet materials such as woven and nonwoven polyethylene liners. The sheets are overlapped with the EMA material at the interface and fed past a small coil, which welds them as they pass through the electromagnetic field.

With multiplane joints, heat generation by mechanical-friction techniques becomes difficult or impossible. Irregular and contoured welds in different planes are readily welded with the EMA process. An interesting side benefit of the electromagnetic process is the ability to reactivate the bond line and separate the weld.

Figure 16-28 is an example of welding 2 in. (51 mm)-diameter threaded HDPE fittings directly to the opening of 55 gal (208 L) blow-molded drums. For reconditioning drums, the fitting can be removed and replaced.

**FASTENERS**

This section will discuss mechanical fasteners for plastics, fasteners for composite materials, and the use of bolt-nut combinations.

![Fig. 16-25 Split coil.](image)

![Fig. 16-26 Typical joint void ratios.](image)
Mechanical Fasteners for Plastics

The more extensive use of plastics in various products and the many types of plastics available have increased the demand for special fasteners. Advantages of such fasteners over standard types often include lower torque requirements for driving the fasteners into assemblies, higher shear strengths because of the special threads used, and the capability to withstand higher torque loads before the fastener threads begin to strip the plastics. Screw thread inserts are used extensively to hold fasteners in plastics.

Many types of special fasteners are available, because requirements vary with the plastics used in the assemblies. The plastics must have sufficient strength to withstand the strain of fastener insertion, and the fasteners must distribute the loads and stresses properly. General requirements for special fasteners used in plastics include large flank areas on their threads, wide thread spacing, and sharp threads.

Special fasteners of the thread-forming type that eliminate the need for tapping and inserts, thus resulting in lower costs, are used most extensively for softer plastics. Thread-cutting fasteners are more common for harder plastics. Metal inserts are sometimes provided in the plastic components, especially if the fasteners are removed periodically. Most fasteners are available with a variety of head and point styles.

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Thread-forming types of special fasteners for plastics are generally made of low-carbon steels, SAE 1018–1022, and are case hardened to about Rc 45. The fasteners are commonly zinc plated, but other finishes are also available. One fastener design has a single-lead, spaced (high-pitch) thread with a sharp 40° profile and large root diameter. This design provides ample material between the threads formed.

Another type of special fastener has a trilobular-shaped, single-lead, coarse thread with a one-to two-thread tapered point. It roll forms threads in plastics without cutting and minimizes radial stresses. A fastener developed specifically for use with heat-sensitive thermoplastics has a twin-lead thread. The number of threads is the same as in a single-lead fastener, but each of the two leads has only half as many threads. This design permits faster insertion with less frictional heat generated.

Another special fastener for plastics has a double-lead thread of dual-height design. The lower thread on this fastener varies in height from one-third to one-half that of the higher thread. This design provides high strength and resistance to pullout forces.
Push-in or push-on fasteners that require no rotation during assembly are also available. These fasteners have flexible barbs, rings, ribs, or threads on their shanks and are pressed into thermoplastic assemblies. The pressure flanks of the barbs, rings, ribs, or threads grip the material.

**Fasteners for Composite Materials**

The advent of advanced composite materials, which are finding increased use in the aircraft and aerospace industries because of their strength and light weight, has posed some fastening problems. Many metallic fasteners are fairly incompatible with composite materials because of corrosion. Stainless steel and titanium fasteners work relatively well for composites, but stainless steel introduces weight penalties, and titanium results in increased costs.

Fasteners made of glass or graphite-reinforced plastics do not corrode galvanically, are lightweight, and reduce costs because corrosion-resistant coatings and sealants are not required.

One design for a sleeve-and-pin-type fastener made of glass-reinforced epoxy is illustrated in Fig. 16-29. When these fasteners are made from thermosetting plastics, they are installed with an adhesive. When made from thermoplastic materials, they swell on installation, thus eliminating the need for close hole tolerances.

**Bolt-nut Combination**

A self-retaining, positive-locking bolt-nut combination is shown in Fig. 16-30. The locking feature of this special-purpose fastener consists of a spring-loaded plunger pin and two hardened steel balls positioned within the shank of the bolt. Spring force maintains the plunger in an extended position, securely maintaining the balls in an expanded position. This expansion provides a mechanical lock with mating axial grooves or splines in the nut. To unlock the fastener, the plunger pin is depressed, allowing the balls to retract and permitting the nut to rotate freely on the bolt. Because of the hollow bolt design, tension applications are not recommended. Shear applications, such as clevis joints, where the bolt-nut is free to turn with the joint, are the primary uses for this type of fastener.

**REQUIREMENTS CHECKLIST**

The following checklist is to help comprehensively define machine vision application requirements and can be used as a review of requirements for the assembly process. While virtually all machine vision vendors have application description forms, they typically only review a few of the issues buyers must understand.

When completed, the checklist becomes the basis for a procurement document that conveys the application’s technical and contractual requirements to prospective vendors. Bids that reflect a consistent understanding of the requirements should result from using the checklist.

The form helps determine if pursuing a project makes sense and is a valid corporate objective. In addition, it permits examining the application from two perspectives: what the system must do and what appearance variables the system must tolerate. Critical to the success of any machine vision installation is understanding the variables that can cause contrast and positional uncertainty.

On the form, requirements, such as material handling, operator and line interfaces, and environmental issues, are defined. Goals, such as reliability, and policies, such as warranty, field service, spare parts, documentation, installation, and training, are also addressed. Most importantly, the user describes buy-off procedures, performance acceptance criteria, and the responsibilities of the buyer and vendor before delivery to avoid later concerns.

Using the checklist to define machine vision requirements does not guarantee success. It does, however, help identify the type of system that best meets the user’s requirements.

**Section 1: Production Process**

1. What is the product?
2. How is it made?
3. What is the expected product life?
4. Is the product (or the problem) going to be in production long enough to justify the purchase of a system?
5. Why are inspection and control needed? Are there problems? Is process improvement the goal?
6. What is the current part reject rate?
7. What is the accuracy of the current inspection system?
8. If parts are inspected or control is improved, what are the specific benefits expected?
9. Will the system be for a new or an old line (retrofit)?
10. Does the application involve:
   - One object at a time?
   - Different objects? If so, how many?
   - Multiple objects?
   - Different part numbers? If so, what are they?
11. Is it a batch operation or a continuous, dedicated process/line?
12. What are the changeover times and the frequency of changeovers?
13. What are the skill levels involved in a changeover?
14. How is the inspection and/or function to be replaced currently being performed? Is it effective?
15. Is inspection to be on or off line?
16. Must every item produced be inspected, or is random sampling acceptable?
17. Will new part models or variations be added to the system at a later date? Define any potential future inspections that may be required of the same machine vision systems.
18. Are product design or production process changes anticipated?
19. Where do parts come from?
20. Can rejected parts be repaired?
21. Can vision assist in the diagnosis?
22. Where do pass and fail parts go?
23. When is the machine vision system needed?
24. How many shifts will use the system?
25. How many lines/machines will need the system?
26. What is the attitude of the plant floor personnel toward machine vision/automation?
27. What is the attitude of the plant’s management toward machine vision/automation?
28. What is your attitude toward machine vision/automation?
29. Can a representative sample of parts be provided to system vendors or integrators for evaluation?
30. Can drawings be provided?
31. Can a video of the line be provided?
32. Can the vision suppliers observe production at your facility?

Section 2: Benefits of Inspection

1. When an incorrect or flawed part escapes detection, what are the downstream effects (quality, repair, machine downtime, etc.)?
2. If a bad part is assembled, does it cause problems with the overall assembly?
3. If inspection is implemented, can any downstream testing requirements be relaxed?
4. If inspection is implemented, is improvement in the yield through testing expected?
5. At the inspection point, what is the cost (qualitative or quantitative) of a bad (faulty) part that escapes?
6. At the inspection point, what is the cost (qualitative or quantitative) of a good part that is falsely rejected?

Section 3: Application

1. Describe the application.
2. What distinguishes a bad part from a good part?
3. Does the application involve gaging? (Show a sketch or drawing, if possible. Highlight critical items.)
   • What are the tightest tolerances?
   • On what dimension are the tolerances tight?
   • What is the design goal for accuracy?
   • What features serve as references?
   • Describe the calibration requirements.
4. Assembly verification:
   • What are the assembly dimensions?
   • Is there a presence/absence check?

Section 4: Part Inspection

1. Describe the part(s) to be inspected (consider those conditions that can change the appearance of the part or background). Are drawings available?
2. What is the material (steel, plastic, etc.)?
3. What is the finish (texture)?
   • Is the surface finish the same on all part faces?
   • Is the surface finish the same for all part numbers and/or production runs? Describe any differences.
   • Describe the platings.
   • What is the coating?
   • Are there thin films (oils, mist, etc.)?
   • Is the paint dull, glossy, specular, highly reflective (mirror-like), poorly reflective, matte, etc.?
   • Will the reflectivity change from part to part or over time?
Section 5: Material Handling

4. Are there any machining marks on the part?
   • Does the part have scratches, nicks, burrs, dents, etc.?
   • Is there porosity in the parts?
5. What are the shapes of the parts?
6. Is the part always oriented in the same direction?
7. What is the part temperature?
8. What is the part size? What are the smallest and largest parts?
9. Are there different colors for different models?
   • Does the color change from part to part?
   • Is the color single hue?
   • Are there saturation variations?
   • Are there subtle color variations?
   • Are there discrete color variations?
   • Are broad and discrete colors mixed?
10. Discuss conditions such as warpage, shrinkage, or bending.
11. Is there an appearance change over time due to the environment (rust inhibitors, corrosion, lubricants, dirt, perishability, etc.)?
12. Are there any markings on the part?
13. Can a reference mark be made on the part if necessary?
14. What are the part appearance variables?
15. Is the surface translucent? Describe variations in translucent optical density/degree of opaqueness.
16. Is the surface totally or partially (or not) transparent?
17. Is the part heat sensitive?
18. Is the part light sensitive? If yes, to what type of light (ultraviolet, visible, infrared)?

Section 6: Operator Interface

1. Describe the desired operator interface. Describe the “must have” and “like to have” items.
2. Describe the operators who will operate the equipment (educational level; familiarity with machinery, electronics, computers; experience; etc.).
3. Describe the personnel access requirements (password protection, etc.).
4. Are there enclosure requirements?
5. Is it desirable to display the last reject condition?
6. Is it desirable to display the last reject condition?
7. Is fail-safe operation required (part considered a reject unless it passes)?
8. What are the desired program storage requirements?
9. What are the desired data storage requirements?
10. Is there power-failure program storage preservation? Is there power-failure data storage preservation?
11. Describe the reporting requirements. Must reports be generated without interrupting the inspections?
12. What type of data will the system be required to display to a CRT or communicate to an external device? If statistics are required, how often will the reports be generated? Will the reports need to be printed and/or displayed?
13. What false reject rate is acceptable?
14. What escape rate or false acceptance rate is acceptable?

Section 7: Machine Interfaces

1. Are alarms desired?
2. What other machines must this system be integrated with mechanically or electrically?
3. What event will trigger an inspection?
   • How will the event be detected?
   • How will this be communicated to the inspection system?
4. How will the results of the inspection be communicated and implemented?
5. Describe the machine interfaces/handshaking signals, etc., required. Is signal conditioning required? Describe other interface details.
6. Describe the hierarchical interfaces anticipated (to host computer, PLC, data, programs, etc.).
Section 8: Environmental Issues
1. Describe the environment in which the system must operate. Include the factory, clean room, laboratory, and indoor/outdoor environments.
2. Describe the air quality. Include dust/smoke, steam, oil, etc.
3. Describe the ambient light (incandescent, fluorescent, etc.).
4. Is there dirt or lubricant on the parts?
5. Describe the wash-down requirements.
6. Is there a corrosive atmosphere?
7. What are the operating and storage temperature ranges?
8. What are the operating and storage humidity ranges?
9. Is there exposure to electromagnetic interference (EMI) or radio frequency interference (RFI) radiation?
10. Is there exposure to shock or vibration?
11. Is a hazardous environment present?
12. Describe the available utilities.

Section 9: System Reliability/Availability
1. How many hours per week will the system be used?
2. How many hours per week are available for maintenance?
3. Describe the calibration procedures required.
4. Describe the challenge procedure used to routinely verify performance.
5. How much maintenance time is allowed between failures?
6. How much maintenance time is allowed for repair?
7. What is the response time to service?

Section 10: Other System Issues/Requirements
1. Are there special paint colors?
2. Is shipping provided?
3. Is installation provided?
4. Is a warranty provided?
5. Are spare parts available?
6. Is documentation provided?
7. Is training provided? Where and when?
8. Software issues:
   • Will the vendor be required to support software revisions? If so, for how long?

References

Bibliography

Section 11: Acceptance Test/Buy Off Procedure
1. What assures that the machine is functioning properly? (Describe performance test hurdles.)
2. Tests at vendor site:
   • Can good, bad and/or marginal parts be provided?
   • What is the sample size for each challenge?
   • Define acceptability criteria for each challenge.
   • Define part variations or parts to be used during acceptance testing.
   • Define part position variations to be used during acceptance testing.
   • Define lighting variations to be used during acceptance testing.
   • Define environmental conditions.
3. Tests at installation site:
   • Can good, bad and/or marginal parts be provided?
   • What is the sample size for each challenge?
   • Define acceptability criteria for each challenge.
   • Define part variations or parts to be used during acceptance testing.
   • Define part position variations to be used during acceptance testing.
   • Define environmental conditions.

Section 12: Other Responsibilities
1. Describe the responsibilities for the designing and building of fixtures, installation, and start-up.


*Technical Resources on Coating Processes*, (Dearborn, MI: Association for Finishing Processes of the Society of Manufacturing Engineers).

CHAPTER 17

QUALITY CONTROL, ASSURANCE AND IMPROVEMENT

INTRODUCTION

Quality control attempts to reduce costs by minimizing variations and eliminating waste. Minimizing costs improves profitability and makes sustained competitive pricing possible. Quality is focused on meeting the customer's needs at a reasonable cost. Meeting the client's requirements increases satisfaction and a willingness to continue doing business. Taken together, cost and quality produce value.

Companies compete based on the value represented to their customers and shareholders. Even when price seems to dominate other considerations, quality remains part of the equation. In these cases, quality is at some competitively acceptable level. Without quality, even the lowest price represents poor value.

Reducing costs while improving quality increases value, and this is the essence of this chapter.

WHAT IS QUALITY?

The word quality is derived from the Latin word qualis, meaning of what kind. Other definitions reflect a variety of views. They run from the measurable “degree of conformance to specifications” to the unmeasurable “point where the tangible and intangible meet.” Some common definitions are:

• The degree of fitness for a particular purpose.
• The degree of excellence exhibited compared to similar items.
• The generation of minimum loss to society as a whole.
• The totality of the characteristics that affects the ability to satisfy needs.

No all-encompassing definition of quality exists. It is often defined according to the needs of the evaluator. As a result, the ultimate quality definition usually rests with the customer. Quality is defined in this chapter as the degree of conformance to requirements.

WHY IMPROVE QUALITY?

Manufacturing is constantly evolving. Knowledge is increasing exponentially. New communication methods quickly apprise competitors of the latest advances. Expectations increase as knowledge, communications, and access come together, making the once adequate obsolete. Change is often required just to maintain a competitive position.

Quality touches every aspect of manufacturing, from the original planning to the customer's perceptions that persist after the sale is final. Quality operates on many levels and interfaces among the levels. Unfortunately, quality is often implemented poorly, leading to increased costs and poor returns on the quality investment.

CHAPTER OVERVIEW

There are many ways to implement quality. Several basic requirements include:

• Management commitment and leadership that go beyond visible support.
• Communication and education that create a widespread consistency of purpose.
• The tenacity to keep moving forward and trying new approaches even though some of them may fail.
• The use of quality systems and tools to bring structure to the process.

This chapter is an introduction to some of the tools and techniques used to control, assure, and improve quality.

Quality systems list the minimum elements that are addressed in a comprehensive quality approach.

Quality Systems

Plastic manufacturing covers many quality systems. They have developed from a number of U.S. government agencies: the Department of Defense (DoD), the Federal Aviation Administration (FAA), the Atomic Energy Commission (AEC), the Food and Drug Administration (FDA), the Department of Transportation (DOT), and the National Aeronautics and Space Administration (NASA). All of these agencies require documentation supporting a quality product.

The aircraft and automotive industries have adopted U.S. government manufacturing are MIL-Q-9858A, Quality Program Requirements; MIL-I-45208, Inspection System Requirements; and ANSI/NCSL Z 540-1-1994, Calibration System Requirements.

The aircraft and automotive industries have adopted...
DI-9000 and QS-9000 standards, which are similar to the ISO 9000 standards. 

MIL-Q-9858A. This quality program has eight sections that are outlined as follows:

1. Scope and applicability. This specification applies to all items when referenced on the contract or order.
   - Contractual intent.
   - Summary.
   - Relation to other contract requirements.
   - Relation to MIL-I-45208.

2. Superseding, supplementation, and ordering. Contract or order modification procedures.
   - Ordering government documents.

3. Quality program management.
   - Organization. Management for quality is clearly prescribed by the contractor.
   - Initial quality planning. The quality, process, tooling, fixtures, testing, and skills required to assure product quality are defined.
   - Work instructions. Documented instructions include all manufacturing, inspections, testing, and handling of the product.
   - Records. Quality program records include documentation of work flow, process control, testing acceptance, work performance, and management actions.
   - Corrective action. The quality program shall promptly detect and correct assignable conditions adverse to quality.
   - Costs related to quality. These data identify the cost of preventing and correcting nonconforming product and are reported to management on a timely basis.

   - Drawings, documentation, and changes.
   - Measuring and testing equipment.
   - Production tooling used as media of inspection.
   - Use of contractor’s inspection equipment.
   - Advanced metrology requirements.

5. Purchase Control.
   - Responsibility. Selection of suppliers and quality clauses.
   - Purchasing data. Quality assurance approves all data necessary to assure product quality such as materials, chemical and physical properties, heat treatment processing, plating, and subcontract definition.

6. Manufacturing control.
   - Materials and materials control.
   - Production processing and fabrication.
   - Completed item inspection and testing.
   - Handling, storage, and delivery.
   - Nonconforming material.
   - Statistical quality control and analysis.
   - Indication of inspection status.

   - Government inspection at subcontractor’s or supplier’s facilities.
   - Government property.
   - Damaged government-furnished material.
   - Bonded material.

8. Other. ISO 9000 series would also include service, training, and continuous improvement requirements.
   - Intended use.
   - Exemptions.

The MIL-Q-9858A quality system covers most of the ISO 9001 requirements except training and servicing.

ISO 9000. Globalized economics have fostered continuous improvement, partnerships, upgrading of skills, and improving customer satisfaction. As a result, a quality system that enhances these areas, called ISO 9000, has been developed.

There are five standards that comprise the ISO 9000 quality series; they are listed in Table 17-1.

The International Organization for Standardization (ISO) requires reconfirmation of all standards every 5 years.

Table 17-2 lists equivalent standards that are used in the United States, United Kingdom, France, Germany, the Netherlands, and other countries. Table 17-3 shows requirements for ISO 9000.

In most cases, companies involved in plastics manufacturing seek the ISO 9001 standard.

### Table 17-1
ISO 9000 Standards

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 9000</td>
<td>Guide to selection and use of the appropriate part of the ISO 9000 series</td>
</tr>
<tr>
<td>ISO 9001</td>
<td>Specification for design, development, production, and servicing</td>
</tr>
<tr>
<td>ISO 9002</td>
<td>Specification for production and installation</td>
</tr>
<tr>
<td>ISO 9003</td>
<td>Specification for final inspection and testing</td>
</tr>
<tr>
<td>ISO 9004</td>
<td>Guide to quality management and quality system elements</td>
</tr>
</tbody>
</table>

### Table 17-2
ISO-Equivalent Standards

<table>
<thead>
<tr>
<th>International</th>
<th>United States</th>
<th>U.K.</th>
<th>Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 9000</td>
<td>ANSI/ASQC Q90</td>
<td>BS5750 Part 0</td>
<td>EN29000</td>
</tr>
<tr>
<td>ISO 9001</td>
<td>ANSI/ASQC Q91</td>
<td>BS5750 Part 1</td>
<td>EN29001</td>
</tr>
<tr>
<td>ISO 9002</td>
<td>ANSI/ASQC Q92</td>
<td>BS5750 Part 2</td>
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<td>ANSI/ASQC Q93</td>
<td>BS5750 Part 3</td>
<td>EN29003</td>
</tr>
<tr>
<td>ISO 9004</td>
<td>ANSI/ASQC Q94</td>
<td>BS5750 Part 4</td>
<td>EN29004</td>
</tr>
</tbody>
</table>

### Table 17-3
ISO 9000 Quality System Requirements

<table>
<thead>
<tr>
<th>Management responsibility</th>
<th>Inspection, measuring, and testing equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design control</td>
<td>Corrective action</td>
</tr>
<tr>
<td>Purchaser-supplied product</td>
<td>Internal quality audits</td>
</tr>
<tr>
<td>Inspection and testing</td>
<td>Statistical techniques</td>
</tr>
<tr>
<td>Control of nonconforming product</td>
<td>Contract review</td>
</tr>
<tr>
<td>Quality records</td>
<td>Purchasing</td>
</tr>
<tr>
<td>Servicing</td>
<td>Process control</td>
</tr>
<tr>
<td>Quality system</td>
<td>Inspection and test status</td>
</tr>
<tr>
<td>Document control</td>
<td>Handling, storage, packaging, and delivery</td>
</tr>
<tr>
<td>Product identification and traceability</td>
<td>Training</td>
</tr>
<tr>
<td></td>
<td>Quality costs</td>
</tr>
</tbody>
</table>
The inputs and outputs applicable to the quality planning process may vary according to the product and process, and customer needs and expectations. Some recommendations are as follows.

**Inputs:**
- Voice of the customer.
- Market research.
- Historical warranty and quality information.
- Team experience.
- Business plan/marketing strategy.
- Product/process benchmark data.
- Product/process assumptions.
- Product reliability studies.
- Customer inputs.

**Outputs:**
- Design goals.
- Reliability and quality goals.
- Preliminary bill of material.
- Preliminary process flow chart.
- Preliminary listing of special product and process characteristics.
- Product assurance plan.
- Management support.

**VOICE OF THE CUSTOMER**
The “voice of the customer” encompasses the complaints, recommendations, data, and information obtained from internal and/or external customers. Some methods for gathering this information appear in the following sections.

**Market Research**
The product quality planning team may obtain market research data and information reflecting the voice of the customer. The following sources can assist in identifying customer concerns and translate those concerns into product and process characteristics:
- Customer interviews.
- Customer questionnaires and surveys.
- Market test and positioning reports.
- New product quality and reliability studies.
- Competitive product quality studies.

**Historical Warranty and Quality Information**
A list of historical customer concerns is prepared to assess the potential for recurrence during the design, manufacture, installation, and use of the product. These are considered an extension of the other design requirements and are included in the analysis of customer needs.

The following items can assist the team in identifying customer concerns and prioritizing appropriate resolutions:
- Warranty reports.
- Capability indicators.
- Supplier plant internal quality reports.
- Problem resolution reports.
- Customer plant returns and rejections.
- Field return product analysis.

**Team Experience**
The team may use any appropriate source of information, including the following:
- Input from higher system levels or past quality function deployment (QFD) projects.
- Media commentary and analysis. For example: magazine and newspaper reports.
- Customer letters and suggestions.
- Dealer comments.
- Fleet operator’s comments.
- Field service reports.
- Internal evaluations using surrogate customers.
- Road trips.
- Management comments or direction.
- Problems and issues reported from internal customers.
- Government requirements and regulations.
- Contract review.

Planning includes a business plan and marketing strategy, a product assurance plan, and management support.

**BUSINESS PLAN/MARKETING STRATEGY**
The customer business plan and marketing strategy set the framework for the product quality plan.

The business plan may place constraints on the team (for example, timing, cost, investment, product positioning, and research and development resources) that affect the direction taken. The marketing strategy defines the target customer, the key sales points, and key competitors.

**Product/Process Benchmark Data**
Benchmarking provides input for establishing product/process performance targets. Research and development may also provide benchmarks and concept ideas. Other methods for successful benchmarking include:
- Identifying the appropriate benchmarks.
- Understanding the reason for the gap between current status and the benchmark.
- Developing a plan to either close the gap or match or exceed the benchmark.

**Product/Process Assumptions**
Assumptions are made that the product has certain features, design, or process concepts. These include technical innovations, advanced materials, reliability assessments, and new technology. All information is used as inputs.

**Product Reliability Studies**
These data consider the frequency of repair or replacement of components within designated time periods and the results of long-term reliability/durability tests.

**Customer Inputs**
Product users can provide valuable information relating to their needs and expectations. These inputs are used by the customer and/or supplier to develop agreed upon measures of customer satisfaction.
Design Goals
Design goals are a translation of the voice of the customer into tentative and measurable design objectives. The proper selection of design goals assures that the voice of the customer is not lost in subsequent design activity.

Reliability and Quality Goals
Reliability goals are established based on customer needs and expectations, program objectives, and reliability benchmarks. Examples of customer expectations include no safety failures or good serviceability. Some reliability benchmarks are competitor product reliability, consumer reports, or frequency of repair over a set time period. Overall reliability goals are expressed in terms of probability and confidence limits. Quality goals are targets based on continual improvement. Some examples are parts per million, defect levels, or scrap reduction.

Preliminary Bill of Material
The team should establish a preliminary bill of material based on product/process assumptions and include an early subcontractor list. To identify the preliminary special product/process characteristics, the appropriate design and manufacturing process is selected.

Preliminary Process Flow Chart
The anticipated manufacturing process is described using a process flow chart that is developed from the preliminary bill of material and product/process assumptions.

Preliminary Listing of Special Product and Process Characteristics
Special product and process characteristics are identified by the customer, in addition to those selected by the supplier, through knowledge of the product and process. At this stage, the team develops a preliminary list of special product and process characteristics resulting from analyzing the input of customer needs and expectations. This list may be developed from the following items:

- Product assumptions based on the analysis of customer needs and expectations.
- Identification of reliability goals/requirements.
- Identification of special process characteristics from the anticipated manufacturing process.
- Similar-part failure mode and effects analyses (FMEAs).

PRODUCT ASSURANCE PLAN
The product assurance plan translates design goals into design requirements. The effort devoted to the product assurance plan by the product quality planning team depends on the customer needs, expectations, and requirements. The product assurance plan can be developed in any format and should include the following actions:

- Outlining program requirements.
- Identifying reliability, durability, and apportionment/allocation goals and/or requirements.
- Assessing new technology, complexity, materials, application, environment, packaging, service, and manufacturing requirements or other factors that may place the program at risk.
- Developing a failure mode analysis (FMA).
- Developing preliminary engineering standards requirements.

MANAGEMENT SUPPORT
One of the keys to the product quality planning team's success is the interest, commitment, and support of upper management. The team should update management at the conclusion of every product quality planning phase to maintain their interest and reinforce their commitment and support. Updates and/or requests for assistance can occur as frequently as the team requires. Formal updates provide the opportunity for questions and answers. A functional goal of the product quality planning team is to maintain management support by demonstrating that all planning requirements are met and concerns are documented and scheduled for resolution. Participation by management in product quality planning meetings is vital to the success of the program.

PRODUCT DESIGN AND DEVELOPMENT
The product quality planning team should consider all design factors in the planning process, even if the design is owned by the customer or is shared.

INFORMATION REQUIREMENTS
The product quality planning process as described earlier, is designed to assure a comprehensive and critical review of engineering requirements and other related technical information. At this process stage, a preliminary feasibility analysis is made to assess potential problems that could occur during manufacturing.

Good product design and development is always preceded by good product planning. This includes inputs such as: market research, warranty histories, company-wide experiences, product/process benchmark data, product/process assumptions, product reliability studies, design goals, reliability and quality goals, preliminary bill of material information, process flow chart, listing of special product and process characteristics, and a product assurance plan.

The steps for design include a prototype build to verify that the product or service meets the customer's objectives. A feasible design must meet (a) production volumes and schedules, (b) engineering requirements, and (c) quality, reliability, investment cost, weight, unit cost, and timing objectives. Although feasibility studies and control plans are primarily based on engineering drawings and specification requirements, valuable information is also derived from the analytical tools described in this section.

DESIGN ACTIVITY
After processing information is acquired from the planning stage, the following are done:

- Design failure mode and effects analysis (DFMEA).
- Design for manufacturability and assembly.
- Design verification.
- Design reviews.
- Prototype build control plan.
- Engineering drawings (including math data).
- Engineering specifications.
- Material specifications.
- Drawing and specification changes.
Design Failure Mode and Effects Analysis (DFMEA)
The DFMEA is a disciplined analytical technique that assesses the probability of failure as well as the effect of such failure. A form of DFMEA is a systems failure mode and effects analysis (SFMEA). A DFMEA is a living document that is continually updated as customer needs and expectations require. Preparing the DFMEA provides the team with an opportunity to review the previously selected product and process characteristics and make necessary additions, changes, and deletions.

Design for Manufacturability and Assembly
Design for manufacturability and assembly is a simultaneous engineering process that is designed to optimize the relationship between design function, manufacturability, and ease of assembly. The scope of customer needs and expectations that were previously defined determines the extent of the supplier’s product quality planning team involvement in this activity. At a minimum, the items listed here are considered by the product quality planning team:

- Design, concept, function, and sensitivity to manufacturing variation.
- Manufacturing and/or assembly process.
- Dimensional tolerances.
- Performance requirements.
- Number of components.
- Process adjustments.
- Material handling.

The product quality planning team’s knowledge and experience, the product/process, government regulations, and service requirements may require consideration of other factors.

Design Verification
This step verifies that the product design meets the customer requirements that were derived from the previously described activities.

Design Reviews
Design reviews are regularly scheduled meetings led by the supplier’s design engineering activity and must include other affected areas. This review is an effective method of preventing problems and misunderstandings; it also provides a mechanism to monitor progress and report to management.

Design reviews are a series of verification activities that are more than an engineering inspection. At a minimum, design reviews should evaluate:

- Design/functional requirement(s).
- Formal reliability and confidence goals.
- Component/subsystem/system duty cycles.
- Computer simulation and bench test results.
- DFMEA(s).
- Review of the design for manufacturability and assembly effort.
- Design of experiments (DOE) and assembly build variation results.
- Test failures.
- Design verification progress.
- Product and process validation of components and assemblies through the application of a comprehensive test plan.

Prototype Build Control Plan
Prototype control plans are descriptions of the dimensional measurements, material, and functional tests that occur during prototype build. The product quality planning team should ensure that a prototype control plan is prepared.

The manufacture of prototype parts provides an excellent opportunity for the team and the customer to evaluate how well the product or service meets the voice-of-the-customer objectives. All prototypes that are the product quality planning team’s responsibility are reviewed to:

- Assure that the product or service meets specification and data are reported as required.
- Ensure that attention is given to special product and process characteristics.
- Use data and experience to establish preliminary process parameters and packaging requirements.
- Communicate any concerns, deviations, and/or cost impact to the customer.

Engineering Drawings
Customer designs do not preclude the planning team’s responsibility to review engineering drawings. Engineering drawings may include special characteristics (for example, governmental, regulatory, and safety) that are shown on the control plan. When customer engineering drawings are nonexistent, the control drawings are reviewed by the planning team to determine which characteristics affect fit, function, durability, and/or governmental regulatory safety requirements.

Drawings are reviewed to determine if there is sufficient information for a dimensional layout of the parts. Control or datum surfaces/locators are clearly identified so that appropriate functional gages and equipment can be designed for ongoing controls. Dimensions are evaluated to assure feasibility and compatibility with industry manufacturing and measuring standards. If appropriate, the team assures that math data is compatible with the customer’s system for effective two-way communications.

Engineering Specifications
A detailed review and understanding of the controlling specifications help the product quality planning team to identify the functional, durability, and appearance requirements of a component or assembly. Sample size, frequency, and acceptance criteria of these parameters are defined in the in-process test section of the engineering specification. Otherwise, the sample size and frequency are determined by the supplier and listed in the control plan. In either case, the supplier should determine which characteristics affect or control the results that fulfill functional, durability, and appearance requirements.

Material Specifications
In addition to drawings and performance specifications, material specifications are reviewed for special characteristics that relate to physical properties and performance, and environmental, handling, and storage requirements. These characteristics are also included in the control plan.

Drawing and Specification Changes
Where drawing and specification changes are required, the team must ensure that the changes are properly documented and promptly communicated to all affected areas.
OUTputs BY PRODUCT QUALITY PLANNING TEAM
Factors to consider are:

• New equipment, tooling, and facilities requirements.
• Special product and process characteristics.
• Gages/testing equipment requirements.
• Team feasibility, commitment, and management support.

New Equipment, Tooling, and Facilities Requirements
The DFMEA, product assurance plan, and/or design reviews may identify new equipment and facilities requirements. The product quality planning team should address these requirements by adding the items to the timing chart. The team should ensure that the new equipment and tooling is capable and delivered on time. Facilities progress is monitored to assure completion and surpass planned production tryout.

Special Product and Process Characteristics
In the stage of quality planning described, the team identifies preliminary special product and process characteristics resulting from understanding the voice of the customer. The product quality planning team should build on this listing and reach consensus during the review and development of design features through the evaluation of the technical information.

Gages/Testing Equipment Requirements
Gages and testing equipment requirements are also identified at this time. The product quality planning team should add these requirements to the timing chart. Progress is then monitored to assure that the required timing is met.

Team Feasibility, Commitment, and Management Support
The product quality planning team must assess the feasibility of the proposed design at this time. Customer design ownership does not preclude the supplier’s obligation to assess design feasibility. The team must be satisfied that the proposed design can be manufactured, assembled, tested, packaged, and delivered in sufficient quantity on schedule, and at an acceptable cost to the customer. The design information checklist allows the team to review its efforts and make an evaluation of its effectiveness.

The team consensus that the proposed design is feasible is documented, along with all open issues that require resolution, and presented to management for their support.

PRODUCT AND PROCESS VALIDATION

This section discusses the major features of validating the manufacturing process by evaluating a production trial run. During a trial run, the product quality planning team should validate that the control plan and process flow chart are followed and the products meet customer requirements. Additional concerns are identified for investigation and resolution prior to regular production runs.

The inputs and outputs applicable to the process steps in this section are as follows.

Inputs:

• Packaging standards.
• Product/process quality system review.
• Process flow chart.
• Floor plan layout.
• Characteristics matrix.
• Process failure mode and effects analysis (PFMEA).
• Prelaunch control plan.
• Process instructions.
• Measurement systems analysis plan.
• Preliminary process capability study plan.
• Packaging specifications.
• Management support.

Outputs:

• Production trial run.
• Calibration
• Equipment certification.
• Measurement assurance.
• Incoming inspection.
• Nonstatistical control.
• Dimensions

PRODUCTION TRIAL RUN
The production trial run is conducted using production tooling, equipment, the environment (including production operators), the facility, and cycle time. Validating the effectiveness of the manufacturing process begins with the production trial run. The minimum quantity for a trial run is usually set by the customer but can be exceeded by the product quality planning team. Output (product) of the production trial run is used for:

• Measurement systems evaluation.
• Preliminary process capability study.
• Production part approval.
• Production validation testing.
• Packaging evaluation.
• Production control plan.
• Quality planning sign-off and management support.

Measurement Systems Evaluation
The specified measurement devices and methods are used to compare the control plan’s identified characteristics to engineering specifications. The devices are subjected to measurement system evaluation during or prior to the production trial run.

Preliminary Process Capability Study
This capability study is performed on characteristics that are identified in the control plan. The study assesses the readiness of the process for production.

Production Part Approval
Production part approval validates that products made from production tools and processes meet engineering requirements.
Production Validation Testing
This refers to engineering tests that validate products made from production tools and processes meet engineering standards.

Packaging Evaluation
All test shipments (where feasible) and test methods must assess the protection of the product from normal transportation damage and adverse environmental factors. Customer-specific packaging does not preclude the product quality planning team’s involvement in evaluating the packaging method.

Production Control Plan
The production control plan is a written description of the systems that control parts and processes. This plan is a living document and is updated to reflect the addition/deletion of controls based on experience gained in producing parts. Approval of the procuring organization(s) may be required. The production control plan is an extension of the prelaunch control plan. Mass production provides the producer the opportunity to evaluate output, review the control plan, and make appropriate changes.

Quality Planning Sign-off and Management Support
The product quality planning team should ensure that all control plans and process flow charts are followed. The team should perform its review at the manufacturing location(s) and coordinate a formal sign-off. A review of the following items prior to the first production shipment is required:

- Control plans. These plans should be available at all times for all affected operations.
- Process instructions. These documents must contain all of the special characteristics specified in the control plan, and all of the PFMEA recommendations must be addressed. The process instructions and process flow chart are compared to the control plan.
- Gage and test equipment. Where special gages, fixtures, or test equipment are required by the control plan, gage repeatability, reproducibility, and proper usage are verified.

Management support is necessary prior to the quality planning sign-off. The team should show that all planning requirements are met or that concerns are documented, and schedule a management review. This review informs upper management of the program status and gains their commitment to assist in open issues.

CALIBRATION
All calibration standards and test and measuring equipment are periodically calibrated and calibrated only in a controlled environment. A controlled environment is one where reasonable care is taken to ensure that heat, cold, humidity, and vibration are within boundaries that do not affect the precision of the test or measurement. The following are required for effective calibration:

- All inspection, testing, and measuring equipment is calibrated using only certified standards that are traceable to the National Institute of Standards and Technology (NIST).
- All calibration equipment requires proven accuracy supported by appropriate reports and certificates, and provides pertinent test information such as tolerances, test dates, and the general conditions under which the test was conducted.
- A system is required that permits the mandatory recall of all calibration standards and test and measuring equipment within fixed time intervals.

- Calibration standards and measuring and test equipment are calibrated by outside contractors or commercial facilities whose calibration systems conform to ANSI/NCSL Z 540-1-1994.

Calibration Frequency
Three equipment classifications relate to how often a device is recalibrated. A device is in a category heading according to its purpose, recorded stability, and frequency of usage. The three frequency intervals are:

1. Calibrate every three months.
   - Inside micrometers.
   - Depth micrometers.
   - Outside micrometers.
2. Calibrate every six months.
   - Dial calipers.
   - Vernier calipers.
   - Dial indicators.
   - Coordinate measuring machines.
3. Calibrate every year.
   - Gages.
   - Surface plates.
   - Block sets.
   - Ovens and associated recording instrumentation.
   - Thermometers.

All process equipment, including ovens, thermometers, dryers, process tank meters and gages, and scales, are calibrated yearly using only certified standards that are traceable to the National Institute of Standards and Technology in accordance with the requirements of ANSI/NCSL Z 540-1-1994 and ISO.

Calibration is important because all materials processed are inspected and tested to meet the following requirements:

- An accuracy ratio of 10:1.
- If the inaccuracy is greater than 10% of the tolerance, the measured value is adjusted to compensate for the measuring equipment inaccuracy to ensure that a reading within the required value is attained.

Calibration Labels and Status Identification
All calibrated gages and processing equipment are labeled by the subcontractor calibration laboratory with the following information:

- Identification of person performing calibration.
- Test number.
- Calibration date.
- Next calibration due date.

All gages require a permanent identification number that is traceable to calibration records.

Recall System
A card file or computer system for identification numbers is maintained to provide mandatory recall of calibration-due equipment. Equipment that is retained by a subcontractor or outside source is monitored by internal quality assurance, but notification of calibration due remains the responsibility of the subcontractor.

When equipment is due for calibration, the quality assurance department will remove it from service using a tagging system.
Identifying the Measurement Process

The need to control the manufacturing process generates the need to measure it. However, this does not dictate the method of measurement that is used. It becomes the responsibility of the development engineers and quality control personnel to select or develop a satisfactory measurement method. This is an important step in many measurement situations.

Once the measurement method is selected, the elements of the measurement process are then defined. The following questions may be considered:

- What if different instruments of the same type and from the same manufacturer are used?
- Does the type or brand of instrument affect the measurement process results?
- Is the process sensitive to environmental conditions such as temperature, moisture, dust, or vibration?
- What affect does operator experience have on the process?
- How sensitive is the process to changes in the procedure?
- How does sample preparation (cleaning, mixing, deburring, etc.) affect the measurement?

These are examples of questions that must be answered to ascertain the adequacy of the selected measurement process.

Gage Variation Study

This study determines the degree of measurement variability caused by gage changes. The analysis calculates the percent of the engineering specification consumed by measurement variability. Unlike calibration studies which determine gage precision and accuracy, a gage variation study addresses gage reproducibility and repeatability.

It is often assumed that measurements are exact. However, all measuring equipment is subject to variation. In many cases, there is more variation in the measurement systems than in the parts that are measured. Therefore, if a key characteristic is not capable, the measurement system is analyzed before investigating variation sources in the manufacturing process.

The gage variation study in this section addresses variation within the measurement device (repeatability) and situations that occur when different people use the equipment (reproducibility).

Three basic sources of measurement variation are as follows:

- Accuracy. The difference between an average obtained by a measurement device and the true average of the same measurements (see Fig. 17-1).
- Repeatability. The difference between repeated measurements (see Fig. 17-1).
- Precision. The difference between various measurements (see Fig. 17-1).

Three basic sources of measurement variation are as follows:

- Accuracy. The difference between an average obtained by a measurement device and the true average of the same measurements (see Fig. 17-1).
- Repeatability. The difference between repeated measurements (see Fig. 17-1).
- Precision. The difference between various measurements (see Fig. 17-1).

Maintaining a Master Inventory List

A master list of all inspection equipment should be maintained, showing the classification of equipment and its calibration cycle, location, and ownership.

Gage Records

Quality assurance, at fixed intervals, analyzes gage records to determine how much wear and deterioration has occurred. Quality assurance also determines, from these records, the adequacy of the equipment maintenance. These periodic reviews help make better assessments about schedules and recalibration procedures. If the information warrants, intervals are shortened to ensure continued accuracy as evidenced by the results of preceding calibrations. The calibration frequency is lengthened only when the results of previous calibrations provide clear indications that such action will not adversely affect the accuracy of the system.

Newly purchased equipment, after the initial inspections and/or calibrations, are maintained by regular calibrations.

EQUIPMENT CERTIFICATION

Equipment information certificates and labels for instruments and gages that an outside laboratory calibrates are reviewed by the quality assurance department for adequacy and acceptability.

Limited-use Devices

Blocks, plug gages, drill blanks, and other gages of limited use must feature a label denoting “reference use only” and “measure dimension/dial prior to each use of this device.”

Noncalibrated Devices

Devices that are not calibrated or that require a functional check are labeled to indicate their status. If a noncalibrated inspection gage is found, the quality manager takes appropriate action to verify or correct the nonconforming gage or instrument.

Products Inspected With Out-of-Tolerance Equipment

If, during calibration, a gage or instrument is found out of tolerance, the calibration lab notifies the quality manager so that appropriate action is taken. Once notified, the quality manager takes steps to locate and correct any discrepancies that may have resulted from manufacturing product with an out-of-tolerance tool. If the involved product has been shipped, the customer is notified of the condition for its engineering review, evaluation, and/or appropriate action.

Storage and Handling

All measuring and testing equipment is handled, stored, and transported in a manner that does not adversely affect its calibration or condition.

MEASUREMENT ASSURANCE

Measurement assurance is a program to establish, evaluate, and control the quality of measurement. Although special measurement assurance programs (MAPs) were established by the National Bureau of Standards (now NIST) for specific types of measurements, the term is used here in a much broader sense: it refers to a general program designed to improve the quality of any measurement process to which it is applied.

Fig. 17-1 Accuracy and repeatability in a measurement system.
Performance of Incoming Inspection

Acceptance of supplies is performed in a number of ways. Some acceptance criteria are listed below:

• 100% inspection.
• Sampling inspection.
• Identification and transportation damage check.
• Evidence of prior inspection by the supplier or other plant.
• Supplier data use (for example, statistical process control).
• Supplier certification use.
• No inspection; material sent directly to stores or processing.

Incoming inspection is also based on the following criteria:

• Prior quality history of supplier.
• Criticality of the part in the end item or next operation step.
• Warranty or use history.
• Supplier process capability information.
• Availability of required inspection skills and equipment.
• Cost of inspection versus consequences of no inspection.

Controlling Elements

The incoming inspection process should have the following pre-qualifications:

• Supplier selection.
• Vendor survey.
• Purchase order review.
• First-piece acceptance.
• Vendor rating.
• Test methods for plastics.

Supplier selection. Purchasing personnel must use great care in selecting suppliers that have the qualifications and motivation to consistently provide products and materials at ever-improving quality levels. Purchasing has the prime responsibility, but it may solicit engineering, finance, or quality input to assist in the evaluation.

Vendor survey. Due to the complexity of the product, a supplier’s facility is usually established on the basis of the product. The Quality department assists in the survey or performs the task on its own.

Purchase order review. The terms and conditions of a purchase are contained in the body of the purchase order. A quality review of material/components that make up the product includes the proper engineering change letter, specifications, and quality clauses where applicable.

First-piece acceptance. The initial shipment from the supplier requires a qualification that normally consists of examining one piece or a select sampling to determine conformance to the engineering drawing or material specification.

Once the product is accepted, it may be subjected to the sampling plan. Many companies use ANSI/ASQC Z1.4-1993 for lot sampling to reduce inspection time and cost. Companies that do not have in-house laboratories may use outside resources to determine raw material, chemical, and physical properties, or to conduct environmental testing.

Vendor rating. Vendor ratings are used to determine total company quality and include a total quality evaluation. Vendor evaluations include:

• Quantitative measures of supplier conformance.
• Quality levels and percent of on-time delivery.
• Corrective actions of suppliers.1,2

Test methods for plastics. The use of testing procedures for plastics is increasing. Many U.S. companies rely on the American Society for Testing and Materials (ASTM) methods for testing. In other countries, the International Organization for Standardization (ISO) testing method is widely used.

Engineered plastic manufacturers are standardizing the way in which plastic material is available through computer-aided material preselection by uniform standards (CAMPUS). This software is available at no cost from most engineered plastic manufacturers. With CAMPUS, test methods and results are available for most of the current molded engineering materials.
NONSTATISTICAL CONTROL

Nonstatistical tools for plastics manufacturing include knowing the current engineering materials and knowing how they react to wall thickness, shrinkage, and dimensional callouts.

Shrinkage and tolerance charts are advantageous to design, quality, and manufacturing personnel as they recognize the following advantages:

• Provide ready reference for discussion purposes.
• Limit calculation errors.
• Provide stack-up dimensions and fit-up tolerances.
• Enable easier review of process changes.

Wall Thickness

For cost competitiveness, plastic parts are designed with the minimum wall thickness required for part strength and performance. In addition, each plastic material has a range of thickness in which it is most easily processed.

Table 17-4 shows recommended wall thickness values for some common materials.

### TABLE 17-4

<table>
<thead>
<tr>
<th>Material</th>
<th>Minimum, in. (mm)</th>
<th>Maximum, in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>0.030 (0.76)</td>
<td>0.125 (3.18)</td>
</tr>
<tr>
<td>Acetal</td>
<td>0.015 (0.38)</td>
<td>0.125 (3.18)</td>
</tr>
<tr>
<td>Acrylic</td>
<td>0.025 (0.64)</td>
<td>0.250 (6.35)</td>
</tr>
<tr>
<td>Nylon (amorphous)</td>
<td>0.030 (0.76)</td>
<td>0.125 (3.18)</td>
</tr>
<tr>
<td>Nylon (crystalline)</td>
<td>0.015 (0.38)</td>
<td>0.125 (3.18)</td>
</tr>
<tr>
<td>Phenolic</td>
<td>0.045 (1.14)</td>
<td>1.000 (25.4)</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.040 (1.02)</td>
<td>0.400 (10.2)</td>
</tr>
<tr>
<td>Polyester (T/P)</td>
<td>0.025 (0.64)</td>
<td>0.125 (3.18)</td>
</tr>
<tr>
<td>Polyester (T/S)</td>
<td>0.040 (1.02)</td>
<td>0.500 (12.7)</td>
</tr>
<tr>
<td>Polytetrafluoroethylene (HD)</td>
<td>0.020 (0.51)</td>
<td>0.250 (6.35)</td>
</tr>
<tr>
<td>Polytetrafluoroethylene (LD)</td>
<td>0.030 (0.76)</td>
<td>0.250 (6.35)</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.025 (0.64)</td>
<td>0.300 (7.62)</td>
</tr>
<tr>
<td>PPO (modified)</td>
<td>0.030 (0.76)</td>
<td>0.400 (10.2)</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.030 (0.76)</td>
<td>0.250 (6.35)</td>
</tr>
<tr>
<td>PVC</td>
<td>0.040 (1.02)</td>
<td>0.400 (10.2)</td>
</tr>
</tbody>
</table>

* These values are for rigid and semirigid materials. Foamed and flexible materials vary from these values.

DIMENSIONS

The following guidelines promote appropriate dimensioning:

• Use U.S. Customary and SI (metric) numbers when showing dimensions on a drawing. The prime dimension is shown first, and the secondary one follows in parentheses.
• Review the drawing to ensure that all features are dimensioned. Especially note hole locations, angles, radii and fillets.
• Ensure that datum lines are accessible with standard measuring equipment.
• Review the drawing for conflicting or double dimensions. If duplicate dimensions are required for clarity, the duplicate is noted as a reference dimension.
• Reasonable tolerances facilitate manufacturing. Tighter tolerances increase product cost. Recommended tolerances for a 1 in. (25 mm) dimension are shown in Table 17-5.4

### TABLE 17-5

<table>
<thead>
<tr>
<th>Material</th>
<th>Preferred (+), in. (mm)</th>
<th>Tight (+), in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>0.0040 (0.102)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>Acetal</td>
<td>0.0055 (0.140)</td>
<td>0.0025 (0.064)</td>
</tr>
<tr>
<td>Acetate</td>
<td>0.0040 (0.102)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>Acrylic</td>
<td>0.0040 (0.102)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>Nylon (6/6)</td>
<td>0.0055 (0.140)</td>
<td>0.0035 (0.089)</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.0080 (0.203)</td>
<td>0.0040 (0.102)</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.0070 (0.178)</td>
<td>0.0040 (0.102)</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.0035 (0.089)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>PVC (rigid)</td>
<td>0.0035 (0.089)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>Styrene</td>
<td>0.0040 (0.102)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>0.0035 (0.089)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>PPO (modified)</td>
<td>0.0035 (0.089)</td>
<td>0.0020 (0.051)</td>
</tr>
<tr>
<td>Polyester (TP)</td>
<td>0.0055 (0.140)</td>
<td>0.0025 (0.064)</td>
</tr>
</tbody>
</table>

Glass-filled materials:

<table>
<thead>
<tr>
<th>Shrinkage of</th>
<th>Preferred (+), in./in. (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001–0.004 in./in. (0.001–0.004 mm/mm)</td>
<td>0.0025 (0.064)</td>
</tr>
<tr>
<td>0.005–0.008 in./in. (0.005–0.008 mm/mm)</td>
<td>0.0040 (0.102)</td>
</tr>
</tbody>
</table>

Thermoset materials:

<table>
<thead>
<tr>
<th>General purpose</th>
<th>Preferred (+), in. (mm)</th>
<th>Tight (+), in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass-filled</td>
<td>0.0055 (0.140)</td>
<td>0.0025 (0.064)</td>
</tr>
<tr>
<td>Glass-filled</td>
<td>0.0025 (0.064)</td>
<td>0.0010 (0.025)</td>
</tr>
</tbody>
</table>

STATISTICAL METHODS FOR DESCRIBING DATA

This section will discuss statistical methods for describing data that include the following:

• Key characteristics and process capability.
• A control plan.
• Statistical process control charting.
• Calculating \( C_p \) and \( C_{pk} \).

The science of statistics draws conclusions from observed data. In modern plastics manufacturing, statistical quality control, statistical process control, and design and analysis of experiments are the most common statistical tools.

Most statistical investigations, whether they analyze the effect of a new material used in an old mold, methods of adjusting shrinkage to process times, customer reaction to a new product, or the quality of manufactured products, depend on observations, even if they are rudimentary. In plastics manufacturing experimentation, these observations are taken to study the effect of variation on certain factors or the relationship between these factors.

An evaluation may focus on the quality of a plastic material from a new supplier, the melt flow for a particular plastic material, or the optimum combination of conditions in a molding process. Ultimately, these observations are used for making decisions.
The following sections discuss established charting methods that are used to make process decisions.

**KEY CHARACTERISTICS AND PROCESS CAPABILITY**

With the use of statistical data and upfront investment, downstream costs are dramatically reduced. By applying variation reduction methods to processes, the quality of the finished product is enhanced.

Variations in key characteristics are monitored and controlled through statistical process control (SPC) methods. These methods are used to make the process stable and assess the capability of meeting engineering specifications. If control cannot be maintained or a manufacturing process is incapable, sources of variation are identified and controlled. Designed experiments are effective tools that are used to identify significant variation sources and indicate more productive operating methods. The goal is continuous improvement.

**Variation and Building to Nominal**

The goal is to aim for the engineering nominal. If a nominal is not specified, it is considered as halfway between the specification limits. Any deviation from the nominal dimension imparts a loss to the manufacturer or customer. Characteristics outside of the specification limits are considered defective. Sufficiently reducing variation and assuring that the process is stable eventually reduces the risk of defective products to an extent that they are considered defect free.

**Concept of Continuous Loss**

Deviation from nominal imparts some economic loss. These losses are difficult to quantify, since they require knowledge of the downstream impact of variation within the tolerance band. Nevertheless, some relationship exists between variation and economic loss. Losses mount faster, however, as the characteristic drifts farther from the nominal.

This loss curve has no relationship to scrap or rework costs. Such costs are tied to impacts that are induced when the part is rejected. The loss function focuses on downstream losses caused by parts that are in fact used. The concept of continuous loss was first considered by Gauss in the early 1800s. In modern times, Dr. Genichi Taguchi popularized the concept known as the Taguchi loss function.

Control and capability are measured by control charts. The control chart monitors the process average, variability, or conformity of some attribute. A control chart identifies whether the process is stable or changing. For quantitative (that is, measurable or variable) data, this identification is independent from the engineering specifications.

Control charts measure the degree of variability that is tied only to common causes. The natural fluctuation of plotted statistics (such as averages or ranges) is defined as plus or minus three sigma (3) from their average. Under “normal” conditions, this band captures 99.7% of the common-cause variation. If a data point falls outside of these limits, the operator knows that a change has occurred; that is, the process is no longer in control. Control chart patterns are also used as evidence that nonrandom changes are occurring; if controlled, these changes would reduce the variation in the key characteristic.

In contrast, the capability of the process to achieve specified tolerances depends on the engineered requirements. The process spread (or capability) can be determined only if the process is stable, that is, in statistical control. The \( C_p \) index is a simple comparison of the tolerance band to the six process spread. \( C_p \) is not, however, affected by any movement in the process average. A process that has strayed from nominal is not performing as capably as one in which the process is centered on the nominal. For this reason, a second index, called \( C_{pk} \), is used. This index penalizes a process for both increases in variability and drifts away from the center of the tolerance band. For this reason, \( C_{pk} \) is often called the process performance. \( C_p \) is called the process potential, since it is the maximum value that \( C_{pk} \) (the performance) can achieve without decreasing its variability.

\( C_p \) and \( C_{pk} \) are jointly used to determine the process fallout. The fallout is the percentage of measurement that is outside of the tolerance region. This measurement depends on the process being in statistical control, with a known form of distribution. This form is generally assumed as normal, a reasonable assumption for most manufacturing processes.

**Typical Process in Statistical Control**

In statistical control, processes exhibit behavior much like the pattern previously discussed. Most of the plotted points lie near the center of the chart. In fact, under normal conditions, about two-thirds of the plotted points lie in the inner third of the control chart. Ninety-five percent of the points lie in the inner two-thirds of the chart, and 99.7% lie within the control limits.

**Assigning Special Causes of Variation**

After special causes of variation are identified by the control chart, the operator log is consulted to identify abnormalities in the process that may have caused the out-of-control condition. When reasons are labeled as special causes, they are called assigned causes of variation.

**Removing Special Causes of Variation**

After special causes of variation are assigned, they are removed from the manufacturing process. This applies only to out-of-control points violating a three limit. It is appropriate to remove the causes from those indicated by warning limits as well. Removing a special cause variation does not mean simply adjusting or recentering the process. It means removing from the calculations but not from the chart the abnormality that causes the process to change.

**Process Fallout**

If the process is centered (the process average lies precisely between the upper and lower specification limits), the \( C_p \) index can be used to predict the process fallout, that is, the number of characteristics made outside of the tolerance.

Even a “just barely capable” process with a \( C_p \) value of 1.0 has some risk of producing defective characteristics. If, for example, the variability increases by 33%, then the \( C_p \) value will decrease from 1.0–0.75. This produces approximately a ninefold increase in the defect rate. The converse is also true. A change in \( C_p \) from 1.0–1.2 may seem small, but the number of defective units drops by roughly one-ninth of its original value.

**CONTROL PLAN**

An important phase of the quality planning process is the development of a control plan. A control plan is a written description of the system for controlling parts and processes. A single control plan may apply to a family of products that are produced by the same process at the same source. Sketches, as necessary, are attached to the plan for illustration purposes. In support of a control plan, process monitoring instructions are defined and used continually.
CHAPTER 17

STATISTICAL METHODS FOR DESCRIBING DATA

The purpose of the control plan methodology is to aid in manufacturing quality products that meet customer requirements. It does this by providing a structured approach for the design, selection, and implementation of value-added control methods for the total system. Control plans provide a written summary of the systems used in minimizing process and product variation. An example of a control plan is shown in Fig. 17-2.

The control plan does not replace the information contained in detailed operator instructions. This methodology is applicable to a wide range of manufacturing processes and technologies. The control plan is an integral part of an overall quality process and is used as a living document.

In effect, the control plan describes the actions that are required at each phase of the process, including receiving, in-process, outgoing, and periodic requirements, to assure that all process outputs are in control. During regular production runs, the control plan provides the process monitoring and control methods that control the characteristics. Since processes are continually updated and improved, the control plan reflects a strategy that is responsive to these changing process conditions.

The control plan is maintained and used throughout the product life cycle. Early in the cycle, its primary purpose is to document and communicate the initial plan for process control. Subsequently, it guides manufacturing in controlling the process and ensures product quality. Ultimately, the plan remains a living document, reflecting the current methods of control and measurement systems used. The control plan is updated as measurement systems and control methods are evaluated and improved.

For effective process control and improvement, a basic understanding of the process is necessary. A multidisciplined team is established to develop the control plan by using all of the available information to gain a better understanding of the process. This information includes:

- Process flow diagram.
- System/design/process failure mode and effects analysis.
- Special characteristics.
- Lessons learned from similar parts.
- Team’s knowledge of the process.
- Design reviews.
- Optimization methods (that is, QFD, DOE, etc.)

The benefits of a control plan include:

- Quality. The control plan methodology reduces waste and improves the quality of products during design, manufacturing, and assembly. This structured discipline provides a thorough evaluation of the product and process. Control plans identify process characteristics and help to identify their sources of variation (input variables), which cause variation in product characteristics (output variables).
- Customer satisfaction. Control plans focus resources on processes and products related to characteristics that are important to the customer. The proper allocation of resources on these major items helps to reduce costs without sacrificing quality.
- Communication. As a living document, the control plan identifies and communicates changes in the product/process characteristics, control method, and characteristic measurement.

Features

The following list describes the features of the control plan shown in Fig. 17-2.

1. Prototype, prelaunch, production. Indicate the appropriate category.
   - Prototype. A description of the dimensional measurements, material, and performance tests occurring during the prototype build.
   - Prelaunch. A description of the dimensional measurements, material, and performance tests that occur after prototype and before normal production.
   - Production. A comprehensive documentation of product/process characteristics, process controls, tests, and measurement systems occurring during normal production.

2. Control plan number. Enter the control plan document number used for tracking, if applicable. For multiple control plan pages, enter page number.

3. Part number latest change. Enter the number of the system, subsystem, or component that is controlled. When applicable, enter the latest engineering change level and/or issue date from the drawing specification.

4. Part name description. Enter the name and description of the product/process that is controlled.

5. Supplier/Plant. Enter the name of the company and the appropriate division/plant/department preparing the control plan.

6. Supplier code. Enter the identification number (DUNS, Z-Code, GSD) as requested by the procuring organization.

7. Key contact/phone. Enter the name and telephone number of the primary contact responsible for the control plan.

8. Core team. Enter the name(s) and telephone number(s) of the individual(s) responsible for preparing the control plan to the latest revision.

9. Supplier/plant approval/date. Obtain the responsible manufacturing plant approval (if required).

10. Date (original). Enter the date that the original control plan was compiled.

11. Date (revised). Enter the date of the latest control plan updates.

12. Customer engineering approval/date. Obtain the responsible engineering approval (if required).

13. Customer quality approval/date. Obtain the responsible supplier quality representative approval (if required).

14. Other approval/date. Obtain any other agreed upon approval (if required).

15. Part/process. This item number is usually referenced from the process flow chart. If multiple part numbers exist (as in an assembly), list the individual part numbers and their processes accordingly.

16. Process name/operation description. All steps in manufacturing a system, subsystem, or component are described in the process flow diagram. Identify the process/operation name on the flow diagram that best describes the activity that is addressed.

17. Machine, device, jig, tools for manufacturing. For each operation that is described, identify the processing equipment, that is, the machine, device, jig, or other manufacturing tools.

18. Characteristic number. A characteristic is a distinguishing feature, dimension, or property of a process or product on which variable or attribute data are collected. Use visual aids where applicable. Enter a cross-reference number from all applicable documents such as the process flow diagram, numbered blueprint, FMEAs, and sketches.

19. Product characteristics. These characteristics are the features or properties of a part, component, or assembly that...
are described on drawings or other primary engineering information. The core team should identify the special product characteristics from all sources that are important. All special characteristics are listed on the control plan. In addition, the manufacturer may list other product characteristics for which process controls are routinely tracked during normal operations.

20. Process characteristics. These characteristics are the process variables (input variables) that have a cause-and-effect relationship with the identified product characteristic. A process characteristic can only be measured at the time it occurs. The core team should identify process characteristics that are controlled to minimize product variation. There may be one or more process characteristics listed for each product characteristic. In some processes, one process characteristic may affect several product characteristics.

21. Special characteristic classification. Use the appropriate classification as required by the characteristic OEM to designate the type of special characteristic; this field is left blank for other undesignated characteristics. Customers may use unique symbols to identify important characteristics, such as those that affect customer safety, compliance with regulations, function, fit, or appearance.

22. Product/process specification/tolerance. Specification/tolerance is obtained from various engineering documents such as drawings, design reviews, material standards, computer-aided design data, and manufacturing and assembly requirements.

23. Evaluation/measurement technique. This identifies the measurement system that is used. Systems include gages, fixtures, tools, and/or test equipment required to measure the part/process/manufacturing equipment. An analysis of the linearity, reproducibility, repeatability, stability, and accuracy of the measurement system is done prior to relying on a measurement system, and improvements are made accordingly.

24. Sample size/frequency. When sampling is required, list the corresponding sample size and frequency.

25. Control method. This column contains a brief description of how the operation is controlled, including procedure numbers where applicable. The control method used is based on effective process analysis. The method is determined by the type of process that exists. Operations are controlled by statistical process control, inspection, attribute data, mistake-proofing (automated/nonautomated), and sampling plans. The control plan descriptions should reflect the planning and strategy that is implemented in the manufacturing process. If elaborate control procedures are used, the plan typically references the procedure document by a specific identification name and/or number.

26. Reaction plan. This plan specifies the corrective actions necessary to avoid producing nonconforming products or operating out of control. The actions are normally the responsibility of those closest to the process (the operator, jobsetter, or supervisor) and are clearly designated in the plan. Provisions are made for documenting.

**Process Analysis**

Different types of processes present challenges in controlling and reducing variation. The process types are related to their most common sources of variation or the dominant factors in determining product quality. There are many effective methods of performing process analysis.

**Examples include:**
- Fault tree analysis.
- Design of experiments.
- Cause-and-effect diagram.

**STATISTICAL PROCESS CONTROL CHARTING**

This section discusses the calculations for the following charts:
- The X-bar (\( \bar{X} \)) and R chart.
- The target X-bar and R chart.
- The p, np, c, and u charts.
- Histograms.
- Cause-and-effect diagrams.
- Calculating \( C_p \) and \( C_{pk} \).

**X-Bar and R Chart**

This chart is used when monitoring the behavior of a single measurable characteristic produced in relatively high volumes. Sample averages (X-bar) and ranges (R) are plotted on separate charts. This permits independent monitoring of the process average and the variation about that average.

The X-bar and R chart relies on a constant sample size, and one characteristic is plotted per chart. At least 20 samples are required before calculating control limits. Table 17-6 shows formulas for the X-bar and R chart.

The X-bar plot point, shown in Fig. 17-3, is the average of the sample data; the sample size (n) is 4. The range plot point is the difference between the largest and smallest measurement within the sample data. Figure 17-4 shows a completed X-bar and R chart that was started by using these data.

This chart, as shown in Figure 17-4, is used to monitor a single characteristic; the inside diameter of a hole. On the left side of the chart is a table of constants that is used in calculating the control...
Fig. 17-4 Completed X and R chart.
limits. The “Comments” section at the top is used to note any potential special cause variations that could impact the measurements. The original data are written in the “Samples” section, and the plot point calculations are performed below each sample. The X-bar (average) plot point is shown in the first row. The R (range) plot point is in the second row. The centerline and control limit calculations are shown on the left side of the control chart.

The X-bar chart shows that the process is centered on 59.9, and if the process is in control, the sample averages must remain between 56.9 and 62.9. However, plot point 11 is below the lower control limit, which indicates that there is a special cause of variation impacting the process. In this case, the out-of-control point was caused by movement of the fixture. The correction was to reset the fixture (see the comment at the top of the chart).

The range chart shows that the average expected variation within samples is 4.1 units. (The 4.1 is a coded value for 0.00041, or 4.1 ten-thousandths of an inch [0.01041 mm].) The highest expected variation is 9.6 units. There are no patterns on the range chart that indicate an out-of-control condition.

**Target X-Bar and R Chart**

This chart is used in short-run situations to continually monitor the behavior of a process that is running different part numbers, while retaining the ability to assess statistical control. The chart codes the measured readings as a deviation from a common target value, and this value becomes the zero point on the X-bar control chart scale.

All parts on this chart have the same units and similar average ranges. A constant sample size is required, and a minimum of 20 samples is required before calculating control limits. Refer to Table 17-7, which shows formulas for the target X-bar and R chart.

As an example, long pieces of 0.75 in. (19 mm) diameter plastic stock are cut to length to fill three orders (Table 17-8). Each order requires different lengths. All three orders are plotted on the same control chart by standardizing the data.

To calculate the X-bar plot point, find the average of the sample data and subtract the target value. The range plot point is the difference between the largest and smallest measurement in the original data (see Table 17-9).

Figure 17-5 is a target chart that was started using these data. For this example, three different part numbers were cut on the same machine and monitored on a single target chart. Plot points between part numbers may or may not be connected. In this case, all of the part numbers were cut to length. Since these operations are identical regardless of part number, the plot points were connected.

On the left side of the chart is an area for writing the targets for each part number. The “Comments” section is used to note potential variations that could impact the process. The original data are written in the “Samples” section. Plot point calculations are performed below each subgroup. The coded X-bar plot point is the first row, and the range plot point is shown in the second row. The centerline and control limit calculations are shown on the left side of the control chart.

The X-bar chart shows no unnatural patterns and is in control. On the range chart, all of the part numbers have similar average ranges, and they are also in statistical control.

**Individual X and Moving-Range Chart**

This chart is used where opportunities to obtain data are limited, such as in low-production volumes or when testing. It is also used when sampling sizes greater than one do not apply, such as in accounting measures (overtime forecasting), when sampling from homogeneous batches (contaminants in a clean room), or when samples have very small short-term variations (sheet stamping).

Each measurement on an individual X (IX) chart and the moving range between each successive measurement on a moving-range (MR) chart are plotted (see Figure 17-6). This technique assumes a sample size of one and normal distribution of the data. Table 17-10 shows formulas for the individual X and moving-range chart.

To calculate the IX plot point, plot the individual measurements. The range plot point is the difference between each successive individual measurement. For example, the first moving-range plot point in Table 17-11 is the difference between 4.25 and 4.78, which is 0.53. The next is the difference between 4.78 and 3.95, which is 0.83, and so on.

Figure 17-6 is an IX-MR chart that was started using these data. The data are weekly concentration samples taken from a chemical process tank. On this chart, there is no part number monitoring, but the chemical concentration from a chronic acid anodize bath is charted. Notes regarding when “adds” were made to the tank are in the “Comments” section. The two shaded rows labeled “Individual X” and “Moving-Range” are the plot points.

**Formulas for the Target X and R Chart**

<table>
<thead>
<tr>
<th>Chart</th>
<th>Control Limits</th>
<th>Centerlines</th>
<th>Plot Point</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>UCL = Coded X̄ + A₂ R</td>
<td>Coded X̄ = Σ coded X⁻¹/k</td>
<td>Coded X̄ = X̄ - target value</td>
<td>2 – 9 but 3 – 5 preferred</td>
</tr>
<tr>
<td></td>
<td>LCL = Coded X̄ – A₂ R</td>
<td>X̄ = kΣ R⁻¹</td>
<td>R</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Order</th>
<th>Target, in. (cm)</th>
<th>Number of Pieces</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.00 (7.62)</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>5.25 (13.34)</td>
<td>33</td>
</tr>
<tr>
<td>3</td>
<td>7.50 (19.05)</td>
<td>21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plot Point Calculation Steps for the Target Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample data</td>
</tr>
<tr>
<td>2.90</td>
</tr>
<tr>
<td>3.05</td>
</tr>
<tr>
<td>3.10</td>
</tr>
<tr>
<td>Total of the sample data = 9.05</td>
</tr>
<tr>
<td>Calculate the average (X̄) = 9.05/3 = 3.02</td>
</tr>
<tr>
<td>Target value = 3.00</td>
</tr>
<tr>
<td>X̄ - target value = 0.02 Coded X̄ plot point</td>
</tr>
<tr>
<td>Range (3.10 – 2.90) = 0.20 Range plot point</td>
</tr>
</tbody>
</table>
### Table 17-1 Example Data Table

<table>
<thead>
<tr>
<th>Part #</th>
<th>Chart #</th>
<th>Dept #</th>
<th>Machine #</th>
<th>Characteristic</th>
<th>Date</th>
<th>Time</th>
<th>Part#</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>23</td>
<td>10</td>
<td>Characteristic</td>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

### Table 17-2 Summary Statistics

<table>
<thead>
<tr>
<th>Part #</th>
<th>Chart #</th>
<th>Dept #</th>
<th>Machine #</th>
<th>Characteristic</th>
<th>Date</th>
<th>Time</th>
<th>Part#</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>23</td>
<td>10</td>
<td>Characteristic</td>
<td></td>
<td></td>
<td>1 2 3 4 5 6 7 8 9</td>
</tr>
</tbody>
</table>

### Calculation of X-bar and R Chart

#### X-bar Chart

- **Total (Σ X):**
  
  $\sum X = 9.05 + 3.02 + 3.00 + 0.02 + 0.20 + 2.85 + 3.00 + 0.07 + 0.15 + 0.03 + 0.07 + 0.10 + 0.02 + 0.00 + 0.25 + 0.25 + 0.20$

- **Average (\( \bar{X} \)):**
  
  $\bar{X} = \frac{\sum X}{n} = \frac{22.65}{20} = 1.13$

- **Centerline (\( \bar{X} \)):**
  
  $\bar{X} = 1.13$

- **UCL (\( \bar{X} \)):**
  
  $UCL_{\bar{X}} = \bar{X} + \frac{A_2 \times R}{4}$

- **LCL (\( \bar{X} \)):**
  
  $LCL_{\bar{X}} = \bar{X} - \frac{A_2 \times R}{4}$

#### R Chart

- **Total (Σ R):**
  
  $\sum R = 2.57 + 5.25 + 7.50 + 2.85 + 3.00 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143 + 0.143$

- **Average (\( \bar{R} \)):**
  
  $\bar{R} = \frac{\sum R}{n} = \frac{22.65}{20} = 1.13$

- **Centerline (\( \bar{R} \)):**
  
  $\bar{R} = 1.13$

- **UCL (\( R \)):**
  
  $UCL_R = D_4 \times \bar{R}$

- **LCL (\( R \)):**
  
  $LCL_R = D_3 \times \bar{R}$

### Additional Calculations

- **Target Cpk:**
  
  $C_{pk} = \min\left\{ \frac{X_{USL} - \bar{X}}{3\sigma}, \frac{\bar{X} - X_{LSL}}{3\sigma} \right\}$

### Figures

- **Fig. 17-5 Target X and R chart.**
### CHAPTER 17
### STATISTICAL METHODS FOR DESCRIBING DATA

#### Part # | Chart # | Dept # | Machine # | Characteristic | U/D |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

#### Data | Time | Part# |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Individual X

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Part#</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.25</td>
<td>4.78</td>
<td>4.25</td>
</tr>
<tr>
<td>3.93</td>
<td>4.02</td>
<td>4.78</td>
</tr>
<tr>
<td>3.86</td>
<td>4.09</td>
<td>4.25</td>
</tr>
<tr>
<td>3.72</td>
<td>4.16</td>
<td>4.25</td>
</tr>
<tr>
<td>3.57</td>
<td>4.61</td>
<td>4.25</td>
</tr>
<tr>
<td>3.45</td>
<td>4.55</td>
<td>4.25</td>
</tr>
<tr>
<td>3.90</td>
<td>4.39</td>
<td>4.25</td>
</tr>
<tr>
<td>3.05</td>
<td>5.25</td>
<td>4.89</td>
</tr>
</tbody>
</table>

#### Moving range (MR)

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Part#</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.53</td>
<td>0.83</td>
<td>0.53</td>
</tr>
<tr>
<td>0.89</td>
<td>0.14</td>
<td>0.83</td>
</tr>
<tr>
<td>1.43</td>
<td>0.10</td>
<td>0.89</td>
</tr>
<tr>
<td>0.62</td>
<td>0.05</td>
<td>1.43</td>
</tr>
<tr>
<td>0.50</td>
<td>0.41</td>
<td>0.62</td>
</tr>
<tr>
<td>0.35</td>
<td>0.66</td>
<td>0.50</td>
</tr>
<tr>
<td>0.06</td>
<td>0.03</td>
<td>0.41</td>
</tr>
<tr>
<td>0.43</td>
<td>0.17</td>
<td>0.35</td>
</tr>
<tr>
<td>0.48</td>
<td>0.24</td>
<td>0.06</td>
</tr>
</tbody>
</table>

### IX Chart

#### UCL

\[
\text{UCL}_X = \frac{\bar{X}}{X} + (A2 \times \text{MR})
\]

\[
= 4.39 + (2.66 \times 0.53) = 5.80
\]

#### Centerline

\[
\bar{X} = \frac{\sum X}{k} = 87.75 = 4.39
\]

#### LCL

\[
\text{LCL}_X = \bar{X} - (A2 \times \text{MR})
\]

\[
= 4.39 - (2.66 \times 0.53) = 2.98
\]

### Range Chart

#### UCL

\[
\text{UCL}_{MR} = D4 \times \text{MR}
\]

\[
= 3.27 \times 0.53 = 1.73
\]

#### Centerline

\[
\overline{\text{MR}} = \frac{\text{MR}}{k} = 9.98 = 0.53
\]

#### LCL

\[
\text{LCL}_{MR} = 0 \times D3 \times \text{MR} = 0 \times 0.53 = 0
\]

---

**Fig. 17-6** Individual $\bar{X}$ and moving-range chart.
Since the IX plot point represents a single measurement, the specification limits are also drawn on this chart. The IX chart is the only control chart where this is done. For a chemical process, specifications on the chart could be used to indicate when an add is necessary, and can point out a Cpk problem earlier than the control limits alone would.

On the MR chart, one point falls outside the upper control limit, and there are a couple of other spikes. These were caused when adds were made to the tank to boost the concentration level. On the IX chart, notice the spike followed by a gradual downward trend, another spike, and then a second downward trend. This graphically shows the behavior of the tank when adds are made, followed by depletions. These patterns, although not random, are normal for this kind of process.

**P Chart**

The p chart is used in the following instances:
- When variable data cannot be obtained.
- When charting fraction rejected as nonconforming from a varying sample size.
- When screening multiple characteristics for potential monitoring on variable control charts.
- When tracking the quality level of a process before rework is performed.

The technique is done by counting the number of defective items from a sample and then plotting the percent defective.

As the quality level increases, a larger sample size is required to contain rejects. For example, if 20% of a product is rejectable, a sample size of five is needed. However, a sample of 1,000 gives an average of only one reject per sample if 0.1% of the product is rejectable. Formulas for the p chart are shown in Table 17-12.

The p plot point is the fraction defective in a sample. The centerline is the average fraction defective in a series of samples.

Figure 17-7 is a cross-section that shows countersunk holes for rivet installation. In a plastic assembly shop, plastic riveting is a common process. Because of the combined variation in the rivets, the drilled holes, and the bucking process, quality problems may occur. After the rivets in an assembly are bucked into place, they are checked for nonconformity. A p chart is used to track the first-time-through fraction defective.

Table 17-13 represents the fraction defective for two samples of plastic rivets. A completed p chart, shown in Fig. 17-8 is based on these data.

Plotted on this chart are the average number of defective plastic rivets. Points higher on the chart represent a greater number of defects. The calculation formulas are shown in the upper left corner. The centerline, 0.067, indicates that, on average, 6.7% of the plastic rivets are defective before rework is done. The control limits vary inversely with the sample size. Because of the difficult calculations, this chart is used only if the sample size (n) varies.
CHAPTER 17
STATISTICAL METHODS FOR DESCRIBING DATA

---

### Table: p Chart

<table>
<thead>
<tr>
<th>Number of defectives</th>
<th>5</th>
<th>1</th>
<th>13</th>
<th>3</th>
<th>35</th>
<th>40</th>
<th>22</th>
<th>0</th>
<th>3</th>
<th>14</th>
<th>9</th>
<th>3</th>
<th>2</th>
<th>0</th>
<th>5</th>
<th>3</th>
<th>8</th>
<th>3</th>
<th>0</th>
<th>4</th>
<th>6</th>
<th>0</th>
<th>218</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample size (n)</td>
<td>92</td>
<td>36</td>
<td>212</td>
<td>96</td>
<td>172</td>
<td>448</td>
<td>364</td>
<td>48</td>
<td>204</td>
<td>530</td>
<td>198</td>
<td>15</td>
<td>97</td>
<td>36</td>
<td>65</td>
<td>54</td>
<td>82</td>
<td>67</td>
<td>18</td>
<td>52</td>
<td>72</td>
<td>96</td>
<td>3624</td>
</tr>
<tr>
<td>Proportion defective (p)</td>
<td>0.07</td>
<td>0.03</td>
<td>0.19</td>
<td>0.15</td>
<td>0.20</td>
<td>0.08</td>
<td>0.03</td>
<td>0</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.20</td>
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<td>0.08</td>
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<td>0.10</td>
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<td>0.08</td>
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<tr>
<td>UCL</td>
<td>0.15</td>
<td>0.19</td>
<td>0.19</td>
<td>0.15</td>
<td>0.12</td>
<td>0.10</td>
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<td>0.16</td>
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<td>0</td>
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<td>0.03</td>
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<td>0.01</td>
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<td>0</td>
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<td></td>
</tr>
<tr>
<td>Defect log sheet</td>
<td>Tool/die mark</td>
<td>4</td>
<td>1</td>
<td>25</td>
<td>9</td>
<td>18</td>
<td>23</td>
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<tr>
<td></td>
<td>Cracked</td>
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<td>1</td>
<td>8</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clinched</td>
<td>1</td>
<td>1</td>
<td>11</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>18</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gap</td>
<td>6</td>
<td>1</td>
<td>6</td>
<td>10</td>
<td>2</td>
<td>1</td>
<td>7</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

---

*Control limits are calculated separately for each plot point.*

Fig. 17-8 Completed p chart.
The defect log sheet below the control chart shows the type of defect found in the rivets. The largest contributors to the defect count are tool and die marks, followed by gap and cracking problems.

This process is not in statistical control, but more importantly, the overall 6.7% defective rate is not acceptable. The defective tool was replaced after plot point 7; this is the only improvement to date. The next areas to investigate are the cracks and gaps.

Although there is a relationship between percent defective and Cpk values, there is no Cpk calculation for a p chart.

**NP Chart**

The np chart is used under the following circumstances:
- When variable data cannot be obtained.
- When charting the number rejected as nonconforming from a constant sample size.
- When screening multiple characteristics for potential monitoring on variable control charts.

This technique is done by plotting the number of defects from a series of equal-size samples.

The higher the quality level, the larger the sample size required to contain rejects. For example, if 20% of a product is rejectable, a sample size of five is needed. However, a sample of 1,000 gives an average of only one reject per sample if 0.1% of the product is rejectable. Formulas for the np chart are shown in Table 17-14.

The np plot point is the number of defects in each sample. The centerline is the average number of defects in a series of samples.

The quality of bearings is determined by dimensional tests as well as a noise test. The dimensional tests produce variable data; the noise test requires a trained ear to detect defects such as concentricity, out-of-round, and surface blemishes. Each day, 100 bearings are noise tested, and an np chart is kept on the number of defective bearings. The centerline is the average number of defects per sample. The data shown in Table 17-15 represent the number of defective bearings from two samples.

**C Chart**

A c chart is used only in the following instances:
- When plotting the number of defects per unit.
- When screening multiple characteristics for potential monitoring on variable control charts.

Each unit is examined, and the number of defects found are plotted. As a rule, the unit size is chosen so that at least two defects per unit are found.

A c chart relies on a constant unit size and a constant sample size. A unit is different from a sample. For example, a unit may be defined as 1 ft² of material. If 12 ft² were inspected, the sample size is 12, but the unit size remains at 1.

There are potentially several different types of defects per unit, none of which would necessarily render the part defective (for example, paint blemishes on a skin panel or various electrical faults on a circuit board). A unit can be a single part, an assembly of several parts, an area of material, or any rational grouping in which the likelihood of defect(s) is constant from unit to unit.

For this type of analysis, there should be some defects in each observed unit. Formulas for the c chart are shown in Table 17-16.

The c plot point is the number of defects found in or on a unit. The centerline is the average of all the plot points on the chart. Figure 17-10 shows a completed c chart on page 17-23.

**U Chart**

A u chart is used under the following conditions:
- When variable data cannot be obtained.
- When plotting the average number of defects per unit.
- When screening multiple characteristics for potential monitoring on variable control charts.

Each unit is examined, and the average number of defects found are plotted.

A constant unit size is required, but any convenient number of units per plot point are acceptable. Again, unit size is different from a sample size of 50. Points higher on the chart represent a greater number of defects. The calculation formulas are shown in the upper left corner. The centerline, 2.9, means that, on average, there are 2.9 defective bearings per sample of 50. The control limits are constant because the sample size is constant. The process is in statistical control; there are no significant runs, trends, or extreme points.

The defect log sheet is not filled in because the rejected bearings were not categorized into types of defects.

Although there is a relationship between percent defective and Cpk values, there is no Cpk calculation for an np chart.

### Table 17-14

Formulas for the np Chart

<table>
<thead>
<tr>
<th>Control Limits</th>
<th>Centerline</th>
<th>Plot Point</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$UCL = np + 3 \sqrt{np (1 - \bar{p})}$</td>
<td>$\bar{p}$ = Summation of plot points</td>
<td>$np$ = Number of defective units in a sample</td>
<td>Constant</td>
</tr>
<tr>
<td>$LCL = np - 3 \sqrt{np (1 - \bar{p})}$</td>
<td>$np$ plot points</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 17-15

Number of Defective Ball Bearings

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Number of bearings tested ($n$) = 50</th>
<th>Number of defective bearings ($np$) = 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 2</td>
<td>Number of bearings tested ($n$) = 50</td>
<td>Number of defective bearings ($np$) = 4</td>
</tr>
</tbody>
</table>

### Table 17-16

Formulas for the c Chart

<table>
<thead>
<tr>
<th>Control Limits</th>
<th>Centerline</th>
<th>Plot Point</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$UCL = \bar{c} + 3 \sqrt{\bar{c}}$</td>
<td>$\bar{c}$ = All defects</td>
<td>$c$ = Number of defects counted on a unit</td>
<td>One</td>
</tr>
<tr>
<td>$LCL = \bar{c} - 3 \sqrt{\bar{c}}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Statistical Methods for Describing Data

## CHAPTER 17

## STATISTICAL METHODS FOR DESCRIBING DATA

### Fig. 17-9 Completed np chart.

<table>
<thead>
<tr>
<th>Part #</th>
<th>Chart #</th>
<th>Dept #</th>
<th>Machine #</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### np Chart Formula

\[
\bar{p} = \frac{\sum_{i=1}^{k} np_i}{n}
\]

\[
\bar{p} = \frac{2.9}{50} = 0.058
\]

\[
\text{np} = \sum_{i=1}^{k} np_i = 63
\]

\[
\text{Sample Size} = n = 50
\]

\[
\text{Sample Frequency} = \text{daily}
\]

\[
\text{Chart Type} = \text{np}
\]

### UCL and LCL Formulas

\[
\text{UCL} = np\bar{p} + 3 \sqrt{np\bar{p}(1-\bar{p})}
\]

\[
\text{LCL} = np\bar{p} - 3 \sqrt{np\bar{p}(1-\bar{p})}
\]

\[
np\bar{p} = 2.9 \quad \bar{p} = 0.058
\]

\[
\text{UCL} = 2.9 + 3 \sqrt{2.9(1-0.058)} = 7.9
\]

### Number of Defects (np) and Sample Size

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Sample</th>
<th>np</th>
<th>UCL</th>
<th>LCL</th>
<th>Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/1</td>
<td>2/2</td>
<td>50</td>
<td>4</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/2</td>
<td>2/3</td>
<td>50</td>
<td>4</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/3</td>
<td>2/4</td>
<td>50</td>
<td>3</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/4</td>
<td>2/5</td>
<td>50</td>
<td>4</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/5</td>
<td>2/6</td>
<td>50</td>
<td>3</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/6</td>
<td>2/7</td>
<td>50</td>
<td>2</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/7</td>
<td>2/8</td>
<td>50</td>
<td>3</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/8</td>
<td>2/9</td>
<td>50</td>
<td>2</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/9</td>
<td>2/10</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/10</td>
<td>2/11</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/11</td>
<td>2/12</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
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<td>2/12</td>
<td>2/13</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/13</td>
<td>2/14</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
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<td>2/14</td>
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<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
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<td>2/15</td>
<td>2/16</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
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<td>2/16</td>
<td>2/17</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
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<td>2/17</td>
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<td>5</td>
<td>7.9</td>
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<td>np</td>
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<td>2/18</td>
<td>2/19</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
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<td>2/19</td>
<td>2/20</td>
<td>50</td>
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<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/20</td>
<td>2/21</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
<tr>
<td>2/21</td>
<td>2/22</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
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<td>2/23</td>
<td>50</td>
<td>5</td>
<td>7.9</td>
<td>0</td>
<td>np</td>
</tr>
</tbody>
</table>

\[
\text{Totals} = 63
\]
Fig. 17-10 Completed c chart.
from sample size. For example, one unit could be defined as 1 ft² of material. On a particular day, 12.3 ft² of material are inspected. The plot point represents the average number of defects per unit, but the sample size is 12.3.

For this type of analysis, there should be some defects in each observed unit. Table 17-17 shows formulas for the u chart.

The u plot point is the average number of defects per unit in a sample of n units. The centerline is the average of all the plot points on the chart. Composite materials are generally comprised of several layers of materials that are bonded to form the desired characteristics. Prior to lay-up, each roll was inspected for defects. Since different amounts of the material are used each day, the number of rolls inspected also changes daily. The defects checked were:

- Resin content.
- Transportation temperature.
- Drape (ease of malleability).
- Tackiness.
- Volatile content.
- Fiber area weight.
- Fiber orientation.

The data in Table 17-18 represent the number of defects found per lot on two production days. On Day 1, there was an average of 2.3 defects per lot; on Day 2, there were 2.9 (1 lot = 1 unit = 100 rolls). Notice that the quantity of rolls used changed from day to day. Figure 17-11 shows a completed u chart that was started using these data. Plotted on this chart is the average number of defects per roll. The control limits vary inversely with the sample size. Because of the difficult calculations, this chart is used only if the sample size (n) varies.

The first half of the chart is more stable than the latter half. Point 16 exceeded the upper control limit, and point 17 fell below the lower control limit. Points 12, 19, and 20 are all close to falling outside the limits. The defect log sheet below the control chart shows the types of defects found in the rolls. The “Totals” column serves as a Pareto analysis (see “Definitions and Tools for Continuous Improvement” section at the end of this chapter). The largest contributors to the defect count are incorrect resin content and tackiness.

As with several of the previous charts, there is no Cpk correlation to the u chart.

### Histogram

A histogram is a bar chart that displays the variation within a process. It is also called a frequency distribution chart, because the frequency of occurrence of any given value is represented by the height of the bars.

A histogram provides the following information:

- Allows a quick visualization of a large amount of data.
- Provides clues to causes of problems.
- Can show the relationship between the engineering tolerance and the process capability.

A histogram is used in the following instances:

- When analyzing a key characteristic.
- When using SPC data to justify buying hardware.
- When performing capability studies.
- When analyzing the quality of incoming material.

Measurements (variable data) are collected from a process or key characteristic. A check sheet is constructed to record the data. The range is then found by subtracting the smallest measurement from the largest. Using the information shown in Table 17-19, the proper number of class intervals are determined.

Set the class width so that no data values fall on one of the limits. This is done by adding the next logical decimal value to each limit. For instance, if intervals are created for whole number data with limits of 1–5, 5–10, and so on, a value of 5 could be placed in either the first or second interval. Avoid this problem by setting the intervals at 1–4.9, 5–9.9, and so on.

Construct a frequency table as shown in Table 17-20. Tally the number of observations found in each class. Abnormal histograms may be skewed to the right, bimodal, or truncated, as shown in Fig. 17-12.

A histogram that is skewed to the right can be caused by centering the process toward the low end of the tolerance and sorting the parts that fall out on the low side. This type of histogram also results when the nature of the process physically prohibits any measurements past a minimum value.

A bimodal histogram is comprised of two combined populations. Reasons include two shifts, operators, inspectors, suppliers, machine settings, gages, tools, machines, or measurement locations.
### Chapter 17

**Statistical Methods for Describing Data**

#### u Chart formula

\[
\bar{u} = \frac{\sum u}{k}
\]

- **UCL** = \( \bar{u} + 3 \sqrt{\frac{\bar{u}}{n}} \)
- **LCL** = \( \bar{u} - 3 \sqrt{\frac{\bar{u}}{n}} \)

*Control limits are calculated separately for each plot point.*

#### Control limit calculation for plot point 1

- **UCL** = \( \bar{u} + 3 \sqrt{\frac{\bar{u}}{n}} \) = 5.5
- **LCL** = \( \bar{u} - 3 \sqrt{\frac{\bar{u}}{n}} \) = 1.7

**u Chart formula**

\[
\bar{u} = \frac{1234 56789}{9} = 3.622
\]

**Fig. 17-11 Completed u chart.**

### Tables

| Number of defects (c) | 21 | 19 | 9 | 33 | 23 | 13 | 31 | 21 | 7 | 43 | 25 | 7 | 27 | 17 | 35 | 53 | 1 | 37 | 45 | 2 | 23 | 13 | 497 |
|------------------------|----|----|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|     |
| Number of units (n)    | 9  | 6.5| 4.4| 8.3| 6.6| 3.0| 8.3| 6.0| 3.0| 9.2| 7.4| 4.4| 9.9| 6.2| 6.5| 6.3| 3.3| 9.2| 6.3| 2.7| 4.4| 2.9| 133.8 |
| Average number of defects (\( \bar{u} \)) | 3.6 | 2.9 | 2.0 | 2.0 | 3.5 | 4.3 | 1.7 | 1.5 | 2.3 | 4.7 | 3.4 | 1.6 | 2.7 | 2.7 | 5.6 | 5.6 | 6.6 | 6.2 | 4.5 | 7.5 | 5.2 | 78.4 |
| UCL                    | 3.6 | 2.2 | 2.0 | 2.0 | 3.5 | 4.3 | 1.7 | 1.5 | 2.3 | 4.7 | 3.4 | 1.6 | 2.7 | 2.7 | 5.6 | 5.6 | 6.6 | 6.2 | 4.5 | 7.5 | 5.2 | 78.4 |
| LCL                    | 1.7 | 1.4 | 0.9 | 1.6 | 1.6 | 0.6 | 1.3 | 1.3 | 0.6 | 1.3 | 1.3 | 0.6 | 1.3 | 1.3 | 0.6 | 1.3 | 1.3 | 0.6 | 1.3 | 1.3 | 0.6 | 1.3 |

**Defect log sheet**

- **Resin content** | 16 | 12 | 4 | 21 | 19 | 9 | 33 | 23 | 14 | 5 | 32 | 15 | 15 | 13 | 9 | 27 | 40 | 30 | 26 | 2 | 15 | 7 | 339 |
- **Fiber area weight** | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 25 |
- **Volatile content** | 1 | 3 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 13 |
- **Fiber orientation** | 1 | 1 | 2 | 1 | 1 | 1 | 2 | 3 | 2 | 3 | 2 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 2 | 3 | 25 |
- **Tackiness** | 4 | 2 | 3 | 4 | 1 | 3 | 3 | 3 | 3 | 6 | 6 | 8 | 3 | 3 | 7 | 1 | 4 | 6 | 3 | 4 | 7 | 76 |
- **Transportation temperature** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 10 |
- **Drape** | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 11 |

**Fig. 17-11 Completed u chart.**
TABLE 17-20  
Frequency Record

<table>
<thead>
<tr>
<th>Class</th>
<th>Class Limits</th>
<th>Tally</th>
<th>Number of Observed Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.51 to 5.50</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>5.51 to 10.50</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>10.51 to 15.50</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>15.51 to 20.50</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>20.51 to 25.50</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>25.51 to 30.50</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

(a) Skewed to the right:  
Could be caused by centering the process toward the low end of the tolerance, and sorting the parts that fall out on the low side; or the nature of the process physically prohibits any measurements past a minimum value.

(b) Bimodal: Two combined populations. Reasons: two shifts, operators, inspectors, suppliers, machine settings, gages, tools, machines, measurement locations, etc.

(c) Truncated: This distribution is not normal because there are no gradually tapering outer ends. This can happen when a process is not capable of meeting the specifications, the parts are sorted from both ends, or too few classes are chosen.

Fig. 17-12 Histograms that are (a) skewed to the right, (b) bimodal, and (c) truncated.
A truncated distribution is not normal because there are no gradually tapering outer ends. This can occur when a process is not capable, the parts are sorted from both ends of the specification, or too few classes are chosen.

**Cause-and-effect Diagram**

This diagram is a graphic tool used to represent the relationship between an effect and the causes that influence it. A cause-and-effect diagram is used for the following reasons:

- Helps identify key characteristics and key process parameters.
- Illustrates the various causes affecting a process.
- Helps a group reach a common understanding of a problem.
- Helps reduce the incidence of subjective decision making.

A cause-and-effect diagram is used when performing key characteristic flow downs, looking for the potential causes of a problem, and organizing brainstorming lists. The diagram is constructed by placing a problem statement in a box on the right side of a piece of paper. The major cause category boxes are drawn on the left side of the paper. Finally, the brainstormed ideas are placed under the appropriate major cause category.

An example of a cause-and-effect diagram is shown in Fig. 17-13.

**Unnatural Patterns: Assignable Causes of Variation**

Data that fluctuate too widely or fail to become balanced around the centerline are characteristic of unnatural patterns. There are several types of unnatural patterns.

**Cycles.** Cycles are short trends in the data that occur in repeated patterns so that the pattern becomes predictable or systematic. There is an indication of an assignable cause, because a random pattern is one that does not repeat. Cycles are caused by processing variables that come and go on a regular basis. For example, causes that can create this type of pattern are listed in Table 17-21; cycles are shown in Fig. 17-14.

**Grouping.** Grouping occurs when measurements are clustered in a nonrandom pattern. This clustering can be introduced by a different system of causes. For example, if a group of rejected parts accidentally gets included with good parts, bunching may be observed on the control chart. Other causes that can create grouping are listed in Table 17-22; grouping is shown in Fig. 17-15.

**Strays.** Strays result from a single measurement that is greatly different from the others. Occasionally, a stray is the result of a plotting error, such as when the person plotting the point has mis-

---

**Fig. 17-13 Cause-and-effect diagram.**

**TABLE 17-21**

<table>
<thead>
<tr>
<th>Causes</th>
<th>Methods</th>
<th>Machinery</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal effects</td>
<td>Drive too fast</td>
<td>Underinflated tires</td>
<td>Poor gas mileage</td>
</tr>
<tr>
<td>Worn threads on locking devices</td>
<td>Poor maintenance</td>
<td>Carburetor adjustment</td>
<td></td>
</tr>
<tr>
<td>Gage differences</td>
<td>Poor driving habits</td>
<td>Wrong octane gas</td>
<td></td>
</tr>
<tr>
<td>Voltage fluctuations</td>
<td></td>
<td>Improper lubrication</td>
<td></td>
</tr>
<tr>
<td></td>
<td>People</td>
<td>Wrong oil</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material</td>
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<td></td>
</tr>
</tbody>
</table>

**TABLE 17-21**

<table>
<thead>
<tr>
<th>Causes of Cycles</th>
<th>X-bar Chart</th>
<th>R Chart</th>
<th>p Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal effects</td>
<td>Maintenance schedule</td>
<td>Rotation on fixtures or gages</td>
<td>Sorting practices</td>
</tr>
<tr>
<td>Worn threads on locking devices</td>
<td>Rotation on fixtures or gages</td>
<td>Differences between suppliers</td>
<td>Sampling practices</td>
</tr>
<tr>
<td>Gage differences</td>
<td>Wear of tool or die</td>
<td>Differences between shifts</td>
<td></td>
</tr>
<tr>
<td>Voltage fluctuations</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
interpreted the scale. Strays are among the easiest patterns to recognize, because they are so different from the other readings in the process. Other typical causes that can create control chart strays are listed in Table 17-23; strays are shown in Fig. 17-15.

Mixtures. Mixture patterns fall near the control limits, with an absence of points near the centerline. This pattern is recognized by the unnatural length of the lines joining the points, creating a “sawtooth” effect. A mixture is actually a combination of two different patterns on the same chart, one at a high level and one at a low level. Typical causes of mixture patterns are listed in Table 17-24; mixtures are shown in Fig. 17-16.

CALCULATING $C_p$ AND $C_{pk}$

The parameters of $C_p$ and $C_{pk}$ are obtained through capability studies that consist of calculating ratios that compare the variation of a key characteristic or process to its engineering tolerance. These capability studies assess whether a key characteristic or process is able to meet requirements. They also monitor any changes in process variation.

A capability study is conducted after each batch or logical run on any measured process or characteristic where variable data are collected and engineering specifications exist.

Calculating $C_p$ and $C_{pk}$ values requires knowledge of the engineering tolerance and capability of the process or characteristic that is evaluated.

The formulas used to calculate $C_p$ and $C_{pk}$ are shown in Eq. 17-1.

$$C_p = \frac{\text{Engineering tolerance}}{6\sigma}$$

$$C_{pk} = \text{Smaller of } \left[ \frac{\text{USL} - \text{Avg}}{3\sigma}, \frac{\text{Avg} - \text{LSL}}{3\sigma} \right]$$

where:

$\sigma$ = standard deviation
USL = upper specification limit
LSL = lower specification limit
Engineering tolerance = USL – LSL
Avg = average of the individual measurements

---

Table 17-22

<table>
<thead>
<tr>
<th>Causes of Grouping</th>
<th>X-bar Chart</th>
<th>R Chart</th>
<th>$p$ Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement difficulty</td>
<td>Different difficulty</td>
<td>Mixture of different lots</td>
<td>Change in technique of classification</td>
</tr>
<tr>
<td>Different person making measurements</td>
<td>Change in calibration of a measuring instrument</td>
<td>Changes in sorting of product</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig. 17-14 Cycles.

Fig. 17-15 Grouping and strays.
A standard deviation (σ) is a mathematically derived number that is used to estimate the expected variation about a characteristic or process average. The formula for s, which is used to estimate the standard deviation, is shown in Eq. 17-2.

\[
s = \sqrt{\frac{\sum (X - \text{Avg})^2}{N - 1}} = \sigma
\]  

(2)

where:

- Avg = average of all measurements
- \( s \) = estimate of standard deviation
- \( \sum \) = summation of
- \( X_i \) = individual measurements (one at a time)
- \( N \) = total number of measurements
- \( \hat{s} \) = estimation of
- \( \sigma \) = standard deviation

### TABLE 17-23
Causes of Strays

<table>
<thead>
<tr>
<th>X-bar Chart</th>
<th>R Chart</th>
<th>p Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrong setting corrected immediately</td>
<td>Damage in handling</td>
<td>Variations in sample size</td>
</tr>
<tr>
<td>Error in measurement/plotting</td>
<td>Incomplete/omitted operation</td>
<td>Sampling from different distributions</td>
</tr>
<tr>
<td>Omitted/incomplete operation</td>
<td>Setup parts included in date</td>
<td>A very good or bad lot</td>
</tr>
<tr>
<td>Data included using another scale</td>
<td>Mathematical error</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 17-24
Causes of Mixtures

<table>
<thead>
<tr>
<th>X-bar Chart</th>
<th>R Chart</th>
<th>p Chart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differences in operators</td>
<td>Different lots of material/machines/operator</td>
<td>Nonrandom sampling techniques</td>
</tr>
<tr>
<td>Differences in gages</td>
<td>Differences in gage sources</td>
<td>Lots from two or more machines mixed together</td>
</tr>
<tr>
<td>Over-adjustment of process</td>
<td>Excessive play in fixture</td>
<td></td>
</tr>
<tr>
<td>Output from two or more machines mixed together</td>
<td>Tool needs sharpening</td>
<td></td>
</tr>
<tr>
<td>Chart placed too far downstream</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 17-16 Mixtures.

**DESIGN OF EXPERIMENTS**

**TYPES OF EXPERIMENTAL DESIGNS**

The design of experiments module of statistical quality control is used to construct two types of experimental designs: two-level full factorial and two-level fractional factorial. Two-level factorial designs are generally used to determine how a small number of factors affect a response. The fractional designs are also useful in screening a larger number of factors for importance.

**Two-level Full Factorial Designs**

These are the most straightforward experimental designs. In this type of design, each factor is examined at two levels. The composite parts example is a two-level factorial design, since the material thickness and density can each have one of two possible values. To facilitate the design, the two levels of a factor are usually referred to as “high” (represented by a +1) and “low” (represented by a –1).

The full factorial design consists of runs of every possible combination of high and low levels of each factor. If the number of factors investigated is \( k \), the number of runs required for the full factorial experiment is \( 2^k \).
A full factorial experiment for the composite parts example has a total of $2^k = 4$ experimental runs. Those runs are shown in Table 17-25.

Material thickness is referred to by the label “A” in the table. The number –1 in Column A represents a 0.5 in. (13 mm) material thickness, and the number +1 represents a 1 in. (25 mm) material thickness. Similarly, material density is referred to by the label “B”. The number –1 in Column B represents a density of 3 lb/ft$^3$ (48 kg/m$^3$), and the number +1 represents a density of 5 lb/ft$^3$ (80 kg/m$^3$). For example, the first run of the experiment would use 0.5-in. (13-mm)-thick material with a 3-lb/ft$^3$ (48-kg/m$^3$) density.

**TABLE 17-25**  
Full Factorial Experiment

<table>
<thead>
<tr>
<th>Run No.</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>–1</td>
<td>–1</td>
</tr>
<tr>
<td>2</td>
<td>–1</td>
<td>+1</td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>–1</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>+1</td>
</tr>
</tbody>
</table>

**Two-level Fractional Factorial Designs**

Unfortunately, the number of runs in a full factorial experiment becomes extremely large as the number of factors increases. For example, if ten factors are investigated, the number of runs required for a full factorial experiment is $2^{10} = 1024$. Since an experiment of this size could be unreasonable to perform, a fractional factorial design may suffice.

Fractional factorial designs are created by taking a portion of a full factorial design. For example, instead of running all 1024 runs required for the full factorial design, it is possible to create a design containing only 128 as many runs. In fact, designs are possible that contain any fraction of runs equal to 1 divided by a power of 2 (that is, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, etc.). The letter p is used to represent the power of 2. Since a full factorial design with k factors has $2^k$ runs, a $\frac{1}{2^p}$ fraction of this design would have $2^{k-p}$ runs. Therefore, designs of this type are referred to as $2^{k-p}$ fractional factorial designs.

**Effects and Design Resolution**

The influence that a single factor alone has on the response is referred to as a main effect. In some experiments, the influence of a particular factor on the response may depend on the level of another factor (or factors). In this case, there is an interaction effect. For example, suppose that the composite parts experiment is run, and the results are as shown in Table 17-26.

The responses indicate that whenever 1 in. (25 mm) material is used (A = +1), material with a density of 3 lb/ft$^3$ (80 kg/m$^3$) (B = +1) produces the least amount of shrinkage. However, whenever 0.5 in. (13 mm) material is used (A = –1), material with a density of 3 lb/ft$^3$ (48 kg/m$^3$) (B = –1) produces the least amount of shrinkage. These results indicate an interaction effect between material thickness and density.

**TABLE 17-26**  
Responses to a Factorial Experiment

<table>
<thead>
<tr>
<th>Run No.</th>
<th>A</th>
<th>B</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>+1</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>–1</td>
<td>+1</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>–1</td>
<td>50</td>
</tr>
</tbody>
</table>

The level of an interaction effect is represented by multiplying the levels of the factors that are studied. For example, a column in the experiment table representing the interaction between material thickness and density is calculated by multiplying Columns A and B. This is illustrated in Table 17-27.

Note that there is another column (labeled “I”) that represents the overall mean of the responses. This column always contains ones.

A larger example can demonstrate the interactions and aid in learning a concept called aliasing. Instead of running an experiment with only two factors, consider an experiment with four factors (which are referred to by the labels A, B, C, and D). A full factorial experiment would require $2^4 = 16$ runs.

Besides having two-way interactions as in the composite parts example, an experiment of this size can also have three-way and four-way interactions. These interactions are represented in the same way as two-way interactions. In other words, the three-way interaction between factors A, B, and C is listed in a column labeled “ABC.” The column is derived by multiplying the columns of the three factors.

**TABLE 17-27**  
Interaction Effect of a Factorial Experiment

<table>
<thead>
<tr>
<th>Run No.</th>
<th>I</th>
<th>A</th>
<th>B</th>
<th>AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>–1</td>
<td>–1</td>
<td>+1</td>
</tr>
<tr>
<td>2</td>
<td>–1</td>
<td>–1</td>
<td>+1</td>
<td>–1</td>
</tr>
<tr>
<td>3</td>
<td>+1</td>
<td>+1</td>
<td>–1</td>
<td>–1</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
</tr>
</tbody>
</table>

Table 17-28 shows a $2^{4+1}$ fractional factorial design for the new example. Notice that instead of having a full 16 runs, this fractional factorial design requires only eight runs.

In this example, the eight runs chosen for the fractional factorial design are those for which the ABCD interaction value is +1. A similar design can be derived by taking the other eight runs, which have an ABCD interaction value of –1.

Since the value of the ABCD interaction column never changes, it is impossible to estimate its effect on the response. Furthermore, each column that corresponds to a three-way interaction is identical to the main effect column of the factor not appearing in the interaction (that is, ABC = D). This means that it is not possible to distinguish between a main effect and its corresponding three-way interaction effect. Finally, each two-way interaction column has another two-way interaction column with which it is identical. Therefore, it is impossible to distinguish between the effects of the identical two-way interaction effects.

When two or more columns in an experimental design are identical, they are considered aliased (or confounded). In Table 17-28, each three-way interaction is aliased with a main effect. Each two-way interaction is aliased with another two-way interaction, and the four-way interaction is aliased with the mean (Column I).

In this section, a set of aliased effects is denoted by the effect labels connected with “+” signs. For example, in Table 17-28, AB is aliased with CD. This effect is denoted by AB + CD.

The aliasing patterns that exist in a particular design are easily determined by using design generators. Since Table 17-28 was constructed by taking the eight runs for which the ABCD interaction is +1, the design generator for the experiment is written as I = ABCD.

The other aliasing patterns are obtained from the design generator by performing a special type of multiplication. It is important to remember two rules when performing this multiplication.
CHAPTER 17

LOSS FUNCTION

A common feature of all statistical methods for evaluating process capability (that is, control charts and the $C_p$ index) is that these methods do not directly quantify the economic effects of the process or product’s deviation from the target values. In this section, the loss function method is presented. This method is based on the concept that loss is incurred when a product’s functional quality characteristic (denoted by $y$) deviates from its target (nominal) value (denoted by $m$), regardless of how small that deviation effects. Similarly, a Resolution IV design does not alias main effects with other main effects or with two-way interaction effects, but it aliases main effects with three-factor and higher-order interaction effects, and two-way interactions with each other.

Replication and Randomization

Replication means running an experimental design more than once. Replication helps improve the accuracy of the experiment and helps make the results of the experiment more precise.

Randomization means that the order of the experimental runs is performed randomly. Randomization is important in reducing the possibility of systematic error influencing the results.

Center Points

Two-level designs can only determine linear effects. However, there may be times when a factor does not affect the response linearly. For example, if factor $A$ is low (–1), then the response is low; when factor $A$ is high (+1), then the response is also low. However, when factor $A$ is in the middle (represented by a 0), then the response is high. This is referred to as a quadratic effect. If an experiment only ran factor $A$ at high and low levels, it would incorrectly appear that factor $A$ had no effect on the response.

Quadratic effects are determined by including a few extra runs in an experimental design with all of the factors at their intermediate levels (0). These runs are called center points. They alert the experimenter to quadratic effects, but they do not indicate which factors contribute to these effects.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>I</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>AB</th>
<th>AC</th>
<th>AD</th>
<th>BC</th>
<th>BD</th>
<th>CD</th>
<th>ABC</th>
<th>ABD</th>
<th>ACD</th>
<th>BCD</th>
<th>ABCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>–1</td>
<td>–1</td>
<td>–1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>–1</td>
<td>–1</td>
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<td>–1</td>
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<td>–1</td>
<td>–1</td>
<td>+1</td>
</tr>
<tr>
<td>2</td>
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<td>+1</td>
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<td>+1</td>
<td>–1</td>
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</tr>
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<td>+1</td>
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</tr>
</tbody>
</table>

LOSS FUNCTION

<table>
<thead>
<tr>
<th>TABLE 17-28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional Factorial Design with Four Factors</td>
</tr>
<tr>
<td>Run No.</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 17-29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aliasing Patterns</td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>A</td>
</tr>
</tbody>
</table>

This indicates that the main effect Column A is aliased with the interaction effect Column BCD.

A fractional factorial design may have more than one design generator. A ¼ fraction of the current example (that is, a $2^{4-2}$ fractional factorial design) is constructed by using both I = ABCD and I = ABD. These design generators result in the design shown in Table 17-30.

The amount of aliasing that occurs in a particular experimental design is referred to as the design resolution. Although there are many different levels of design resolution, this section discusses only Resolution III and Resolution IV designs.

Center Points

Two-level designs can only determine linear effects. However, there may be times when a factor does not affect the response linearly. For example, if factor $A$ is low (–1), then the response is low; when factor $A$ is high (+1), then the response is also low. However, when factor $A$ is in the middle (represented by a 0), then the response is high. This is referred to as a quadratic effect. If an experiment only ran factor $A$ at high and low levels, it would incorrectly appear that factor $A$ had no effect on the response.

Quadratic effects are determined by including a few extra runs in an experimental design with all of the factors at their intermediate levels (0). These runs are called center points. They alert the experimenter to quadratic effects, but they do not indicate which factors contribute to these effects.

<table>
<thead>
<tr>
<th>Run No.</th>
<th>I</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>AB</th>
<th>AC</th>
<th>AD</th>
<th>BC</th>
<th>BD</th>
<th>CD</th>
<th>ABC</th>
<th>ABD</th>
<th>ACD</th>
<th>BCD</th>
<th>ABCD</th>
</tr>
</thead>
<tbody>
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<td>3</td>
<td>+1</td>
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<td>–1</td>
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<td>–1</td>
<td>+1</td>
<td>+1</td>
<td>–1</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>4</td>
<td>+1</td>
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<td>+1</td>
<td>+1</td>
<td>–1</td>
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<td>+1</td>
<td>–1</td>
<td>–1</td>
<td>–1</td>
<td>–1</td>
<td>–1</td>
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<td>+1</td>
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<td>+1</td>
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<td>+1</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 17-30</th>
</tr>
</thead>
<tbody>
<tr>
<td>2&lt;sup&gt;n-2&lt;/sup&gt; Fractional Factorial Design</td>
</tr>
<tr>
<td>Run No.</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>
is. Figure 17-17 shows the relationship between quality loss and the amount of deviation from the target value. As shown in this figure, quality loss caused by deviation equals zero when \( y = m \); the loss increases when the value of the functional characteristic moves up or down from \( m \). When the value of the functional characteristic exceeds either of the limits \( (m + \Delta) \) or \( (m - \Delta) \) (where \( 2\Delta \) is the tolerance), the quality loss is equal to the cost of the product’s disposal or rework.

**DERIVATION OF THE LOSS FUNCTION**

Assume that the loss of a defective part (because of discarding, repairing, or downgrading) is \( A \). Then denote the loss function by \( L(y) \) and expand it using Taylor’s expansion. Equations 17-3 and 17-4 are obtained.

\[
L(y) = L(m + y - m) \quad (3)
\]

or

\[
L(y) = L(m) + L'(m)(y - m) + \frac{L''(m)}{2!}(y - m)^2 + \ldots \quad (4)
\]

Because \( L(y) = 0 \) when \( y = m \) and the minimum value of the function is attained at this point (Fig. 17-17), its first derivative is \( L_m = 0 \). The first two terms of Eq. 17-3 are equal to zero. If terms of \( (y - m) \) with powers higher than 2 are neglected, Eqs. 17-3 and 17-4 reduce to Eqs. 17-5 and 17-6.

\[
L(y) = L_0(m)(y - m)^2 \quad (5)
\]

\[
L(y) = k(y - m)^2 \quad (6)
\]

where \( k \) is a constant and its value is obtained as follows.

When the deviation of a product’s functional characteristic equals an amount \( \Delta \) from the target value \( m \), the loss equals \( A \). From Eq. 17-5, Eqs. 17-7 and 17-8 are obtained.

\[
A = k\Delta^2 \quad (7)
\]

\[
k = \frac{A}{\Delta^2} \quad (8)
\]

The loss function given by Eq. 17-5 is a quadratic relationship obtained by using Taylor’s expansion. A different expression of the loss function can be used if such a function is available.

**Uses of the Loss Function**

The loss function is also used to determine the optimal diagnosis period of the process, the optimal adjustment interval for the process parameters, and the acceptable deviation in the product’s characteristic before corrective action is taken. It is used to determine the sensitivity of the product’s characteristics to the parameters of the on-line quality control system.

**Process Assessment**

Once a process is in statistical control, its performance can be assessed. This assessment is accomplished by measuring process variation and relating it to engineering specifications.

To this point, the intrinsic behavior of the process was emphasized, with no reference to product specifications. This emphasis allowed an understanding of the process on its own merits; the process variability was observed and brought under control. However, simply because a process is stable does not ensure that it produces parts within specification. A stable process may still produce defective and nondefective parts.

**Analyzing Process Capability**

Process capability analysis measures not only the uniformity of the process output but also the ability of the process to produce nondefective parts. Process capability is often defined as the process spread.

The estimated process spread is equal to \( 6s \), where \( s \) is the standard deviation of the sample of measurements.

A process is considered capable if the process spread equals the specification width. This relationship is shown in Fig. 17-18. Once the specifications are defined, the process capability is determined by the variability of the process.

One approach in evaluating the capability of a process is to take measurements of a quality characteristic, construct a histogram of those measurements, and compare the histogram to the upper and lower specification limits. Doing this graphically provides valuable insight into the variation and location of the process relative to the specifications. If the variation is too large or if the process is not centered, the process may not be capable (see Fig. 17-19).
Once the specifications are established and the natural variability of the process is determined, the process potential, \( C_p \), is calculated (see Fig. 17-20). USL and LSL are the upper and lower specification limits, respectively.

\( C_p \) assumes that the measurements are centered between the specification limits and are normally distributed, and that the process is in control.

Table 17-31 shows the expected number of defective parts per million produced with various values of \( C_p \).

Considering the large number of parts on an airplane, for example, the impact of improving \( C_p \) is clearly significant.

**COMPUTING \( C_{pk} \)**

While \( C_p \) assumes that the process is centered, \( C_{pk} \), a closely related statistic, does not make this assumption. \( C_{pk} \) is a measure of process performance. Figure 17-21 shows the distances used in computing \( C_{pk} \). The numerator is the positive distance between the average of the measurements and the nearest specification limit. The denominator is one-half of the process spread.

When the process is centered, \( C_p = C_{pk} \). Figure 17-22 shows the relationship between values of \( C_p \) and \( C_{pk} \), illustrating their difference when the distribution remains the same but is no longer centered.

Table 17-32 shows the number of defects per million (fallout) for shifts in \( C_{pk} \) for various values of \( C_p \).

The table reflects the process shift from the center of the specification limits. To reduce the number of defects, that is, to improve \( C_{pk} \), the process is centered (moved left across the table), the process variability is reduced (moved down the table), or preferably both.
TABLE 17-31

Process Fallout for Various Values of \( C_p \)

<table>
<thead>
<tr>
<th>( C_p )</th>
<th>Parts per Million: Defective (two-sided)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>13,360,000.0000</td>
</tr>
<tr>
<td>0.75</td>
<td>24,400.0000</td>
</tr>
<tr>
<td>1.00</td>
<td>2,700.0000</td>
</tr>
<tr>
<td>1.10</td>
<td>967.0000</td>
</tr>
<tr>
<td>1.20</td>
<td>318.0000</td>
</tr>
<tr>
<td>1.30</td>
<td>96.0000</td>
</tr>
<tr>
<td>1.40</td>
<td>26.0000</td>
</tr>
<tr>
<td>1.50</td>
<td>6.8000</td>
</tr>
<tr>
<td>1.60</td>
<td>1.6000</td>
</tr>
<tr>
<td>1.70</td>
<td>0.3400</td>
</tr>
<tr>
<td>1.80</td>
<td>0.0600</td>
</tr>
<tr>
<td>2.00</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

Fig. 17-21 Distance used to compute \( C_p \) when the distribution is shifted toward the upper specification limit.

Fig. 17-20 Process spread within specification limits.

Fig. 17-22 Relationship between \( C_p \) and \( C_{pk} \).
Once the specifications are given, a reduction in the process spread improves $C_{pk}$. Again, reducing process variability becomes a primary objective of continuous improvement (Fig. 17-23).

**SUMMARY**

Various means of improving process quality are presented in this chapter. They are tools that, when used correctly, yield significant results:

- The number of defects is substantially reduced.
- Lower design and manufacturing costs will result.
- Throughput is increased, with reduced development and production time.
- Products are more reliable and function better.
- Satisfied customers will result.\(^5,6\)

---

**TABLE 17-32**

| Process Fallout for Shifts in $C_{pk}$ from Various Values of $C_p$ |
|------------------------|--------|--------|--------|--------|--------|
| $C_p$                  | 0      | 0.10   | 0.20   | 0.30   | 0.40   |
| 0.50                   | 133,614| 151,000| 201,925| 282,451| 385,556|
| 0.80                   | 16,395 | 21,331 | 37,280 | 67,291 | 115,229|
| 1.00                   | 2,700  | 3,950  | 8,357  | 17,913 | 35,944 |
| 1.10                   | 967    | 1,509  | 2,274  | 8,211  | 17,868 |
| 1.20                   | 318    | 532    | 842    | 3,470  | 8,198  |
| 1.30                   | 96     | 172    | 487    | 1,351  | 3,467  |
| 1.40                   | 27     | 51     | 160    | 474    | 1,350  |
| 1.50                   | 7      | 14     | 48     | 159    | 483    |
| 1.60                   | 2      | 4      | 13     | 48     | 159    |
| 1.70                   | 0      | 1      | 3      | 13     | 48     |
| 1.80                   | 0      | 0      | 1      | 3      | 13     |
| 2.00                   | 0      | 0      | 0      | 0      | 1      |

Fig. 17-23 Continuously improving process capability.
The following sections outline continuous quality improvement guidelines.

BROAD CONCEPT OF CONTINUOUS IMPROVEMENT

The concept of continuous improvement is a strategy that companies must adopt. Inspection has little effect on quality. Companies must promote an ongoing effort to seek better performance levels. Once new levels are reached, the effort must continue toward the next level. The journey for continuous improvement lasts indefinitely.

APPROACH FOR IMPROVEMENT

There are many approaches to making improvements. Some are elaborate, while others are straightforward. Almost all approaches are tailored to the company using them. These approaches often center on the following steps:

- Finding the problem that needs resolution.
- Studying the conditions or environment surrounding the problem.
- Developing several solutions to solve the problem.
- Evaluating the solutions to find the best one.
- Implementing the best solution and performance measures to evaluate the solution.
- Comparing the actual results to the expected results.
- Making adjustments for further improvement.

The steps need not be in this order. Certain steps may be done simultaneously. Many popular improvement approaches are based on the Shewhart Cycle, shown in Fig. 17-24. It is also called the “plan-do-check-act” cycle, after its four stages. This approach is well suited for use by cross-functional improvement teams.

DEFINITIONS AND TOOLS FOR CONTINUOUS IMPROVEMENT

The following tools can provide continuous improvement in a process or product:

- Brainstorming.
  1. Generating ideas from a group.
  2. Establishing key characteristics that identify potential sources of variation (either common causes or special causes).

- Pareto analysis.
  1. Displaying the relative importance of each potential key characteristic.
  2. Establishing a key characteristic.
  3. Establishing controls on key process parameters.
  4. Done during preproduction planning.
  5. Illustrating rejection history when collecting data on key characteristics.

- Risk analysis.
  1. Identifying key characteristics from a list of potential key characteristics.

- Process control charts.
  1. Determining where key characteristics are stored.

- Control chart.
  1. Establishing variation of key characteristics or process parameters.

- Histogram.
  1. Illustrating distribution and capability of key characteristics or process parameters.

- Gage variation.
  1. Determining measurement device capability.
  2. Determining percent of engineering tolerance used by measurement system.
  3. Also known as gage R&R.

- Cause and effect diagram.
  1. Identifying sources of variation.
  2. Correlating sources of variation with key characteristics.
  3. Also known as a fishbone chart.

- Design of experiments.
  1. Studying the effects of how changes in process parameters impact key characteristics.

- Scatter plot.
  1. Studying the relationships between variables.

- Meeting notice.
  1. Forming an agenda outline to facilitate the process improvement team’s first meeting.

- Problem-solving report form.
  1. Gathering facts/data to initially detect or define the problem.
References

Bibliography
Amsden, R. T., Butler, H. E., Amsden, D. M., *SPC Simplified* (Quality Resources, A Division of the Kraus Organization, Ltd.)
Masaaki, I., *Kaizen* (Distributed by McGraw-Hill, Inc.)
For the successful operation of a manufacturing facility, there are many diverse subjects that plant engineering and maintenance personnel must consider. Some of them include:

- Recycling (identification and reclaiming processes for plastics).
- Equipment maintenance (reducing equipment downtime).
- Tool surface enhancements (coatings for better mold life and material release).
- Cleaning, preservation, and storage of metal molds and parts.

CHAPTER 18

PLANT ENGINEERING AND MAINTENANCE

For the successful operation of a manufacturing facility, there are many diverse subjects that plant engineering and maintenance personnel must consider. Some of them include:

- Recycling (identification and reclaiming processes for plastics).
- Equipment maintenance (reducing equipment downtime).
- Tool surface enhancements (coatings for better mold life and material release).
- Cleaning, preservation, and storage of metal molds and parts.

RECYCLING PLASTIC MATERIALS

Technological advancements in the latter half of this century have permitted the use of newer materials as substitutes for metals, stones, and wood. These new versatile materials, which meet present-day requirements, are polymers that include plastics, rubber, foam, textiles, adhesives and paints. Polymeric materials are widely used because they have superior ultimate properties, are easy to process, and are lightweight compared to conventional engineering materials. Polymers are also cost effective.

In 1900, the only plastic materials available were gutta-percha, shellac, celluloid, and ebonite. At that time, research led to the development of formaldehyde-based casein and phenolic plastics, and demanding applications led to an annual production of about 175,000 tons (172,235 metric tons) in the 1940s. In subsequent years, urea-formaldehyde, polystyrene, polyethylene, polyvinyl chloride, polyurethanes, and acrylics were commercialized. During World War II, these materials were the best candidates when substituting for hard-to-obtain natural materials.

During this time, U.S. researchers developed synthetic rubbers. Nylon was developed by a DuPont team led by W. H. Carothers. In the 1950s, high-density polyethylene, prepared by the Ziegler and Phillips processes, became commercialized, and shortly thereafter, polypropylene was discovered. A number of new “engineering resins,” such as acetics, polycarbonates, polysulfones, and liquid crystalline polymers, were commercialized.

Other industries were growing at the same time. A large number of specialized additives, such as ultraviolet (UV) stabilizers, antioxidants, antistatic agents, pigments, plasticizers, flame retardants, and fillers, became available. The development of glass fibers and carbon fibers and the knowledge of reinforcement resulted in the rapid growth of the composites industry.

The plastics industry will most likely continue to focus on developing new specialty materials based on existing polymers. Early plastics were made from coal, milk, cellulose, and molasses. Since World War II, plastics were made almost exclusively from petroleum. About 1.5% of the oil and natural gas consumed annually in the United States is used to produce petrochemical feedstocks for the plastics industry. During the 1970s, the global oil crisis made the plastics industry particularly aware of its dependence on petroleum. With this historical demonstration of the depletion of natural resources and the growing concern about environmental issues, numerous studies on the disposal of plastics and the use of plastic waste resulted. Based on the projected plastic consumption, the increasing cost, a scarcity of petroleum, global regulations, and diminishing landfill space, work on recovering and reusing plastics has created a new recycling industry.

To help understand recycling or reusing plastic materials, this section will briefly describe:

- Polymer chemistry (how plastics are composed).
- Materials (the general properties of plastics).
- Environment (what happens after the plastic becomes refuse).
- Sources of plastic waste.
- Recycling processes (how to economically and efficiently use plastic again).

CHEMISTRY OF PLASTICS

Plastic materials are polymers, which are made up of monomers that are linked by chemical bonds. Basic and substituted hydrocarbons are the building blocks of plastic materials. From these building blocks, organic compounds (monomers) are formed. These are then linked in a process called polymerization to form a long-chain repeating molecule with a...
high molecular weight (5000 to millions). The polymerization process often involves linking several different monomers to form more complex polymers, which are termed copolymers.

If there are bonds or links between the long chains, the polymer is thermosetting (cross-linked) and therefore intractable (that is, it cannot melt or dissolve). These polymers cannot be reprocessed by melt or solution methods as can their linear or branched counterparts, which are known as thermoplastics. The building blocks for plastics mostly originate with natural gas, liquefied petroleum gases (LPG), or petroleum as a raw material, although there are exceptions. Cellulose (wood), a naturally occurring polymer, forms the basis for plastics such as cellophane and rayon. Some common plastics are described in the following sections. All of these plastics, with the exception of polyurethane, are linear or branched and are thus tractable (thermoplastic) polymers. They can, therefore, be recycled by the melt methods of injection molding, extrusion, etc.

**Polyethylene**

Polyethylene (PE) is an inexpensive plastic. It has excellent moisture barrier properties and good grease and oil resistance properties; it is also readily heat-sealable. Polyethylene is made from ethylene, C₂H₄, under heat and pressure to form long chains comprising of 30,000 or more linked carbon atoms. The chains may be linear or branched (see Fig. 18-1), and the polymer’s density can vary. This leads to the following categories:

- **Low-density polyethylene (LDPE)** (long branches on chains).
- **Linear low-density polyethylene (LLDPE)** (slight branching with comonomers).
- **Medium-density polyethylene (MDPE)** (slight branching).
- **High-density polyethylene (HDPE)** (no branching).
- **Ultra-high-density polyethylene (dynam, Akzo)** (no branching).

LDPE is used in shrink films, bags, and other applications including blow-molded bottles, disposable diapers, coatings and laminations, and mulching for agriculture. LLDPE is used for its greater strength and toughness (such as for grocery bags, garbage bags, or landfill liners). HDPE is a relatively straight-chained structure but has a higher density due to its greater crystallinity. It is used in blow-molded bottles for milk and juices, toiletries and detergents, and in toy and automotive parts.

Ultra-high-density polyethylene, with a very high molecular weight, recently appeared and may replace Teflon® (PFTE).

**Polypropylene**

Polypropylene (PP) has excellent chemical resistance, is strong, has the lowest density, is readily heat-sealable, and is the least expensive plastic. Polypropylene chemically resembles polyethylene; it is a long-chain hydrocarbon, and every alternate carbon atom has a methyl group rather than a hydrogen atom attached, as with polyethylene. This confers a much higher melt index and greater tensile strength than polyethylene. It is used in packaging films for cigarettes, candy, snacks, and automotive parts. Blow-molded polypropylene is used for bottles and squeeze containers, and injection-molded PP is used for bottle closures, toys, and automotive parts. Due to its high melt index, PP is used as the inside layer of food packages that are sterilized at high temperatures (for example, retort pouches and tubs).

**Polyvinyl Chloride**

Polyvinyl chloride (PVC) has excellent clarity, has good puncture resistance, provides barrier properties to grease and oils, and is relatively low in cost. Unlike polyethylene, PVC has a chlorine atom on alternate carbon atoms; this results in a plastic with markedly different properties. PVC is a difficult polymer to process into useful products without using other additives, particularly plasticizers. The use of additives results in versatile products after finishing. In film form, PVC can breathe (is porous to oxygen) and therefore is the film of choice for packing fresh red meats that require oxygen to ensure a bright red surface. It is used in shrink wrap, stretch wrap, bottles for honey, automotive upholstery parts, health care products, window frames, foams, and pipes.

**Polystyrene**

Polystyrene (PS) is a clear, hard, brittle plastic. It is a poor barrier to oxygen and water vapor and has a low melt index. Polystyrene is made by polymerizing styrene monomer. Because of its low cost and ease of processing, it is widely used in containers, lids, bottles, trays, and tumblers. It is commonly used in its impact-modified form (graft copolymer with butadiene [high-impact PS]) or with butadiene and acrylonitrile (ABS). Poly-styrene can be foamed to form expanded polystyrene (EPS). It is also used for meat trays, egg cartons, beverage cups, cushioning materials, and insulators.

**Polyvinylidene Chloride**

Polyvinylidene chloride (PVDC) is an excellent barrier to moisture and gases. It is used in household wraps and as a laminated, extruded, or coated layer on other materials where barrier properties are required.

**Polyethylene-vinyl Alcohol**

Polyethylene-vinyl alcohol (PEVA) is an excellent oxygen barrier but loses this property when exposed to moisture. It is therefore usually sandwiched between moisture barrier materials to ensure that it retains its oxygen barrier properties. Because of its hydrophilicity, it does not readily absorb oils. Since flavor compounds in products such as citrus are oil based, ethylene-vinyl alcohol (EVOH) is now used as an interior coating on citrus juice containers to prevent flavor loss.

**Polyethylene Terephthalate**

Polyethylene terephthalate (PET, polyester) is a relatively high-melting-point polymer. It is clear and tough and has good gas and moisture barrier properties. Polyesters belong to this class of condensation polymers. In this class, the polymerization process consists of joining two different monomers by eliminating small mol-
Plastic materials are widely used because they are superior in ultimate properties, particularly in their strength-to-weight ratios, to other conventional engineering materials. Despite these advantages, plastic materials can create a problem in environmental safety and the ecological balance of the biosphere. Most waste polymeric materials are usually disposed of by landfills and incineration. Because we now demand more short-term, disposable materials, discarded or waste material is accumulating quickly. Recycling these materials can solve or ease environmental issues.

Solid wastes are composed of durable goods, nondurable goods, containers, packaging, food wastes, yard wastes, and miscellaneous inorganic wastes. The solid waste issue, once insignificant, is now an important concern. Plastic wastes constitute approximately 7% by weight and 18% by volume of landfill space (see Tables 18-1 and 18-2 and Fig. 18-2).

**SOURCES OF PLASTIC WASTE**

Plastic waste is generated from two main sources: industrial scrap and postconsumer waste. Industrial scrap is generated by plastics producers and processors, while postconsumer plastic waste is generated by end users. Scrap plastics generated during manufacturing of plastic goods can be reprocessed into commercially acceptable plastic products. This is done by most industries today and the amount of thermoplastic production scrap recycling is increasing. Thermoset plastic wastes are considered as nuisance plastics, and little recycling is occurring.

Based on the utilization process, plastic waste recycling is classified as primary, secondary, tertiary, or quaternary. Primary recycling is the process in which scrap plastics are reprocessed into the same or similar types of products from which they are generated, using conventional plastic processing methods (melt or solution methods). Generally, only thermoplastics are recycled in this manner.

Secondary recycling is the reprocessing of scrap plastics into plastic products used in less-demanding, lower-cost applications. Tertiary recycling involves the recovery of chemicals from waste plastics (either for use as fuel or as raw materials for new products). This type of recycling could result in the original products and is classified as primary in those instances. Finally, quaternary recycling is the recovery of energy from waste plastics; it generally involves incineration.

**LIFE CYCLE OF PLASTICS**

Plastic materials begin their journey at the oil fields. Refinement of the crude oil results in petroleum fractions and natural gases. Further cracking and distillation of refined petroleum fractions lead to hydrocarbons suitable for polymerization. These materials are known as monomers. From these monomers, plastic...
materials are obtained. The plastics manufacturer then supplies these materials to fabricators.

 Scrap plastics from the resin manufacturer are sold to the reprocessor or fabricator as second-grade resins. The fabricator sells his product to the converter, packager, assembler, or consumer. Compounders buy resins from the resin manufacturer, mix them with additives, and resell them to the fabricator. The scrap plastics generated in these operations (postindustrial scrap, including sprues, runners, and rejected parts) can be processed at the compounder's location or sold to a reprocessor, where the various plastics are sorted.

 The converter purchases a semifinished plastic product and converts it into finished goods. The packager, assembler, and distributor purchase finished products from the fabricator or converter, assemble and package them, and sell them to the consumer. This segment generates more scrap plastics. At the end of the plastic part's life cycle, the consumer disposes of the items. These waste items are sent to landfills or incinerators unless curbside collection is used.

### Table 18-2

<table>
<thead>
<tr>
<th>Landfill Constituent</th>
<th>Weight, lb (kg)</th>
<th>As % of Total MSW</th>
<th>As % of Excavated Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodegradable organic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yard</td>
<td>255.9 (116.1)</td>
<td>5.2</td>
<td>2.9</td>
</tr>
<tr>
<td>Food</td>
<td>59.7 (27.1)</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Wood</td>
<td>266.5 (120.9)</td>
<td>5.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Paper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newsprint</td>
<td>790.8 (358.7)</td>
<td>16.0</td>
<td>8.9</td>
</tr>
<tr>
<td>Packaging</td>
<td>699.1 (317.1)</td>
<td>14.1</td>
<td>7.9</td>
</tr>
<tr>
<td>Nonpackaging</td>
<td>486.4 (220.6)</td>
<td>9.8</td>
<td>5.5</td>
</tr>
<tr>
<td>Corrugated</td>
<td>251.3 (114.0)</td>
<td>5.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Magazines</td>
<td>112.2 (50.9)</td>
<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Ferrous metal</td>
<td>399.3 (181.1)</td>
<td>8.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Biodegradable total</td>
<td>3321.2 (1506.5)</td>
<td>67.1</td>
<td>37.5</td>
</tr>
<tr>
<td>Nonbiodegradable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastics</td>
<td>367.2 (166.6)</td>
<td>7.4</td>
<td>4.1</td>
</tr>
<tr>
<td>Rubber</td>
<td>30.3 (13.7)</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Aluminum</td>
<td>60.3 (27.4)</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Glass</td>
<td>187.0 (84.8)</td>
<td>3.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Nonbiodegradable total</td>
<td>644.8 (292.5)</td>
<td>13.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Mixed materials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unidentified</td>
<td>744.9 (337.9)</td>
<td>15.0</td>
<td>8.4</td>
</tr>
<tr>
<td>Textiles</td>
<td>171.0 (77.6)</td>
<td>3.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Diapers</td>
<td>66.3 (30.1)</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Fast-food packaging</td>
<td>16.9 (7.7)</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Mixed materials total</td>
<td>999.1 (453.3)</td>
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<td>11.2</td>
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<tr>
<td>Total MSW</td>
<td>4965.1 (2252.3)</td>
<td>100.0</td>
<td>55.9</td>
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<tr>
<td>Matrix material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fines</td>
<td>2987.1 (1354.9)</td>
<td>-</td>
<td>33.5</td>
</tr>
<tr>
<td>Other (mostly clay)</td>
<td>670.3 (304.0)</td>
<td>-</td>
<td>7.5</td>
</tr>
<tr>
<td>Rock</td>
<td>293.0 (132.9)</td>
<td>-</td>
<td>3.3</td>
</tr>
<tr>
<td>Matrix material total</td>
<td>3590.4 (1791.8)</td>
<td>-</td>
<td>44.3</td>
</tr>
<tr>
<td>Total sample</td>
<td>8915.5 (4044.1)</td>
<td>-</td>
<td>100.0</td>
</tr>
</tbody>
</table>

*aExpressed in billions of pounds.

*bExpressed in billions of kilograms.

*cMSW = municipal solid waste.

The extent of plastics recycling primarily depends on economics, although legislation, such as the 25% recycling rate for packaging plastics that is required in California and Oregon, is also becoming an important factor. Even though plastic scrap, whether postindustrial or postconsumer is quite cheap, expenses are incurred in the handling, size reduction, transportation, separation, and cleaning steps necessary to recycle the material.

### Primary Recycling

In primary recycling, the thermoplastic wastes are generally reprocessed by injection molding, blow molding, or extrusion to manufacture plastic products for applications similar to those of the original parts. Scrap can be reprocessed alone or, more often, blended with virgin resins at various ratios. Both postindustrial and postconsumer scrap can undergo primary recycling as long as the plastics can be separated (by color as well as type).

Primary recycling is always accompanied by a change in polymer structure (and therefore physical properties) due to the elevated processing temperatures. Such changes are due to material degradation from repeated processing; this results in a loss of properties such as appearance, chemical resistance, processibility, and other properties.

Contamination of the reprocessed plastics is also a problem. Volatile components can cause secondary reactions, such as oxidative degradation, as well as cross-linking through radicals. Commercial plastics contain stabilizers and antioxidants that lessen the thermo-oxidative process. Reinforced thermoplastics lose mechanical properties during recycling due to degradation of the.
polymers as well as degradation of the polymer/reinforcement interface and breakdown of the reinforcing fibers. Antioxidants must often be re-added to the recyclate during final processing.

### Secondary Recycling

Plastic wastes that are unsuitable for direct reprocessing into the original or similar parts can also be recycled. In secondary recycling, plastics are reprocessed into less-demanding applications. Since the products of secondary recycling compete with low-cost products (such as timber), secondary recycling was initially developed in countries where the competitive products were relatively expensive. This process is also widely used when plastics cannot be separated, such as in postconsumer waste.

When mixed plastic waste is processed, one of the main issues is to find the best compromise between homogenization and degradation. Different polymers are thermodynamically immiscible and thus can be incompatible with each other. Polymers with different melt indices and different thermal stabilities, especially PVC and PS, are difficult to process together, because at high temperature, PVC is easily decomposed, forming HCl gas and char-like residues. Therefore, optimum processing conditions must ensure good dispersion of the materials. Some mixed plastic wastes can undergo primary recycling if the polymers are naturally compatible or if appropriate compatibilizers are added.

A major point regarding both primary and secondary recycling is particle size. For reprocessing, plastic waste is ground to a particle size close to that of the virgin resin. The size reduction, in most cases, is accomplished by using a granulator. Various types of granulators are used depending on the required throughput, the size of the granulated pieces, and the shape of the plastic waste (films, pipe, sheet, etc.). Each granulator consists of a hopper, cutting chamber (rotor with knives), screen, and drive. Most hoppers have bends, baffles, and/or doors to prevent fly-back of the plastic pieces.

In cryogenic processing, materials are ground at very low temperatures and become embrittled. This technique is used where finely ground powder of ~30 mesh is required. Material cooling before grinding is done with liquid nitrogen, solid carbon dioxide, or mechanical refrigeration.

### Chemical Modification of Mixed Plastic Wastes

Mechanical mixtures of incompatible plastics, such as those recovered from municipal refuse, have inherently poor mechanical properties. Lack of adhesion between various phases results in stress concentration and consequently poor mechanical properties. A considerable amount of research has focused on upgrading the properties of mixed plastic wastes, through improvement in interfacial adhesion by either adding compatibilizers or cross-linking the blends. Separation of mixtures using air classification machines featuring recognition technologies, such as X-ray, infrared, and video, is also possible (allowing primary recycling), but this process has not proven commercially successful on a large scale.

### Use of Waste Plastics as Fillers

Some waste plastics can be used as fillers/extenders in the same type of plastics, different plastics, or nonplastic materials. Thermosetting compounds, such as polyurethanes, polyureas, melamines, epoxies, alkyds, and phenolics are recycled as fillers or extenders. This is generally not a cost-effective process, since this recycle is generally replacing very cheap fillers such as calcium carbonate or silicates. The plastics must be finely ground for this process to work well. Painted parts can be recycled by this technique.

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**TABLE 18-3** Estimated Lifetimes for Plastic Products

<table>
<thead>
<tr>
<th>Market Category/Product Area</th>
<th>Product Lifetime, year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaging</td>
<td></td>
</tr>
<tr>
<td>Flexible packaging except household and institutional refuse bags and film</td>
<td>&lt;1</td>
</tr>
<tr>
<td>All other packaging</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Bottles, jars, and vials</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Food containers (excluding disposable cups)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Household and institutional refuse bags and film</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Building and construction</td>
<td></td>
</tr>
<tr>
<td>Pipe, conduit, and fittings</td>
<td>NA</td>
</tr>
<tr>
<td>Siding (including accessories and structural panels)</td>
<td>NA</td>
</tr>
<tr>
<td>Insulation materials</td>
<td>NA</td>
</tr>
<tr>
<td>Flooring</td>
<td>NA</td>
</tr>
<tr>
<td>Consumer and institutional products</td>
<td>NE</td>
</tr>
<tr>
<td>All categories, excluding other (including disposable cups)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Disposable food serviceware</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Health care and medical products</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Toys and sporting goods</td>
<td>5</td>
</tr>
<tr>
<td>Hobby and graphic art supplies</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Electrical and electronic</td>
<td></td>
</tr>
<tr>
<td>Home and industrial appliances</td>
<td>10</td>
</tr>
<tr>
<td>Electric equipment combined with electronic components</td>
<td>10</td>
</tr>
<tr>
<td>Wire and cable</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Storage batteries</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Communications equipment</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Furniture and furnishings</td>
<td></td>
</tr>
<tr>
<td>Carpet and components</td>
<td>10</td>
</tr>
<tr>
<td>Textiles and furnishings, nec</td>
<td>10</td>
</tr>
<tr>
<td>Rigid furniture</td>
<td>10</td>
</tr>
<tr>
<td>Flexible furniture</td>
<td>10</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
</tr>
<tr>
<td>Motor vehicles and parts</td>
<td>NA</td>
</tr>
<tr>
<td>Ships, boats, and recreational vehicles</td>
<td>NA</td>
</tr>
<tr>
<td>All other transportation equipment</td>
<td>NA</td>
</tr>
<tr>
<td>Adhesives, inks, and coatings</td>
<td></td>
</tr>
<tr>
<td>Inks and coatings, nec</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Adhesives and sealants</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

**TABLE 18-4** Composition of Plastic Waste

<table>
<thead>
<tr>
<th>Waste</th>
<th>Wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyolefins (PE, PP)</td>
<td>50–56</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>15–20</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>12–17</td>
</tr>
<tr>
<td>Other plastics</td>
<td>Approximately 10</td>
</tr>
<tr>
<td>(polyurethane, polycarbonate, etc.)</td>
<td></td>
</tr>
<tr>
<td>Impurities</td>
<td>3–10</td>
</tr>
</tbody>
</table>

NA = not applicable. Category of waste is not normally included in MSW. NE = not estimated. nec = not elsewhere classifiable.
CHAPTER 18
RECYCLING PLASTIC MATERIALS

Tertiary Recycling

Tertiary recycling of plastic wastes results in conversion of the waste to useful chemicals. These processes include thermal treatments (pyrolysis) or chemical treatments at elevated temperature (hydrolysis, hydrogenation, glycolysis, transesterification, and transamination). The resulting products (liquids and/or gases) are used as fuels or raw materials.

In pyrolysis, the waste is heated in an oxygen-free environment and generally results in simple hydrocarbons, both gases and liquids. Hydrogenation is carried out under increased hydrogen pressure. Under hydrogenation conditions, the macromolecular chains are broken down, and the fragments are saturated by hydrogen. During the course of these processes, heteroatoms, such as chlorine, nitrogen, oxygen, and sulfur, are transferred into their corresponding hydrogen compounds. The process of pressure hydrogenation offers higher flexibility as a chemical recycling method for plastic wastes.

A knowledge of the waste mixture composition allows optimization of the hydrogenation products for use in polymer synthesis or for petrochemical applications. Presorting of the plastic wastes by type allows use of the recycled products from this process for production of new plastics or other basic organic chemicals with a quality identical to that of newly synthesized materials (see Fig. 18-3). Separation of the plastic waste is not always necessary, and the monomers resulting from the process can be separated in the gaseous state by fraction distillation.

Polyester

Polyester (PET) can be recycled directly (melt methods—primary recycling) or by chemical treatment (tertiary). Tertiary recycling of PET film is coupled with the simultaneous recovery of silver. Direct primary recycling of PET wastes is by far the most economical process. However, with PET wastes having a higher degree of contamination, other technological processes are applied, including glycolysis, methanolysis, or hydrolysis, yielding products that can be isolated. PET is perhaps the most widely recycled of all plastics, largely because of the bottle deposit laws. The principles of these chemical processes are shown in Fig. 18-4.

Glycolysis is a method for direct reuse of PET, whereas methanolysis and hydrolysis are used for monomer recovery. Goodyear has developed a PET recycling process based on glycolysis that is called Repete . Glycolytic recycling of PET, which is done in a continuous or batch process, is preferentially performed by the addition of PET waste to boiling ethylene glycol; this leads to the formation of low-molecular-weight intermediates and eventually to crystallizable diglycol terephthalate, which is used to make polyols for polyurethane applications (rigid foams). The degradation reaction rate is primarily controlled by varying the dwelling time, temperature, choice of catalysts (for example, titanium derivatives), and the PET-to-glycol ratio.

Methanolysis of PET waste is also carried out. The waste is treated with methanol (in a ratio of 1:2–1:10) usually under pressure at high temperature (320–590 °F [160–310 °C]) in the presence of transesterification catalysts. Once the reaction is completed, dimethyl terephthalate (DMT) is recrystallized from EG-methanol mother liquor and distilled to obtain pure DMT; this is used to make new PET. Ethylene glycol and methanol are purified by distillation.

Aromatic polyesters are water resistant under normal conditions but can be completely hydrolyzed at higher temperatures and pressure. Since acidic or basic catalysts are used, several problems arise, such as corrosion of the equipment and difficulty in ethylene glycol regeneration.

Other Plastics

Recycling of waste thermosetting plastics and composites is of great interest worldwide. Recycling of waste thermosetting plastics and composites is of great interest worldwide. 17, 18, 19 The major recycling processes described in the literature are grinding (particulate used as fillers), pyrolysis, incineration (use of generated heat and use of particulate remnants as fillers), prolonged solvolytic degradation, and decross-linking by transesterification.

In the last two decades, much fundamental research on reclaiming polyurethanes and polyureas was carried out. One process for liquefying scrap polyurethane works by dissolving it in carboxylic acids having molecular weights below 5000 and acid numbers from 50–800. The rate at which the scrap dissolves depends on the relative proportions of carboxylic acid and urethane or urea groups. The higher the acid number in proportion to the number of urethane or urea groups present, the faster the reaction at a given temperature. The reagents used include fatty acids, resin acids, polymerized unsaturated acids, polycarboxylic acids, heterocyclic acids, stearine pitch, fish oil pitch, and linseed oil. The products obtained are used in coatings, adhesives, and foams.

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*Fig. 18-3 Hydrogenation products of polymer materials.

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There is a process for the recovery of polyethers and diamino-toluenes from waste polyurethane foam or elastomers. This is done by thermal decomposition at temperatures below 480˚ F (249˚ C) in the presence of an aliphatic amine, aromatic amine, cyclo-aliphatic amine, heterocyclic amines, or their derivatives. The reaction is accomplished in the presence of alkali metal oxide, alkali metal hydroxides, alkaline earth oxide, or aqueous solutions of these compounds.23

The de-crosslinking (transesterification) of polyurethane reaction injection molding (PU RIM) thermosets and composites uses granulated PU RIM thermosets, glycol, and alkali catalyst. The resulting liquid oligomers are used economically in products such as adhesives, coatings, foams, and composites.24

Thermal and solvolytic degradation of thermoset polymer wastes is the focus of numerous other major studies. Thermo-degradation of the most important thermosets, including PU composites, epoxy composites, sheet molding compounds (SMCs), reaction injection molding (RIM), structural RIM (SRIM), and bulk molding compounds (BMCs), is under study.

**Quaternary Recycling**

Another approach used to dispose of waste plastics, particularly when they contain large amounts of impurities and other combustible solids, is termed quaternary recycling. The process consists of energy recovery from the waste by incineration. Research in this area has been carried out, particularly in Europe and Japan, since the early 1960s. Strong emphasis has focused on optimization of incinerators to reduce the level of air pollution. The combustion of plastics, however, requires three to five times more oxygen than that required for conventional incineration; it produces more soot, and develops excessive heat. Incineration equipment can be adapted to cope with these problems.

Several processes are used to overcome these technological drawbacks. Examples include Leidner’s continuous rotary kiln process. Baliko’s process for glass-reinforced plastics involves incinerating a combination of wood fibers and plastics to provide steam to power equipment. ETH-Zurich’s fluidized bed system for pyrolysis, especially useful for photographic films, is also a proven process.26 The latter system raises the additional problem of forming toxic halogenated compounds, stemming from the presence of silver halides.

Typical quaternary recycling operation takes place at temperatures near 1290˚ F (699˚ C). At lower temperatures, waxy side products are formed, leading to clogging. At higher temperatures, the fraction of desirable mononuclear aromatics decreases. A representative sample, pyrolyzed under optimized conditions, yields in addition to water and carbon dioxide, aromatics such as benzene and toluene, and a variety of carbon-hydrogen and carbon-oxygen gases. Studies were performed to avoid formation of dioxins and disposal of residual ashes containing heavy metals and other stabilizers. Chlorine-containing plastics, such as PVC, are particularly troublesome in this regard due to chlorine formation.

At present, most problems arising from incinerating plastic wastes can be resolved; however, many residual hurdles remain before an economically feasible and ecologically accepted industrial technical process is available. The fuel value of plastics is proven, and incineration can yield as much energy as coal.

**Source Reduction**

Source reduction is another approach for avoiding the use of excess material. An important conservation method, this is a major form of pollution prevention, the present environmental paradigm for industry. Elimination of potentially toxic materials (such as heavy metals and toxic organics) also falls under the category of source reduction and is an equally important pollution prevention measure.

The substitution of plastics for traditional glass, metal, and wood items often results in source reductions. However, cost reduction is normally the primary factor promoting the change. In the case of soft drink bottles, for example, the decrease from over 1 lb (0.45 kg) of glass to about 3 oz (0.09 kg) of plastic represented an 80% weight reduction and over a 50% volume reduction for the same amount of product delivered. Furthermore, since 1977, the weight of the 68-oz (2-L) plastic soft drink bottle was reduced by 25%.

Plastic packagers are continually assessing the thickness of plastic used in film and rigid packaging, attempting to reduce the...
CHAPTER 18

RECYCLING PLASTIC MATERIALS

amount of material used. Recently, plastic films with better gas barrier properties were introduced, permitting a film thickness reduction of 25% while retaining the same gas barrier protection.

Identification and Separation Techniques

Recycling plastic, whether it is postconsumer or postindustrial scrap, begins with the collection and separation (if necessary) of mixed materials including mixed colors. These scrap plastics are typically a mixture of polymers, modifiers, additives, and fillers.

Physical methods, such as those based on density, are not always sufficiently specific to allow separation. Effective identification processes must use methods that can monitor structural or molecular plastic properties. The method must also withstand an industrial environment, demanding robust and fast-scanning instruments.

Various standard methods of chemical analysis are under evaluation. X-ray fluorescence and mass spectrometry are used to analyze recycled materials. Several other methods, such as laser spectroscopy, X-ray diffraction, and video are also successfully used.

Near-infrared (NIR) spectroscopy21 was used in identifying basic polymers, as it allows fingerprints of polymers and provides additional information on some additives. An NIR spectrometer based on an acousto-optic tunable filter scans the spectra range required for identification in milliseconds. A computer system controls the spectrometer, acquiring and analyzing the spectra on-line.

THE PLASTIC INDUSTRY’S VISION AND STRATEGY FOR THE FUTURE

Efforts to recycle increasing amounts of plastics will continue well into the next century. These will be driven both by legislation and cost effectiveness. In periods of recession, the price of virgin plastics drops; therefore, recycled resins show less cost advantage and, in many cases, are more expensive than virgin plastics. When the economy recovers, the price of virgin plastics increases, and they are generally far more expensive than recycled resin. In addition, production problems can severely affect the price of virgin materials.

The natural cycle of production increases also affects virgin prices. Significant production increases, which occur when manufacturers decide that debottlenecking is not sufficient and new production facilities are required, reduce virgin resin prices and thereby make recycling less favorable economically. Furthermore, although the landfill crisis may be less severe than once thought, landfill capacity remains an impending problem.

Most plastics are based on petroleum, a nonrenewable resource. Therefore, it makes sense to recycle them so that we do not deplete this valuable resource. Less energy is also required to recycle plastics than to create and process new plastics. As responsible members of the world community, industry must continue to increase its recycling efforts. At the same time, municipalities must increase their efforts toward developing an infrastructure to collect postconsumer waste.

EQUIPMENT MAINTENANCE

Preventive maintenance is essentially predicting the inevitable and preventing the exceptional. The goal of total productive maintenance (TPM) is to improve overall equipment efficiency with zero omissions and zero errors. When implementing TPM philosophy on the shop floor, good maintenance practices and a thorough preventive maintenance (PM) program are essential. PM helps reduce unplanned downtime and enables the maintenance department to increase machine efficiency through more advanced predictive maintenance techniques. Preventive maintenance is defined as a system of prevention activities that maintains a machine's proper operating condition through lubrication, inspection, machine overhaul, and part replacement. Maintenance department responsibilities may include coolant recycling, hydraulic oil filtering, and mechanical and electrical PM programs. They augment these activities with the predictive maintenance tasks of vibration analysis, oil analysis, coolant analysis, and thermography. Underlying this system is a solid partnership between production and maintenance that supports the program.

Operator-based routines, such as cleaning, inspecting, and lubrication PM, form the first-line defense against equipment failure, though operators generally perform no more than 20% of all PM. Operator involvement in maintenance activities usually takes no more than 60 seconds; tools or ladders cannot be used, and the machine cannot be shut down. Daily start-up and shut-down inspections and adjustments—usually documented on checklists—are examples of these routines. Cleaning and inspecting is a practical task in which operators remove wear-causing dirt and grit from machine surfaces, uncover potential problems, and alert maintenance before production is lost. Operator lubrication responsibilities can also include monitoring and maintaining reservoirs at the proper levels, changing lubricants, and greasing.

The first step is to get the operators involved through communication. Any required tools are made available. For example, operator oiling cards on each machine are an effective communication method. The primary visual control cards on the machines are diagrams that indicate where lubrication is needed and how often it is done.

These instruction sheets, or pictorials, are attached to the machine to both identify key focal points and list operator routines and lubrication tasks. Since TPM’s ultimate goal is to improve overall equipment efficiency, zero omissions and zero errors are critical standards in the pictorial’s development. To ensure optimum equipment performance, every lube point, lube type, and lube task is identified.

Operators build an intuitive “feel” over time for their equipment. By learning how their machines function and how to detect abnormal conditions, operators can control the factors affecting equipment performance.

Implementing an effective PM program involves the entire organization and, depending on the size of the facility, can take six months to a year to accomplish.

ORGANIZING EQUIPMENT

Equipment Inventory

Common practice for equipment inventory is to take a conglomeration of machinery and represent it by a given identification number. This number may represent many different equipment manufacturers. Some free-standing (or stand-alone) equipment—like conveyers, presses, mills, and mobile units—may have a single asset number, and the majority of support equipment—such as heating, ventilating, and air conditioning (HVAC); utilities; and
downstream water treatment equipment—is not numbered. Thus, a true inventory may not exist.

For effective TPM, the facility evaluation must be realistic. A complete inventory is developed from a planned maintenance perspective. For example, some machines have additional or remote hydraulic systems connected via flexible hoses that must be inventoried. Maintenance also has the responsibility for material handling equipment.

When the inventory list is completed, it is separated into three basic categories: critical path equipment, support equipment, and building utilities.

Critical path equipment. Critical path equipment is generally one-of-a-kind prototypes with no back-ups. Product flow stops when this equipment is down. Dissecting a facility in relation to critical path equipment automatically organizes the focus.

Support equipment. Support equipment serves critical path equipment and is found throughout the plant in numbers far exceeding those of critical equipment. Though needed for production, this equipment may be shut down temporarily without interrupting product flow or hindering guaranteed delivery of quality parts.

Building utilities. The focus here is on any equipment supporting production and the building environment, such as HVAC units, air compressors, dryers, boiler rooms, and work treatment plants.

Critical Areas
Each department contains critical equipment. Selecting a few pieces in each department will likely require others to work within the new PM system from the start. Selecting more than 50 pieces of equipment for a pilot project is generally excessive and slows the development stages.

When the PM plan is successfully implemented for this critical equipment, an immediate increase in overall equipment reliability is realized. It is wise to start in the critical areas because reactive breakdowns cause considerable delays to just-in-time deliveries and quality attainment.

Once the project starts, the ultimate goal is to keep the equipment running at 100% capacity during production. Production, in turn, must understand that the PM plan supports a philosophy in which the maintenance department never asks the production department for a machine while it is running. By involving one or two key pieces in each department, or in every cell, all involved strive toward a common goal of keeping critical path pieces moving.

BASIC BUILDING BLOCKS FOR PLANNING PREVENTIVE MAINTENANCE

The Plan
The Phase I plan serves as a format with short-term goals that include organizing a Phase II and a Phase III plan. The Phase I plan serves as a benchmark to measure the overall equipment effectiveness (OEE).

The structure of the plan supports future benchmarking within the corporate structure where multiple facilities exist, and in relation to company competition.

The plan, if done properly, will prevent a complete rework and cultural redefinition.

Auditing the Process
Cruicial to the PM plan is a means to audit its performance. The plan should guarantee a return on investment, increase the reliability and productivity of the machinery from current levels, and improve quality and throughput. Three questions arise in developing this measure of performance:

Where are we now? What is the current situation in the facility regarding productivity, downtime, and quality? What do we like?

In each of these areas, current production status is highlighted. Successful items developed over the years are noted. Remarks can also include the individuals responsible for certain gains.

The next items to address are those where change is desired. With answers to current status and production preferences, the changes are charted. Only one or two changes at a time in each category are implemented and put on a Gantt chart to monitor their implementation. Teams are assigned to make those changes.

The best way to address these issues is to have a short-term plan—the pilot project—that supports the critical path equipment in each department. The next step is to establish a mid-range goal that goes beyond the pilot project and includes analysis and organization of all other production equipment involved in making the product. Finally, there is the long-term goal, which encompasses all other support equipment and utilities.

Determining the Objectives
Many facilities that want to embark on TPM and PM programs borrow objectives from other facilities, failing to capture their own culture. The key to establishing objectives is to determine them against the backdrop of the particular culture and personality of your production departments.

Each facility has a different production personality profile. Some are relaxed, some are intense; some have a high personnel turnover, and others boast workforces with longevity. It is necessary to capture and record the personality of production; from those observations, the culture is defined and developed, and enhancements are made. To capture the culture, the equipment for PM tasks is analyzed without using the OEM manuals. These manuals enhance PM concepts, not vice versa.

Equipment Analysis
One of the greatest challenges in developing a TPM or PM program is equipment analysis. The following sections describe several approaches.

Developing the analytical process. Deciphering what requires analysis is the first item of business. The “what we own” list is reviewed, highlighting the machine, the location of components, the components themselves, and the subcomponents.

Don’t use the OEM manual...yet. The first guideline is to assess the technical level of the maintenance department and to set up the analysis requirements without using the OEM manuals. Most manuals are written by individuals not involved in the production process, and these individuals are often not aware of their equipment’s operating environment.

Follow the power. For an organized approach across all machinery, the power sources into the machinery are followed; they are the key factors. For example, in a CNC machine, one begins by following all of the components—the motor, couplings, ball screws, timing belts, and bearings—until the piece part is reached. The power train is followed through, and the PM is written in relation to the energy movement through the machine. In this way, the person diagnosing the machine has a diagnostic pattern and a logical method for completing the tasks.

Diagnostic evaluation. In diagnosing a piece of equipment, the individual doing the diagnostic work must clearly understand how energy is transduced, that is, converted from electrical power to mechanical to pneumatic, and back to hydraulic and mechanical
EQUIPMENT MAINTENANCE

Some PM cycles extend to three years. On a daily, weekly, monthly, quarterly, semiannual, or annual basis, the frequency is determined on a task-by-task basis; it can be scheduled. When they are easily tracked, with evidence that the task is completed. To illustrate this approach, picture the components of a typical plastic injection molding machine:

- Motor.
- Coupling.
- Guard over the coupling.
- Pump.
- Suction strainer at the pump entry.
- Pressure filter coming off the pump.
- Reservoir oil filter.
- Manifold assembly containing all the valves.

This breakdown helps identify the components in a power sequence. In this manner, each component is identified and placed as the first word of a task description. Throughout the diagnostic concept, an organized approach to parts management is built. Next, after following the previous guidelines, the OEM manual is referred to, and any OEM PM suggestions are then evaluated. Instead of using each OEM manual as the focal point, it is the backup, an enhancer; it is used after a dialogue is developed.

Questions to ask. The diagnostics raise some basic issues. The task needs a frequency, components need descriptions, and energy sources are identified. The task also needs a link name. If the component is described as a motor, it is identified as the drive motor for the hydraulic system, so it must have a link name description. An estimated time to complete the task is also needed. Furthermore, the task needs a category that indicates whether it is a PM task or a daily upkeep task. Any additional skills in this task—electrical or mechanical—are identified.

The ultimate goal with the first diagnostic work is to plan for a paperless system. When all of the components in a power sequence have been identified, the next challenge is to dissect the machine, breaking it down into general areas of assemblies and locations of components and subcomponents. This breakdown helps identify the components in a power sequence. In this manner, each component is identified and placed as the first word of a task description. Throughout the diagnostic concept, an organized approach to parts management is built. Next, after following the previous guidelines, the OEM manual is referred to, and any OEM PM suggestions are then evaluated. Instead of using each OEM manual as the focal point, it is the backup, an enhancer; it is used after a dialogue is developed.

Proper description and methods. Often overlooked when describing components is the future support of parts replacement. Part descriptions are often recorded haphazardly, and this situation requires standardization. Diagnostic work must support parts management—not in a reactive maintenance mode, but in a scheduled and planned mode.

Once the equipment is organized and competent technicians are available for the diagnostic work, the tasks are sequenced so that they are easily tracked, with evidence that the task is completed. Determining task frequency is both critical and complex. Frequency is determined on a task-by-task basis; it can be scheduled on a daily, weekly, monthly, quarterly, semiannual, or annual basis. Some PM cycles extend to three years.

EVALUATING THE MAINTENANCE PROGRAM

A well organized PM program uses all practical concepts available to eliminate reactive maintenance and promote scheduled and planned maintenance. Developing the program and organizing the information on that aspect alone indicates what is supportable in higher technology. Many plants have a handwritten or verbal work order system. Recordkeeping is often at a low level, with less than 50% of the work documented. Evaluating and documenting the current maintenance program pays real dividends.

What constitutes reactive, planned, preventive, and scheduled maintenance? Although many definitions exist, the challenge is to use definitions that best fit your company.

“Scheduled” and “planned” are similar terms. In one facility, for example, scheduled maintenance may mean that maintenance tasks are scheduled only during two plant shut-downs.

Planned maintenance can mean that repairs are planned when the machine normally goes down. In this way, planned maintenance would never shut down a machine for repair or PM work. It is designed to support production at 100% machine uptime, with repairs planned only during nonproduction windows.

DEVELOPING THE TASK

The task is identified as PM, daily upkeep, or scheduled maintenance. There are three main types of maintenance: reactive, predictive, or preventive. Reactive maintenance occurs as a response when a machine becomes inoperable. Predictive maintenance measures physical parameters against a known engineering limit to detect, analyze, and correct equipment problems before production losses occur. It can reveal the cause of a problem, and through planned adjustments, help prevent equipment failure and deterioration. Preventive maintenance is a system of prevention activities that maintains a machine’s operating condition through lubrication, inspection, machine overhaul, and part replacement.

Each task is classified as a “running” or a “down” task. A sound guideline is 75% running tasks and 25% down tasks.

Task Ownership

If the task does not require specific skills, there is no need to develop it as a task that has ownership. If it is a PM task, anyone in the plant can be trained for it. Where possible, ownership concepts are more generic so that the PM team is cross-trained to do all tasks. If the task is associated with sampling oil, ultrasound, infrared vibration, or surge comparison testing, a notation of that fact is made.

The level of the task is also needed. Parameters to determine levels are as follows:

- Level 1: The task can be performed without tools, often while the equipment is running. Even if the machine is down, the task can be done without tools.
- Level 2: Specific tools or support equipment is needed to help with the task.
- Level 3: Data for this level are gathered from the machine’s gages that advise of the machine’s status.
- Level 4: Predictive tasks. Equipment and testing devices (for example, vibration probes and infrared inspection cameras) provide additional information on which to base the complexity level. With this information, the maintenance technician can classify the PM system by the level of task.

A final issue to determine is the length of each task, often known as “wrench time.” This determines PM technician schedules and smooths the flow of plant PM work.

Considerations

Safety. Task safety is paramount, and additional support personnel may be required. Safety issues are addressed first and for each task.

It is necessary to lock out and tag out a machine maintenance. It is helpful to print out all lockout/tagout procedures to know when nonproduction time will permit working on a machine.
Accountability. The last portion of task development is to develop a way of accounting for each task. Answers to five basic questions satisfy this requirement:

- Is it OK?
- Is it damaged?
- Is it dirty?
- Is it leaking?
- Is it hot, cold?

Answers to these questions generate the corrective work orders. By uploading all data into a computer program, each task is easily managed. By making changes globally, the change from a reactive maintenance philosophy to a productive one is smoother.

**MAINTENANCE RECORDS CONTROL**

The current level of maintenance records control is identified. The goal is to develop the maintenance records to support the parts replacement, management concept, and the time management relative to PM and scheduled maintenance. This is done for each machine taking into consideration general factory requirements.

Recordkeeping is generally found at three levels:
- None.
- Some written documents, possibly in a file cabinet.
- An in-house computerized support system, or an internally generated database, that is most often a computerized maintenance management system (CMMS).

It may be practical to purchase a CMMS. A potential pitfall is buying a CMMS prior to identifying a maintenance plan and uncovering cultural needs. As a result, some companies cannot generate the appropriate reports. Their culture will not change, nor will the CMMS program.

**TRACKING THE SYSTEM**

Tracking the system in today’s manufacturing environment mandates the use of computers. Only an automated system can process the volume of data necessary to organize the tasks into a route and to determine task lengths.

Before implementing the PM program, the frequencies (how often), work load, lubrication points, and necessary product volume are known. These are tracked prior to implementing the PM.

After determining the types of data that are tracked, it is easier to decide the complexity of a potential CMMS, the necessary types of reports, whether separate or networked computers are required, and the types of printers required. The nature of the PM system drives the configuration of the computer system and not vice versa.

**Development of Routes**

When a machine analysis is complete, and the critical path machines in the plant and the different departments are identified, a walking route is set up for the maintenance person. This route supports operator involvement, and the person walking the route is the liaison to the operator who services the equipment daily.

**Types of Routes**

Now many tasks are assigned and broken down into a running and a down route. The crucial decision is whether these tasks are done daily, weekly, or on another basis. Organizing patterns of tasks or skills is important. For the most part, on critical path machinery, it is best to develop a walking route. This means that the first machine on the route is No. 1, the second is No. 2, and so on. Thus, the task orders are printed out in a walking route system.

As the PM is expanded into support equipment and all the plant equipment is finally organized, a “megaroute” may develop. That route would enable the support staff to walk the plant in an organized fashion.

If the time is multiplied by the frequency of that route, an hour-long walk can be developed. However, lunch and breaks are also factored into any route.

**Guidelines**

To streamline the process, it is appropriate to organize all “daily upkeep” tasks. With these tasks, the operator inspects his or her machine at the start of each shift. Because the tasks are done without tools, in a safe manner and quickly, they are classified as daily. These tasks are removed from the PM task list and accomplished by the operator. Each task is associated with equipment reliability and part quality.

**DIAGNOSTIC TOOL NEEDS**

Predictive maintenance measures physical parameters against a known engineering limit to detect, analyze, and correct equipment problems before production losses occur. It can reveal the cause of a problem, and through planned adjustments, help prevent equipment failure and deterioration.

The maintenance department typically has at its disposal several different types of analytical instruments, for example, an infrared gun, a thermographic camera, or a vibration monitor. It is necessary to list all analytical instruments and support equipment available. Armed with the existing instrument and equipment list, a predictability pilot project is developed, and any additional equipment needed to support it is identified.

Even if infrared or vibration equipment is not available, it is important to learn to diagnose machinery and record the need for such equipment. Inventory and justification for analytical support equipment are vitally important to predictive maintenance.

In selecting diagnostic tools, it is important to recognize that technology development advances almost exponentially. This is perhaps truer in electronic technology than in other areas. Tools selected today may quickly become obsolete.

The most important step in trend analysis is to gather information from trend testing and make that information part of a trend concept evaluation. For example, when debris is found in oil from an oil analysis, a vibration test and oil analyses are immediately done on the pumps to check for potential problems. An infrared test and visual inspection are also appropriate. Those data are then incorporated into a single report to evaluate plans for scheduled repairs.

**LUBRICATION CONSIDERATIONS**

Lubrication is a critical element of a PM program, yet attention to its importance persists at a low level. A lack of knowledge regarding how to lubricate and what requires lubrication is common.

**Examples**

Many machines have greasable couplings under guards and some are nonlubricated. Reservoirs on some systems have two worm drives: a primary small worm and a secondary large one. The two are bolted together, making it appear as a single worm drive. The maintenance department may never realize that the first worm has a separate reservoir and grease fitting. Manufacturers may put a level gage on one and not the other, giving the illusion of a single reservoir.
Most facility equipment has up to five surfaces/features to diagnose in terms of lubricant protection:
- A turned surface.
- A ground surface.
- A honed surface.
- A shaft.
- A polished surface.

These are the combinations of metal to metal or other materials; their make-up mandates the type of lubricant that is used.

**The Survey**

Lubrication is the backbone of the PM system. The lubrication portion of the PM system must be at 100% with no omissions or errors. As a result, all lubricants applied to the machinery—the greases, oils, or any specialty products—are identified, as well as all supporting systems that link the loop.

When developing a lubrication program, a floor plan of the plant is made first. A top view of the plant is taken and “walked through” in relation to lines, columns, or departments, and each lubrication location is recorded. The location, type of lubricant, vendor’s name, and a short description of its use in the area is noted.

Placing this information in a spreadsheet program provides a quick summary of the floor material in relation to inventory, cost, and the general lubricants in each zone. Knowing that in advance helps develop the operator support lubrication stations so that the correct lubricants are placed in the general area. Next, lubrication concepts are organized, and purchasing is harmonized with the maintenance department. A generic lube code is preferred over a brand name for PM records.

**Status Indicators**

The level or proximity switches that send signals to the main terminal board identifying a loop fault in the system are verified and checked by a trained person to ensure system integrity. When the lube lines going to toggles are verified as being turned off, the system is verified as mechanically in place and electronically supported, and all pneumatic actuators on the central loop system are functioning. In this way, it is clear that the loop systems supplying the product, whether manual or automatic, are intact.

**Use of Codes**

It is good practice to generate a uniform generic code for each product. Lubricant product charts can provide complete breakdowns so that most lubricants are easily cross-referenced.

A generic code is designed to support the immediate development of a PM system. Machinery is analyzed by choosing the general product in a generic form and eventually incorporating your brand product line. The generic codes are then developed into special tags for the machinery. The purchasing department can change vendors and product names, but the products always fit this generic code list. Each product that has a generic code would also have a material safety data sheet supporting it in the maintenance area and at each lube station. Also, a primary and a secondary supplier are preferred for each product.

**Removal and Recycling**

It is important to (a) never change oil and (b) never ship the oil out of the plant. It is very important to save the oil for testing. The oil, when tested, provides valuable information about the equipment’s condition. It is the key to developing an effective predictive maintenance system.

Disposing of oil also dispenses of evidence in the oil. Those data are critical to machine wear analysis and predictive maintenance plotting. By taking a sample of the oil, cleaning it in the reservoir, and looping it through a filter system, an effective repair strategy is developed.

**Reuse and Additives**

Another factor to consider when changing oil is the possibility of recycling it through the plant as a different type of product after it is tested. Most oil suppliers welcome the opportunity to supply additives or to suggest a way to filter the oil and bring it to acceptable cleanliness levels. They can also help in checking the additive level and viscosity. Hydraulic and gear oils are also used to make cutting oil for machine shop equipment or turning and milling operations.

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**TOOL SURFACE ENHANCEMENTS**

**THE SURFACE ENHANCEMENT DILEMMA**

Molders are always looking for an edge over their competition—one that leads to smoother operation and higher profits from their injection molds. As the technology of mold surface enhancements and coatings evolves, processors have increasingly turned to them in hopes of gaining this advantage.

A variety of surface enhancement methods and suppliers are now available, each making claims regarding the benefits of their products. With numerous suppliers offering many products, deciding which technology to use is often difficult.

Most toolmakers and molding shops do not have the resources needed to carefully study these options. In many cases, they treat molds with methods that have worked in the past, even though a current application may have different demands, and newer methods are available.

The first step in determining the best coating or surface treatment is to know what capabilities are needed from that coating. The following areas are evaluated.

**Hardness**

Longer mold life is often achieved by increasing the hardness of the tool surface. Increased wear properties are especially critical with abrasive glass- and mineral-reinforced resins. This is notably important in high-volume applications and high-wear surfaces, such as gate inserts.

**Corrosion Resistance**

Some plastic materials release corrosive chemicals as a natural byproduct of the injection molding process. For example, hydrochloric acid (HCl) is released when molding polyvinyl chloride (PVC). These chemicals can cause pitting and erosion of untreated mold surfaces. Also, untreated surfaces may rust from water in the resin and humidity in the air.

**Lubricity**

Improved release characteristics are a commonly advertised advantage of mold coatings and surface treatments. This is critical.
in applications with long cores, low draft angles, or resins that stick on hot steel in hard-to-cool areas. Coatings developed to meet this need may contain polytetrafluoroethylene (PTFE) or nickel, or tungsten, two metals with inherent lubricity.

**Tool Build-up or Repair**

Some metal platings, such as chromium, are used to build up molds at a significant cost advantage to welding and remachining. Such thick deposits can repair damaged parting lines or surfaces that are eroded from corrosion or wear.

**Reduced Cycle Time**

Many suppliers advertise reduced cycle times with coatings due to reduced flow resistance, better release from the tool, and thus faster ejection.

**Special Needs**

Coating choices may be limited by the substrate, as many conventional coatings are applied only to ferrous materials. The choice of coatings for aluminum tools is quite limited. Molds using brass or beryllium copper may also require special considerations.

**REVIEWING THE CHOICES**

After determining the most critical surface treatment needs, these needs are matched with the treatments that are available to the injection molding industry.

**Guide to Surface Enhancements and Coatings**

Refer to Table 18-5 for a comprehensive guide to tool surface enhancements and coatings that are often applied to tools used in the plastics industry.

**Modified Tungsten Disulfide**

A thin intermetallic coating, modified tungsten disulfide, is often applied with pressurized air at ambient temperatures onto the tool surface in lamellar form. Tungsten disulfide has more lubricity than any other dry substance. In fact, the fine particles do not stick to each other; this ensures a thin uniform coating thickness of 2 × 10⁻⁶ in. (5.0 × 10⁻⁵ mm), supplying a dynamic coefficient of friction of 0.03 against itself.

The compound is stable to at least 1000˚ F (538˚ C), and upon application, a blue-gray color appears on the tool surface. When this color disappears, the coating is reapplied. This coating is used primarily as a friction-reducing agent, to aid in part release, or on sliding mold surfaces such as wear plates and gibs.

**PTFE Infused into Metallic Coatings**

Metallic coatings are designed to reduce the coefficient of friction for the tool surface. The first step involves plating the tool. A conventional nickel or chrome deposition is generally used. The plated layer is treated to open “cavities” in the surface that allow the PTFE to lock into the coating. This opening on the plated surface usually involves thermal fracturing or sandblasting and is often a proprietary supplier process. The theory is to have a layer of PTFE and plating behind the softer PTFE outer layer. As the outer layer wears off, the PTFE captured in the pores continues to provide lubricity.

A layer of PTFE is sprayed or dipped onto the surface and then heat cured. In some cases, the PTFE particles are cryogenically cooled and then sprayed onto the surface. The particles enter the surface pores and expand, locking them into place.

For aluminum, low frictional properties are provided by a PTFE-impregnated, hard-coat anodizing treatment.

Due to the presence of the PTFE, a maximum continuous temperature range of 500–550˚ F (260–288˚ C) is suggested. In high-volume molds, it may be necessary to chemically strip and reapply the coating periodically. These coatings generally add 0.0010–0.0025 in. (0.025–0.064 mm) to the mold surface, but thinner or thicker treatments are also specified.

**Nickel/Phosphorus/PTFE Codepositions**

In these coatings, PTFE particles are mixed into a nickel/phosphorus matrix and applied to the mold using autocatalytic (electroless) codeposition. As the coating wears away, new PTFE particles are continuously introduced to the mold surface, maintaining lubricity over a longer time period. The PTFE particles are generally intermixed at ratios of 23–28%.

Advertised coating thicknesses range from 0.00028–0.0079 in. (0.07–0.2 mm) to 0.005 in. (0.127 mm). The coating improves the chemical resistance of steel surfaces. However, in extremely harsh environments, an electroless nickel sublayer is considered, as the codeposition is slightly porous. These coatings can be chemically stripped.

**Metallic Platings**

These are the original coatings for mold surfaces. Chrome and electroless nickel are still widely used in molds today. The primary benefits of these coatings are increased hardness and chemical resistance. Chrome platings generally contain microcracks. Because of this, it is common to back up a hard chrome plating with an electroless nickel plating for extremely harsh environments.

Chrome platings are also used to rebuild and repair worn or corroded molds, since they are applied at thicknesses up to 0.040 in. (1.0 mm). Electroless nickel has become popular because it is applied at much closer tolerances than electroplated nickel.

Other coatings provide improved chromium plating methods. For example, the electrolyzing process uses a thin, ultrapure chromium surface. This is applied without the characteristic microcracking of hard chrome, which improves the chemical resistance. The Armaloy™ process is a thin, dense chromium alloy applied with a nodular surface. This surface results in reduced surface contact with the part on ejection, thus providing better release and improved mold wear. A satin-like matte finish precludes its use on polished surfaces.

**Surface-hardening Treatments**

Surface-hardening treatments are used on molds that run glass-filled and reinforced resins. Without treatment, the mold wears rapidly due to the abrasive nature of these fillers. Other advantages of these methods include fatigue resistance, better lubricity, and chemical resistance.

In Melonite™ salt bath nitriding, nitrogen-bearing salts react with the substrate, forming nitrides. This is a thermochemical diffusion process: the mold is dipped into a liquid solution at high temperatures (1075˚ F [580˚ C]). A black shiny surface results. The hardness of the surface is 55–70 R, depending on the treatment parameters.

A very thin compound layer (0.0004–0.0080 in. [0.010–0.20 mm]) resists over a 0.002–0.025 in. (0.05–0.64 mm) diffusion layer. The diffusion zone thickness depends on the treatment time and the type of mold steel.

The ion-nitriding process is a plasma glow process. Ionized nitrogen electrons form nitride compounds (optional) and diffusion zones in the substrate. Hardness values of 60–64 R, are typical, and values to 70 R, are possible. The case-hardening depth can be varied in this environmentally friendly process.
A Guide to Tool Surface Enhancements and Coatings Commonly Used in the Plastics Industry

<table>
<thead>
<tr>
<th>Coating</th>
<th>Application Process</th>
<th>Application Temperature</th>
<th>Substrates</th>
<th>Appearance</th>
<th>Hardness</th>
<th>Thickness</th>
<th>Coefficient of Friction</th>
</tr>
</thead>
</table>

| Supplier: Contact the American Electroplaters and Surface Finishers Society or The National Association of Metal Finishers. |

**TABLE 18-5**
Thin-Film, High-Metallic Platings

PTFE Infused Into Nickel/Phosphorous/PTFE Hardness Coatings

Treatments with Microseal. molding by-products. process. improves corrosion resistance.

To 750°F (400°C) oxidation and acidic action of No heat involved in stripping Provides good lubricity and

2,200°F (1,200°C) Resistant to attack by most Strippable without damage to the base material or finish. Can apply to micro finishes. Hardness increases tool life and eases cleaning. Provides good lubricity and improves corrosion resistance.

Molds must be clean and free from other coatings.

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>Corrosion Resistance</th>
<th>Removal Process</th>
<th>Advertised Advantages</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>-350 to 1,000°F (-210 to 540°C)</td>
<td>Minor delay of corrosion only. Fine abrasive powder polishing.</td>
<td>Faster cycle times, fewer rejects, aids release, reduces mold wear. Compatible with releasing agents. More consistent performance.</td>
<td>Can be removed only by heavy abrasion or shearing of the substrate.</td>
<td></td>
</tr>
<tr>
<td>-460 to 1,200°F (-275 to 650°C)</td>
<td>Minor delay of corrosion only. Impermeable to most solvents and refined fuels. Attacked by some acids and alkalines. Polish out with diamond paste. Can be removed with high caustic solution, but not recommended.</td>
<td>Will not flake, chip, or peel off. Becomes part of the substrate. One year total continuous operation. Compatible with most lubricants.</td>
<td>Once applied, cannot be removed without removing part of the substrate. Used on wear plates, gibbs.</td>
<td></td>
</tr>
<tr>
<td>-65 to 500°F (-55 to 260°C) continuous use.</td>
<td>Salt spray resistance &gt;300 hr (ASTM-B-117). Absence of corrosion claimed. Can be chemically stripped without damaging parent material. Reduces cycle time and reject rate, corrosion or resistance make it popular for release sprays. Prolongs tool life and increases hardness.</td>
<td>If two treated surfaces are in contact, mismatch surface hardness by 10 R c, or more. Can mask off areas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500–550°F (200– 300°C) continuous use temperature.</td>
<td>Better chemical resistance than plain hard chrome. Partially dependent upon substrate. Chemically stripped, unless application of chrome, it is stripped electrolytically. Permanently locks PTFE into chrome. Gains sliding characteristics of PTFE and hardness, conductivity, and wear of chrome. Good release properties.</td>
<td>The surface may take on a white appearance after use (caused by light etching), but coating still maintains lubricity.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-250 to 550°F (-155 to 290°C)</td>
<td>Salt spray resistance 500 hr (ASTM-B-117). Resists etching from PVC by-products. Can be stripped off chemically without damage to the substrate. Can be recarburized repeatedly if necessary. Precise control of thickness for close tolerance parts, even in deep cavities. Resists wetting by most liquids. Low friction.</td>
<td>Can produce different surface enhancements, depending on applying to polished or glass beaded surfaces.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 500°F (260°C)</td>
<td>Salt spray resistance &gt;2,000 hr (ASTM-B-117) using 6061 alloy with smooth finish. 0.022 in. coating. Chemical stripping process removes the coating plus the substrate material to the penetration thickness. Allows substitution of aluminum for steel in many situations. Uniform thickness in all areas. Improved flow and release characteristics.</td>
<td>Does not adhere well to welded surfaces. Usually doubles the RMS value of finished surfaces.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Up to 750°F (400°C)</td>
<td>Salt spray resistance 500–1,000 hr (ASTM-B-117). Highly resistant to alkaline and process acid media. Proprietary chemical stripping process. Varies according to substrate. Extreme uniformity of thickness. Can coat complex parts with thinner coatings for release. Use thicker coatings for corrosion resistance.</td>
<td>Cannot maintain a #1 diamond surface polish.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500°F (260°C) maximum.</td>
<td>Salt spray resistance 500–1,000 hr (ASTM-B-117). Highly resistant to alkaline and process acid media. Proprietary chemical stripping process. Varies according to substrate. Extreme uniformity of thickness. Can coat complex parts with thinner coatings for release. Use thicker coatings for corrosion resistance.</td>
<td>Surface contaminates and imperfections must be removed before plating.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>550°F (285°C) maximum use temperature.</td>
<td>Good chemical resistance, but due to porous nature of Nye-tef an underlying coat of electrotocchrome is usually applied. Alkaline or nitric acid stripping baths are used. The method depends upon the substrate material. PTFE particles are dispersed in the range of 23–25% and remain throughout the life of the coating. Chemical bonding ensures strong adhesion to the substrate.</td>
<td>Does not adhere well to welded surfaces. Usually doubles the RMS value of finished surfaces.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Begins softening at 400°F (200°C).</td>
<td>Good corrosion resistance, but all Cr deposits have microcracks. A sublayer of electrotocchrome is suggested to prevent corrosion. Caustic solution with electrical current, or hydrochloric acid.</td>
<td>Can salvage worn or mismatched parts by restoring dimensions. Good adhesion. Hard, slippery surface.</td>
<td>Stresses develop in the Cr during deposition, causing microcracks which can spread to the substrate if not applied carefully.</td>
<td></td>
</tr>
<tr>
<td>Up to 1,600°F (870°C)</td>
<td>High-purity chromium is applied without microcracking, providing improved chemical resistance vs. regular hard chrome. Chemically stripped in a reverse alkaline chemical bath. Bonds absolutely to substrate. Increases wear resistance, reduces friction, aids release, can be used to repair mold surfaces.</td>
<td>Involves cleaning and removal of the base metal’s surface.</td>
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<td></td>
</tr>
<tr>
<td>570°F (300°C) maximum continuous use for most tool steels.</td>
<td>Improves environmental corrosion resistance. Outperforms hard chrome and electrotocchrome nickel (ASTM B-117). Can be stripped chemically in acidic bath or mechanically, but must remove substrate to depth of diffusion zone. Excellent sliding and running properties. Extremely resistant to wear—better than hard chrome. Improves fatigue properties by 20–100%.</td>
<td>Thickness of compound and diffusion zone depends on treatment time and the carbon and alloy content of the substrate.</td>
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<td></td>
</tr>
<tr>
<td>≥1,000°F (540°C)</td>
<td>Depends on the substrate and application. Improves corrosion resistance, reduces oxidation and rusting of molds. Grinding, machining, or burning. Low cost. Uniform case depth, regardless of geometry. Used to improve fatigue resistance, wear, and lubricity.</td>
<td>Can vary case hardness and depth to suit needs. Masking available. No cyanides used in process. Can be plated over ion nitriding.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥1,000°F (540°C)</td>
<td>Not soluble in most acids and alkalines. Coating can be removed by grinding, polishing or EDM, or chemically stripped. Repaired molds can be recoated. Reduces friction. Uniform thickness of thin coating will not affect dimensional tolerances. Good for glass-reinforced resins.</td>
<td>Burned surfaces will not coat. “White” EDM layer must be removed before coating.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,200°F (1,200°C) oxidation. Limit to 750°F (400°C) with Microseal.</td>
<td>Resistant to attack by most chemicals. Protects mold from oxidation and acidic action of molding by-products. Strippable without damage to the base material or finish. No heat involved in stripping process. Can apply to micro finishes. Hardness increases tool life and eases cleaning. Provides good lubricity and improves corrosion resistance.</td>
<td>Molds must be clean and free from other coatings.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 18

TOOL SURFACE ENHANCEMENTS

Thin-film High-hardness Coatings

Thin-film coatings, 0.00008–0.0002 in. (0.002–0.005 mm) with an extremely high hardness (above 80 Rc), are commonly applied to molds that run glass-reinforced resins. Two such coatings are titanium nitride and boron carbide.

Titanium nitriding is frequently used when hardness is required on mold surfaces. The thin nature of the coating 0.00008–0.0002 in. (0.002–0.005 mm) allows its application to polished surfaces without affecting critical part dimensions. This coating is characterized by its gold-yellow appearance and 85 Rc hardness.

The diamond black boron carbide alloy is a dark gray, thin coating (0.00008 in. [0.002 mm]) applied by magnetic sputtering. This coating is extremely hard (93 Rc) and resists attack by most chemicals. It can be combined with tungsten disulfide for improved lubricity.

CLEANING, PRESERVATION, AND STORAGE OF METAL MOLDS AND MOLD PARTS

The primary objective of this section is to present a safe and proven method that exceeds the present state of the art for cleaning, degreasing, and descaling ferrous and nonferrous molds and mold parts. This cleaning process is accomplished by using food acids, which are noncorrosive, nontoxic, biodegradable, and do not generate hazardous waste.

To enhance and complement the primary objective, additional information relative to metal molds and mold parts is included in this section. The subjects include:

- Corrosion.
- Basic chemistry.
- How to identify toxic and hazardous materials.
- Government standards for waste discharged into sewers.
- Methods for cleaning steel mold parts.
- Treatment/disposal of spent acid and neutralizing solutions.

CORROSION

Billions of dollars are lost due to corrosion, which is the deterioration of a metal or a process whereby the metal returns to its original state. Corrosion covers all phases of deterioration; however, rust is limited to iron and its alloys.

MECHANICS OF CORROSION

For corrosion to occur, three items are required.

- A difference in electromotive force (EMF). This electrical potential is different for each metal. It is the ability of the metal to exert a flow of electrons when the metal is put into a wet cell configuration.
- A conductor: either wire or different metals are touching each other.
- An electrolyte, a substance whose aqueous solutions conduct electricity.

When two metals of different EMFs are coupled by contact with each other or by a wire that conducts electricity, and this configuration is placed in an electrolyte, current begins to flow. The metal with the lower EMF conducts the electrons from the electrolyte through the conductor to the metal with the higher EMF. The metal with the higher EMF supplies the protons that neutralize the electrons in the electrolyte to give off hydrogen gas. In the process, the metal with the higher EMF begins to decompose (corrode) because it has changed from a balanced to an unbalanced metal (that is, it has lost its protons or positive ions).

Preventing Corrosion

To prevent corrosion, the EMF difference, conductor, or electrolyte is removed. Two metals with different EMFs may also be insulated to prevent corrosion.

All molds and mold parts must be kept as clean as possible to prevent corrosion and costly losses. On plated parts, sufficient plating thickness prevents pitting corrosion. Plating thickness is
checked by using a salt fog cabinet or by testing a metallography specimen.

### Storage Considerations

Metal molds are protected against corrosion by:

- Storing in an area with less than 40% relative humidity.
- Dipping in a 2% solution of water and white 85% phosphoric acid, and air drying.
- Wrapping in a moisture-proof barrier material when the humidity is greater than 40%.
- Wrapping in a moisture-proof barrier material to which silica gel or another type of desiccant is added.

### BASIC CHEMISTRY

There are several basic laws of chemistry that assist in the processes of cleaning, degreasing, and descaling mold parts.

#### Temperature

The reaction rate doubles for every 10° F (5.5° C) increase in temperature to about 120° F (49° C).

The higher the concentrations, the faster the reaction rate.

#### Compounds in Chemistry

A compound may be acidic, alkaline (basic), or neutral. An acid is any compound that contains the hydrogen ion H. An alkali is a compound that contains the hydroxyl group OH. When the hydrogen and hydroxyl groups are mixed in the proper ratio, the resulting compound is neutral. This is illustrated by using water as an example. Water is composed of H2O or HOH. The H portion is acidic, and the OH is alkaline; when mixed, they produce water.

Scale in or on mold parts cannot be removed with a neutral solution such as a chlorinated solvent. An acid-based solution not only removes scale, it also removes corrosion from mold parts.

### What is pH?

A solution’s acid or alkali content is defined by pH. It is a measure of the hydrogen (H) ion, which is the acidic component. The pH scale includes the numbers 1 through 14. Any pH reading from 1 to 6.9 is acidic. The lower the pH, the stronger the acid. Any reading from 7.1 through 14 is alkaline or basic. The higher the number, the stronger the alkali. A value of 7 is considered neutral.

#### Zinc

Any metals containing zinc are attacked by any type of acid, regardless of how weak the acid is. This may also apply to high-zinc solders.

### Causes of Hardness in the Water Supply

Hardness is caused by calcium and magnesium only. A facility’s location determines the water’s hardness (resistance to foaming action). Water can be “softened” by exchanging the calcium or magnesium for another metal that does not cause hardness. This is accomplished by using a water softener, which replaces the calcium or magnesium with sodium or a resin softener. These softening systems are inexpensive and in the long run prolong mold life.

### Defining Biodegradability

A biodegradable item is one that living organisms can break down. Biodegradability applies only to organic items (those made from living organisms) and not to inorganic items such as metals and chemicals.

## HOW TO IDENTIFY TOXIC AND HAZARDOUS MATERIALS

Cleaning of molds may result in the use and disposal of toxic and hazardous chemicals. The Environmental Protection Agency (EPA) issues a document listing extremely hazardous substances and toxic chemicals. This document lists all chemicals by the chemical abstract service (CAS) registry number so that dangerous chemicals are readily identified. There is also information on identifying hazardous waste. This document is a must for every manufacturing facility. To obtain a copy at no charge write to Section 313 Document Distribution Center, P.O. Box 12505, Cincinnati, OH 45212 and specify document no. EPA 560/4-92-001. This information is also available by calling toll-free 1-800-535-0202.

### GOVERNMENT STANDARDS FOR WASTE DISCHARGED INTO SEWERS

Waste from cleaning processes must be disposed of responsibly. The federal guidelines as established in Title 40, Code of Federal Regulations, Part 136, or as approved by the regional administrator, U.S. Environmental Protection Agency (EPA), are normally used by cities and states. However, to preclude using erroneous data, the appropriate sanitary sewer regulations should be requested from the local wastewater department. The unit of waste measurement is milligrams per liter (mg/L). One mg/L equates to one part per million (ppm). There are 3.84 liters per gallon. A calculation example is the amount of copper permitted per liter of wastewater (10 mg/L). Using 3.84 L/gal times 10 mg/L equates to a total of 38.4 mg of copper per gallon allowable for discharge into the sewer. Some important limits for sewer discharges are:

- No liquid or vapor having a temperature higher than 150° F (66° C) is permitted.
- No water or waste that contains more than 100 ppm by weight of fat, oil, or grease is permitted.
- No gasoline, benzene, naphtha, fuel, or other flammable or explosive liquid, solid, or gas is permitted.
- No water or waste having a pH lower than 5 or higher than 9.5, or having a corrosive property capable of damaging structures, equipment, and sewage-works personnel is permitted.
- Dissolved sulfides: up to 0.5 ppm.
- Cyanide (amenable to chlorination): up to 0.2 ppm.
- Total cyanide: up to 2.0 ppm.
- Heavy metals (ppm limits):
  - Arsenic 0.1
  - Barium 10.0
  - Boron 10.0
  - Cadmium 0.1
  - Chromium VI 0.5
  - Copper 10.0
  - Lead 0.5
  - Manganese 0.5
  - Mercury 0.05
  - Selenium 0.1
  - Silver 0.5
  - Zinc 50.0

Manufacturing facilities containing any of the foregoing heavy metals should have a complete analysis of wastewater performed by an approved EPA laboratory. This report should be kept on file in case it is requested by the EPA or wastewater board in the area where the plant is located.
Cleaning, Preservation, and Storage of Metal Molds and Mold Parts

METHODS FOR CLEANING STEEL MOLD PARTS

For many years, the most common cleaning solvent was methylene chloride. Its drawbacks were tolerated because it dissolved plastic and, when used with various metal polishes, aided in cleaning mold components.

The following information indicates possible side effects of overexposure to methylene chloride as taken from its material safety data sheet:

- Eyes: can cause irritation.
- Skin: can cause irritation.
- Breathing: excessive vapor inhalation can cause nasal and respiratory irritation, dizziness, weakness, fatigue, nausea, headache, possible unconsciousness, and asphyxiation.
- Swallowing: can cause gastrointestinal irritation, nausea, vomiting, and diarrhea.

Protection is provided by wearing solvent-resistant gloves, splash goggles, impervious clothing, and boots.

However, with the ever-tightening regulations placed on industrial chemicals by OSHA and the EPA, along with the cost of purchasing methylene chloride and then paying for its disposal, finding a better way to clean steel parts is mandatory.

Another method consists of a formulation of food acids and a surfactant package (hereafter referred to as mold cleaner). This cleaner is environmentally benign, is easy and safe to use, is easily and inexpensively disposed of, and has proven itself in replacing methylene chloride. Its drawbacks were tolerated because it dissolved plastic and, when used with various metal polishes, aided in cleaning mold components.

The following cleaning procedure is recommended for stainless steel and nonferrous metals:

1. Place part in Tank No. 1, the cleaning solution. Allow the part to soak for 10–15 seconds to neutralize the acid on the part. Remove part from the tank and shake off excess solution.
2. Place part in Tank No. 2, the sonic tank. Allow sonics to agitate about one minute, and then, if piece is not clean, scrub part to remove the remaining contaminant. Time is a major consideration when cleaning ferrous parts, because pieces that are exposed for more than 4–5 minutes may discolor and can readily oxidize after cleaning. After cleaning, remove part from the tank and shake off excess solution.
3. Place part in Tank No. 3, the neutralizing solution. Allow part to soak for 10–15 seconds to neutralize the acid on the part. Remove part from the tank and shake off excess solution.
4. Place part in Tank No. 4, the clear water rinse. Allow part to soak for 30 seconds to absorb the heat from solution to aid in drying.
5. Remove part from Tank No. 4 and immediately wipe or air dry. The hair line must feature an oil/water filter.

Ferrous Steels

Cleaning procedure recommended for ferrous steels are:

1. Place part in Tank No. 1, the cleaning solution. Allow the sonics to agitate about one minute, and then, if piece is not clean, scrub part to remove the remaining contaminant. Time is a major consideration when cleaning ferrous parts, because pieces that are exposed for more than 4–5 minutes may discolor and can readily oxidize after cleaning. After cleaning, remove part from the tank and shake off excess solution.
2. Place part in Tank No. 3, the neutralizing solution. Allow part to soak for 10–15 seconds to neutralize the acid on the part. Remove part from the tank and shake off excess solution.
3. Place part in Tank No. 4, the clear water rinse. Allow part to soak for 30 seconds to absorb the heat from solution to aid in drying.
4. Remove part from Tank No. 4 and immediately wipe or air dry. The hair line must feature an oil/water filter.

Stainless Steel and Nonferrous Metals

The following cleaning procedure is recommended for stainless steel and nonferrous metals:

1. Place part in Tank No. 2, the sonic tank. Allow the sonic action to clean part, or to speed the process, scrub with brushes. Remove part from tank when clean and shake off any excess solution.
2. Place part in Tank No. 3, the neutralizing rinse. Allow part to soak for 10–15 seconds. Remove part and shake off any excess solution.
3. Place part in Tank No. 4, the clear water rinse. Allow part to soak for 30 sec, permitting it to absorb heat from the water to aid drying.

Mixing Instructions for Mold Cleaner Solution

A satisfactory solution concentration for mold cleaner is one part of concentrated mold cleaner to three parts of tap water. Although this concentration has proven effective in general use, stronger or weaker solutions are obtained by varying the mix of concentrated mold cleaner and water as necessary.

Cleaning Small Mold Parts

The recommended cleaning station for small parts consists of the following:

- Tank No. 1: Heated/sonic tank with 1 gal (3.8 L) plastic insert, mold cleaning solution mixed 1:3, temperature set at 110–120˚ F (43–49˚ C). Use for ferrous materials, CRS, H13, A6, and S7.
- Tank No. 2: Heated/sonic tank with 1 gal (3.8 L) plastic insert, mold cleaning solution mixed 1:3, temperature set at 110–120˚ F (43–49˚ C). Use for stainless steels and nonferrous materials.
- Tank No. 3: Heated/static tank with perforated plastic insert. Tank contains 5 gal (19 L) of neutralizing solution (tap water/1 tbsp. baking soda—pH = 7.6–8.0) heated to 120–130˚ F (49–54˚ C).
- Tank No. 4: Heated/static tank with perforated plastic insert. Tank contains 5 gal (19 L) of clear tap water final rinse—pH = 7.6–8.0 heated to 120–130˚ F (49–54˚ C). The higher temperature facilitates part drying.

Permanent filter system includes tank No. 2, the sonic tank. A 1-gal (3.8-L) plastic insert is placed in the sonic tank to aid drying.

The following station is recommended for cleaning small mold parts

Tools and Equipment

- Unit A: Sonic generator unit for sonic Tank No. 1.
- Unit B: Sonic generator unit for sonic Tank No. 2.
- Perforated plastic inserts are placed in the four tanks to preclude setting up an electrolytic cell (see “Corrosion” section).

Table 18-6 lists daily average effluent limitations and their effective dates.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Effective through December 31, 1993</th>
<th>Effective on January 1, 1994</th>
<th>Effective on January 1, 1995</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>0.1 mg/L 100 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boron</td>
<td>10.0 mg/L 5600 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.1 mg/L 47 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium VI</td>
<td>0.5 mg/L No limit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>No limit 1400 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>10.0 mg/L 1700 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyanide</td>
<td>2.0 mg/L 2000 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>0.5 mg/L 500 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>0.05 mg/L 50 µg/L 4.6 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>No limit 5000 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil &amp; grease (TPH)</td>
<td>100.0 mg/L 100.0 mg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selenium</td>
<td>0.1 mg/L 100 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>0.5 mg/L 500 µg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfides</td>
<td>No limit 10.0 mg/L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>50.0 mg/L 5400 µg/L</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Unit A: Sonic generator unit for sonic Tank No. 1.
- Unit B: Sonic generator unit for sonic Tank No. 2.

Perforated plastic inserts are placed in the four tanks to preclude setting up an electrolytic cell (see “Corrosion” section).
4. Remove part from Tank No. 4 and immediately wipe or air-blow dry. The air line must feature an oil/water filter.

See Fig. 18-5, which shows a small mold part cleaning system configuration.

To clean the mold's water circuit (with the mold in the press or in the toolroom), to clean mold plates, or to test the water system for pressure, a mold water system tester/cleaner cart is required. The test cart (Fig. 18-6) consists of two separate and complete water rinse systems capable of maintaining 200 psi (1.4 MPa). Each has its own pump, 8-gal (30 L) fluid reservoir, and associated supply and return lines, as well as pressure gages on the supply and return lines, valves to regulate return line pressures, and particulate filters on the return lines. This cart is used for several purposes:

- Pressure testing a mold's water circuits after the mold is serviced in the toolroom.
- Chemically cleaning a mold's water circuits with the rust-attacking mold cleaner and subsequent rinsing of the system in or out of the press.
- In conjunction with the mold plate wash station. Here, large mold plates are cleaned of rust and gas while they are serviced in the toolroom.

Cleaning a Mold's Water Circuit

The water circuit of a mold is cleaned as follows:

1. Attach the mold cleaner supply line from the tester to the in port of the mold water circuit, and the mold cleaner return line of the tester to the out port of the mold.

2. Engage the mold cleaner pump, and allow the cleaner to flow unrestricted through the mold for 15–30 minutes. Note the pressure reading on the supply line gage at the start of the cleaning process, and monitor that pressure while the solution is flowing. As the mold gets progressively cleaner, the input pressure should drop. This helps determine how long to flush the mold. The supply and return lines can be reversed during this process to aid in dislodging material in the system.

3. After cleaning the mold, remove the supply line from the test cart and blow through the line and mold with compressed air to purge the water system of the mold cleaner.

4. Connect the supply and return lines to the supply and return ports on the test cart. Rinse the system with water and repeat the procedure, allowing flow for 3–5 minutes.

5. After rinsing, repeat Procedure No. 3; then reconnect the cooling lines and run the mold.

For washing large mold plates or other large parts, a ladder-frame cradle is required. See Fig. 18-7 for a typical plate-cleaning configuration.

Washing Mold Plates

Mold plates are washed using the following procedure:

1. Place mold plate in the wash station’s ladder-frame cradle, either by hand or with an overhead crane.

2. Connect special adapter for plate washing to the supply and return fixtures on the cart’s mold cleaner system.
3. Open the side door on the test cart, and withdraw the return line attached to the mold cleaner pump. Attach the return line to the drain fixture on the bottom of the plate wash station with the ball valve in the closed position.

4. Attach the wash hose and brush assembly to the plate wash adapter. With the ball valve initially in the closed position, turn on the mold cleaner pump. Fully open the ball valve on the wash hose and begin washing the plate. The return line ball valve can either be adjusted to just keep up with the supply line or periodically opened fully to drain the wash station. Scrubbing the plate with brushes, abrasive pads, or other abrasives make the cleaning process go faster.

5. After cleaning the mold plate, turn off the supply hose ball valve, and using the ball valve on the return line (with the pump still running), drain as much mold cleaner from the wash station as possible. Close the ball valve and turn off the pump motor. Then, using compressed air, blow the mold plate dry. With a spray bottle or other applicator, spray the mold plate with a neutralizing solution of water and a small amount of baking soda, and blow the plate dry again.

6. Remove the plate from the wash station. With the ball valve still in the closed position, remove the return line from the wash station and return the hose to the bottom of the wash cart. Remove the wash hose from the plate wash adapter, after opening the ball valve (pump off) and holding up the hose to drain into the adapter. Remove the hose, and return it to the cart’s storage area. Connect an air hose to the plate wash adapter, and with the ball valve still in the open position, clear the adapter with several short air blasts. Remove the air hose and adapter, and return the adapter to its storage area in the cart.

**Water System Pressure Test**

Although the mold cleaner and rinse systems are equally equipped to water test molds, testing is done with the rinse side, to avoid having the mold cleaner seep into the mold where it can cause accelerated oxidation of mold components.

To test a mold’s water system, connect the rinse supply and return ports of the test cart to the mold’s in and out ports, respectively. Turn on the rinse-side motor, and open the rinse system’s return line valve to obtain the desired back pressure. The gage on the rinse system’s supply line reads higher than the return gage due to flow restrictions in the hoses and mold. Read the return-side gage to obtain the true pressure in the mold.

After testing, remove the supply line from the cart, and blow out the hoses and mold with compressed air after fully opening the return line valve.

**TREATMENT AND DISPOSAL OF SPENT ACID AND NEUTRALIZING SOLUTIONS**

**Acid Solutions**

The mold cleaner and neutralizing solutions used in this cleaning system are nontoxic and can be disposed of through the local sewer system after the pH value of each solution is adjusted to an acceptable range. The EPA requires pH readings of between 5 and 9.5 for disposal in a city sewer. A more acceptable pH range is 6–8.

The mold cleaning solution is neutralized by using common baking soda and the following procedure:

1. Calibrate the pH meter prior to any testing.
2. Mix the contaminated mold cleaning solution from one of the part-cleaning containers (usually 1 gal [3.8 L] or less)
with enough tap water to obtain 4–5 gal (15–19 L) of a diluted solution.

3. Test this new solution to obtain a starting pH value.

4. Use this pH value to determine the amount of baking soda needed to neutralize the solution to the pH level required for disposal.

5. Mix the baking soda very slowly with the mold cleaning solution, stirring constantly, because the neutralizing reaction between the mold cleaner and soda is violent. Safety glasses are required for this operation.

6. After adding the required baking soda, allow the solution to stabilize for about 5 minutes to ensure a total reaction, and then retest with the pH meter to ascertain the final pH level.

Figure 18-8 shows a neutralization table that is used to determine the amount of alkali needed to obtain the proper pH prior to disposing of spent acid solution.

Alkali (Base) Solutions

The following procedure is used to treat alkaline solutions:

1. If the solution needing disposal is too alkaline (pH reading exceeding 9.5), it is brought to disposable ranges by adding very small amounts of mold cleaning solution or even smaller amounts of mold cleaner concentrate.

2. For any solution that is disposed of in a city sewer system, a complete, accurate record of each dumping occasion is required.

Fig. 18-8 Mold cleaning solution neutralization graph.

References


17. Polyurethane Fibers, Chemistry and Technology, 14 (2), 125 (1986).


28. Safe-Tee Chemical Products Co., Phoenix, AZ.
29. Texas Plastic Technologies, Georgetown, TX.
Plastics manufacturers are becoming more competitive. They are fostering team work and flatter organizations, and are increasing employee involvement. Becoming more competitive requires focusing energies and empowering employees, members, associates, business partners, and suppliers toward value-added activities. Communication and setting goals and strategies are the roles of modern management.

Revolutions in manufacturing have occurred over the past hundred years due to competitive forces and the changing needs of the marketplace. Craftsmen, the earliest form of manufacturers, made custom, one-of-a-kind products. Assembly lines were introduced to manufacturing in the early 1900s to increase production efficiency. A good example of mass production was the early Ford assembly line. Each individual was responsible for a specific task in building the Model T (note: no plastic parts were used.) In the mid-1900s, computerized machines were introduced to automate tasks. Mass production with automation provided greater efficiency and more consistent quality under conditions of limited change. But change did come, and it continues to do so at an ever-increasing rate.

There are competitive forces that cause change in the marketplace and impact the profitability of the plastics manufacturer. A plastics company must particularly understand and position itself against six external forces:

1. Existing competition. In the plastics industry, price, quality, delivery, reliability, product design capability, and flexibility are the primary influencing factors. How well an organization measures up to the customer’s expectation is critical.

2. New entrants or competition. With new acquisitions creating greater buying power and economies of scale, plastics processors must find strategies that differentiate them from their competition. Close ties with the customer is the strategy that works best, whether that customer is a large producer or a consumer. If the customer is a manufacturer, a company must create a strong bond through product design and engineering capabilities. If one is a consumer, a strategy of high quality and competitive price tied to brand loyalty is required.

3. The threat of substitute products. Plastics resin can take on many shapes and physical properties. Plastics are often a substitute for steel and wood products. As the technology to make new materials and new resins continues to change, a processor's ability to understand this change and process the new materials determines his or her success when substitute products are invented.

4. The supplier's ability to negotiate prices. Being too dependent on too few suppliers puts a company at risk; this in turn may price it out of the market.

5. The customer's willingness to buy. Customer expectations and choices are increasing. The purchasing power of the customer is a strong force. A manufacturer must answer the questions “Who is the customer?” and “How are the demands of the customer changing?”

6. The impact of government regulation. The best-laid plans for a new plastic processing facility, for example, can be delayed if government regulations disallow the use of planned materials. Remaining aware of environmental impacts and showing concern for the community help an organization deal with these uncertainties.

Successful organizations understand the competitive forces that affect their company. They address the tough questions about their customers, and they communicate effectively throughout their organization. This is done by defining a mission and setting goals and strategies for the enterprise. Four goals and strategies are linked with the key business processes that make up the company:

- New products, process designs, and introduction processes.
- Order acquisition and fulfillment processes.
- Forecast and demand management processes.
- Material acquisition and conversion processes.

How effectively these processes are executed depends on the skills and the knowledge of the people empowered to execute them. Understanding the competitive forces, setting goal-defining strategies, and executing key business processes are essential to remaining profitable.

MODERN MANAGEMENT AND ISO 9000

The fundamental elements of executing key business processes have been known for some time. However, these principles, taught by business schools, are often not implemented properly. To ensure quality and to build trust between companies on an international basis, the International Organization for Standardization (ISO) created ISO 9000, a series of quality management and quality assurance standards. These standards define 20 elements that are needed to successfully run a business.

The Contributors of this chapter are: Paul Benyovszky, Advisory Engineer, Thomas & Betts Corporation; Robert Fariss, CEO, Hunkar Systems, Inc.; Brian Holmes, Vice President of Operations, Columbia Plastics Ltd.; Chuck Morris, Consultant, Morris Consulting and Training; Dean Stamatis, President, Contemporary Consultants.

The Reviewer of this chapter is: Chuck Morris, Consultant, Morris Consulting and Training.
ISO 9000 is a series of quality management and quality assurance standards written in a common language for a global audience. This is one of the many standards created by the ISO. The ISO number on cameras and film is an example of a long-standing international standard.

The ISO group, comprised of national standards bodies of 91 countries, promotes standardization on a global basis to improve the exchange of goods and services. Compliance requires systems for quality management procedures such as contract review, design control, document control, purchasing, inspection and testing, and handling of nonconforming products.

The ISO 9000 series of specifications covers 20 elements. A brief overview is presented in the following sections.

**MANAGEMENT RESPONSIBILITY AND THE COST OF QUALITY**

Management is responsible for the quality policy. A periodic review of the quality policy and procedures creates an environment for continuous improvement. To become certified, an independent organization must verify compliance with documented procedures.

Quality is a set of attributes that enable a product or service to conform to customer expectations. As long as the specifications are met, the customer is satisfied. When the specifications are not met, not only is the customer unsatisfied, but this dissatisfaction can be measured.

The cost of quality is that cost incurred because of poor quality, however it is defined. Two broad categories of quality costs, prevention and appraisal, are incurred because of poor quality.

Prevention costs are those incurred to keep poor quality products from being produced. Examples include analysis and planning for quality, quality training, and development of process controls.

Appraisal costs result from activities undertaken to prevent poor-quality services from progressing beyond the point at which they become nonconforming, or from being delivered to customers. Examples include the inspection and testing of raw materials and products as well as services.

Products that do not conform to quality standards often cause an organization to incur failure costs. Depending on the point at which quality problems are identified, failure costs are classified as internal or external.

Internal failure costs are those associated with materials or services that fail to meet in-house quality standards and are identified before the product or service is delivered to the customer. Examples include scrap and rework. External failure costs are those incurred because poor-quality products have reached customers. Examples include the costs of handling complaints, product liability, warranty, and returns and allowances.

**QUALITY SYSTEM**

A quality system, which requires maintenance, includes a quality manual, plans, schedules, and a description of the controls used to achieve the desired quality levels. The standards of acceptability require clear definition and must cover all parts of the business.

**CONTRACT REVIEW**

Meeting customer expectations requires a clear understanding of the customer's needs. A contract is used to document the appropriate conditions, and the contract review process is documented. The contract documents commitments made with suppliers and customers. Records are maintained and reviewed to provide continuous improvement.

**DESIGN CONTROL**

Because the product delivery process begins with a quality design, this element of ISO 9000 is critical. Control procedures must cover design and development planning, personnel skills and design tools assignment, organizational structure to support communication and design verification, documented plans, requirements, and product specifications. Design outputs are documented and validated to confirm compliance to the design. As changes occur, design change management procedures are needed to manage and ensure quality.

**Quality Function Deployment**

Quality function deployment (QFD) is a process that provides structure to the product design and development cycle, with the primary focus on customer requirements.

QFD is always driven by the customer and is linked to technology innovations. As a result, it requires a great deal of effort in gathering information for the customer.

**Concurrent Engineering**

Concurrent engineering (CE) is a manufacturing practice in which a multidisciplinary team conducts product conceptualizing, design, and production planning simultaneously. Concurrent engineering is also referred to as simultaneous engineering.

Concurrent engineering’s multidisciplinary team may include specialists from product design, engineering, manufacturing engineering, marketing, purchasing, and finance. Principal suppliers of process equipment, purchased parts and materials, and services may also participate from the outset.

In the plastics industry, CE is revolutionizing the business. It is credited with cycle time reductions, process improvements, customer satisfaction, and positive employee morale.

**DOCUMENT CONTROL**

Procedures are needed to document all parts of the business. A list of data and documents that are controlled must be maintained. Current procedures, distributed to all appropriate personnel, cover changes, approval, accuracy, and current level of drawings and documents.

**PURCHASING AND SUPPLIER QUALITY MANAGEMENT**

A process is needed to ensure that purchased materials and components meet specifications. Increased customer demands and the proliferation of ISO 9000 standards have added quality demands to the plastics industry.

The purchasing organization bears a heavy responsibility in quality, since supplier items significantly impact overall product quality; the supplier also looks to the buyer for direction. Evaluating supplier quality may be difficult for the buyer, because he often depends on others for this task. Good quality management has a positive effect on productivity:

- As rejections decrease, procurement costs and production delays are similarly reduced.
- A correctly placed purchase order eliminates renegotiations, ambiguities, and rejections.
- Purchasing agents and buyers alike accept the responsibility for quality along with price and delivery.

A sound quality program within a supplier company benefits not only its customers, but also its own organization. The best quality program is achieved when a supplier recognizes the importance of quality and initiates its own program. Several benefits accompany a solid supplier quality program:
• Improved reputation among customers.
• Reduced costs due to less rework and scrap.
• Improved marketability of parts and products.
• Improved employee motivation and satisfaction.
• Increased sales and profits.

A good supplier quality management program includes many of the following items:

• Quality specifications and standards and the accompanying documentation.
• How to evaluate and select good subsuppliers.
• Establishment of good relationships with valued suppliers.
• Legal aspects of buying and selling, with quality as a key factor.
• Established evidence of performance, including statistical process control documentation.
• Incoming inspection and testing of purchased goods.
• A well-defined program that takes corrective action for poor supplier performance.

PURCHASER-SUPPLIED PRODUCT

Written procedures for verification and storage of customer-supplied subassemblies and components are required. Furthermore, an efficient communication path to the customer quickly resolves problems should they arise.

PRODUCT IDENTIFICATION AND TRACEABILITY

Written procedures specify how the product is identified. For certain critical products, such as those for the medical industry, the supplier must trace the end product from the batch or lot from which it was produced. A unique identifier system facilitates traceability.

PROCESS CONTROL

Documented and understood production and assembly processes are required. Clearly defined employee work instructions and workmanship standards promote process control. Conformance to these standards permits meeting not only workmanship but regulatory and environmental standards. Ongoing documentation is kept on equipment and personnel evaluations.

INSPECTION AND TESTING

Purchased materials are evaluated for compliance to specifications. Appropriate records identify defective material and its source. In-process inspection is performed in accordance with the quality plan, and reliable product recall practices are required. Final inspection and test records are maintained for all products. The quality plan depends on the customer, quality workmanship, and in some cases, government requirements.

INSPECTION, MEASURING, AND EQUIPMENT

Quality measurements depend on reliable tools and techniques. Procedures for maintaining and calibrating test equipment assure that it remains capable. Product tests must show clear definition in terms of the test equipment used and the testing limits imposed.

Gage Repeatability and Reproducibility

Gage repeatability and reproducibility (GR&R) studies analyze the variation of gage measurements (repeatability) and the variation in operator measurements (reproducibility). For the plastics industry, GR&R studies are especially important, since most automotive customers demand them.

Geometric dimensioning and tolerancing (GD&T) helps define the geometry or shape of a part on an engineering drawing. GD&T can vastly improve communications in the design-to-manufacture cycle. In the plastics industry, GD&T has implications for machining, fixturing, and inspecting.

The fundamentals of GD&T are:

• Geometric characteristics and their symbols.
• Related symbols and terms.
• The feature control frame and the datum feature symbol.
• Maximum material condition and regardless-of-feature-size descriptor.
• Distinctions between form, orientation, profile, runout, and location-type tolerances.
• Tolerance zones.

Inspection and Test Status

Product marking, relative to inspection and test results, may be accomplished by traceability systems such as bar codes. Inspection and test conformance verification are identified on the product; records further document these results.

Control of Nonconforming Product

Nonconforming product is properly identified, segregated, and dispositioned. The appropriate personnel are notified about the product. Procedures that cover the process of dealing with defective product must be available to employees. If required contractually, nonconforming product is reported to the purchaser.

CORRECTIVE ACTION

Tracking quality is important, but correcting nonconforming product problems leads to continuous improvement, lower costs, and satisfied customers. The nonconformance process must lead to a corrective action process. Written procedures for corrective action are needed, and the skills to follow these procedures must be acquired through training. Root-cause analysis of problems is part of the corrective action procedure. Proper corrective action includes changing the appropriate documents and processes, and ensuring that a follow-up is conducted; this verifies the success of the corrective action.

PACKAGING, STORAGE, HANDLING, AND DELIVERY

Product variety demands different handling methods. The correct methods depend on customer expectations, government regulations, and quality workmanship standards. Once defined, the procedures covering storage and handling are made available to operation personnel.

Product is handled carefully to prevent damage and contamination. It is then packaged for shipment and stored in secure areas. Periodic inspection for sources of corrosion, shock, or shelf-life loss promotes continuous improvement of procedures.

QUALITY RECORDS

A documented system for maintaining and managing quality records facilitates communication throughout an organization. The system ensures that records exist, that they can be filed and retrieved, and that they are legible and identifiable. The system covers design reviews, supplier performance, product identification and traceability, process qualifications, and nonconformance repair or rework.

INTERNAL QUALITY AUDITS

Internal quality audits, performed by an independent group such as a quality department, are essential. Even the quality department
should be periodically audited by a group such as operations or product design. An internal audit verifies procedural compliance, process evaluation, product performance, quality activities, and the quality systems. The audit system, documented by appropriate procedures, ensures that problems are addressed by the appropriate personnel and are corrected. The audits are performed on a given schedule.

SERVICING

Servicing is like a product in that the customer’s expectations are defined and described, usually in a contract. Procedures for performing the service are required, and a process is needed to verify that the services are performed to specifications.

STATISTICAL TECHNIQUES

Well documented procedures and techniques guide employees in effective data analysis. The specific requirements depend on the product and the customer’s needs.

Design of Experiments and Capability Studies

Design of experiments (DOE) often reveals hidden causes of process variation. DOE breaks up variations into components, often revealing primary causes.

By using DOE in the plastics industry, the effects of several variables are studied concurrently; interrelationships and interactions are also evaluated. DOE techniques are useful for deliberately disturbing causes that are usually in balance, for breaking apart the effects of hidden variables, and for studying the possible effects of variables during process design and development.

Process experiments range from informal changes introduced randomly to carefully planned, highly structured experiments. To study the effects of these changes, three evaluation methods are common today: the classical study, the Taguchi evaluation, and the Shainin method. Because each method has advantages and disadvantages, the appropriate method depends on (a) the application and (b) the understanding of the method and the process by the experimenter.

A capability study is an organized, systematic approach used to determine whether a manufacturing process can consistently make products within specification limits. The capability study analyzes random variability found in a process. Random variability is attributed to common causes that behave like a constant system of chances, forming a unique, describable distribution.

Capability studies allow predictions regarding the quality of process output. This, in turn, enables adjustment of the process, taking steps that minimize or eliminate defects. To begin a capability study, a critical dimension or variable is selected. Measured data for that dimension are then collected over a specified period of time. The capability study analyzes the understanding of the method and the process by the experimenter.

The measurement result takes the form of a C_p, C_m, or C_pk index. The C_p index is the ratio of the specification tolerance to six standard deviations (6). A C_p index of 1.33 is the minimum acceptable value; higher values indicate better process capability. C_m only measures the spread or dispersion of a distribution; it does not indicate whether a process is centered about a target value. Therefore, C_p is always used in combination with C_pk. The C_m index is the inverse of C_p.

The C_pk index is a measure of both dispersion and centeredness. C_pk is defined as the lesser value of Eqs. 1 and 2 as follows:

\[
C_{pk} = \min \left( \frac{\bar{x} - USL}{3 \sigma}, \frac{LSL - \bar{x}}{3 \sigma} \right)
\]

where:

- USL = Upper specification limit
- LSL = Lower specification limit
- \( \bar{x} \) = Overall average

A high C_pk index is desirable. An index greater than 1.0 indicates that the six-sigma data spread falls entirely within the specification limits. A C_pk value between 0 and 1.0 indicates that part of the six-sigma spread falls outside the limits. For the plastics industry, the C_pk index goal is currently 1.67 for automotive and 2.0 for electronics customers.

OTHER PROGRAMS

Baldrige Award. The Malcolm Baldrige National Quality Award was established by Congress in 1987 to promote quality awareness, recognize quality achievements of U.S. companies, and publicize successful quality strategies. The award is not given for specific products or services.

The Baldrige Award may be given annually in each of three categories: manufacturing, service, and small business. The criteria for the award are leadership, information and analysis, planning, human resource use, quality assurance of products and services, quality results, and customer satisfaction.

Deming method. The Deming method is a formal set of management principles, developed by Dr. W. Edwards Deming, that helps manufacturers achieve higher levels of efficiency, cost effectiveness, and quality of products and services.

At the heart of the Deming method are principles called “The Fourteen Points.” Established in 1950, they have been refined and expanded upon, but have not changed in substance.

Total Quality Management. Total quality management (TQM) is the implementation and management of quality improvement processes throughout a company. The concept, introduced in 1956 by A. Feigenbaum, is currently popular in both manufacturing and service organizations.

Kaizen. Kaizen means gradual, continuous improvement, mainly in small matters, in all aspects of working life. It begins by recognizing that any organization can have problems. Kaizen solves problems by establishing a culture in which everyone can freely admit to these problems.

Poka-yoke. Developed and refined by Shigeo Shingo, poka-yoke means to mistake-proof or make fail-safe. Its basis is to respect the intelligence of workers. By taking over repetitive tasks that depend on vigilance or memory, poka-yoke frees a worker’s mind to pursue more creative and value-adding tasks.

TRAINING

In any organization, employee skills become outdated; reinforcement or reinstatement of these skills is required. Specifically, management must allow the time, identify the task, and provide the talent (employees and instructors) for the appropriate training.
Figure 19-1 presents a dynamic model that provides the necessary training on an as-needed basis. The needed skills are identified by the facility supervisor, and the training is scheduled based on specific objectives. Following the training, an evaluation measures its effectiveness.

Table 19-1 shows a generic training program that is based on 12 recommendations. With each element, a specific focus and several alternatives for appropriate action are provided.

The foundation of the approach shown in Fig. 19-1 and Table 19-1, which relies on using a team effort to achieve desired goals, is based on the following elements:

- Keep the project group at a manageable size (6–8 members).
- Emphasize discussion and participation by all members.
- Work systematically toward achieving consensus.
- Make the team’s tasks and targets specific.
- Use outside resources when needed.
- Know your audience (those you wish to influence).
- Be persistent in making the change occur.

A generic quality system and total quality management schematic are shown in Figs. 19-2 and 19-3, respectively. TQM shifts the quality focus from postinspection to in-process assurance. The training process must emphasize this point.

### UNDERSTANDING PLASTICS

Training for plastics manufacturing begins with the user understanding the unique and beneficial properties of the materials. While it is not necessary to understand the specific organic chemistry involved, an understanding of the shape of the molecules and their bonding methods is helpful in comprehending the properties of the materials. Molecular properties also dictate the method by which a particular material is processed. The manner in which the molecules bond to each other determines whether the material is crystalline or amorphous. Degree of crystallinity has a direct bearing on the thermal, mechanical, chemical, and light-transmitting properties of the material. The degree of crystallinity also affects the processing of the material, because amorphous material has a broader softening temperature range and higher viscosity than crystalline material.

Employees should learn the differences between thermoset and thermoplastic materials. A discussion of plastic’s environmental impact is also beneficial. Some points covering plastics applications provide a vital part of fabricating and processing training.

Just as plastics applications are important, processing also plays a vital role. Processing methods are determined by part shape, part

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**Fig. 19-1 Training model.**
<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Focus</th>
<th>Action Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide employees with better product and process orientation.</td>
<td>A near universal desire exists for greater product and process information. This desire is especially strong on the part of operators and set-up specialists, skilled-trade personnel, and supervisors.</td>
<td>• Design and install an ongoing orientation process that builds upon the success of the initial orientation. • Maximize the use of graphics and visuals to communicate the production process and the final product. • Schedule preventive maintenance employees for tours of production areas.</td>
</tr>
<tr>
<td>Continue to improve management and union cooperation and collaboration.</td>
<td>Throughout the plastics industry, notable gains in management/union relations have been realized in recent years. However, “continuous improvement,” as applied to products and processes, must also apply to management/union relations.</td>
<td>• Explore areas of concern between management and the union, and encourage proposed alternatives. • Form joint leadership positions in task forces and committees.</td>
</tr>
<tr>
<td>Take more advantage of the expertise of the skilled-trade personnel and set-up specialists.</td>
<td>Skilled-trade personnel and set-up specialists have valuable practical knowledge and skills. Although these employees may not have been sufficiently consulted in the past, a strong need now exists to involve them early in machine design efforts.</td>
<td>• Ensure that new work processes are reviewed by the appropriate personnel. Use a systematic sign-off procedure. • Implement special skilled-trades training.</td>
</tr>
<tr>
<td>Initiate changes in the design and management of equipment advisory teams (EATs).</td>
<td>The equipment advisory teams’ sole purpose is to provide appropriate input of experienced operators, set-up personnel, supervisors, and skilled-trade personnel under the leadership of manufacturing process engineers for each work process. Early meetings are encouraged.</td>
<td>• Obtain top-level management and union support. • Assign responsibility for the effective functioning of the teams. • Develop guidelines for effective team functioning, and introduce performance criteria to assess the effectiveness. • Ensure that the training is relevant to the needs, is presented at an appropriate level, and is given at suitable times and locations. • Ensure systematic communication to potential trainees.</td>
</tr>
<tr>
<td>Create a role for manufacturing process engineers that includes design and purchase of equipment, EAT facilitation, contributions to training programs, and extended involvement in new work.</td>
<td>Manufacturing process engineers currently play a large role in equipment purchase and design. However, their involvement typically ends after the design/purchase phase. There is a need to extend their involvement into the work processes that they were instrumental in creating.</td>
<td>• Consider assigning employees to teams and training on a cross-functional basis. • Designate appropriate facilitators throughout the organization. • Involve all appropriate personnel in the decision-making process. • Establish closer communications links among designers, buyers, manufacturing engineers, operators, and floor supervisors. • Design an evaluation method that provides comprehensive and diagnostic information about the success of the training program. • Ensure that the training is relevant to the needs, is presented at an appropriate level, and is given at suitable times and locations. • Ensure systematic communication to potential trainees. • Investigate new ways of communicating about training opportunities. • Attempt to reduce the anxiety associated with “return to school” for those who have not had recent training. • Maximize the application of classroom activities to current work activities. • Provide assistance to employees through life/career counseling.</td>
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**TABLE 19-1**

Generic Training Program

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**continued**

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## TRAINING METHODS

The plastics industry is maturing and becoming more of a science than an art. The industry was traditionally represented by departments of large manufacturing concerns doing captive molding or by small entrepreneurs in a family-based company. In the large companies, training was on the job, but employees often had a technical background and additional problem-solving resources were available to them. In the family-based businesses, the owner typically taught those around him based on his experience. In many cases, those receiving instruction had the aptitude, but little formal education. Many issues were solved without understanding the reason.

The industry has grown and gained scientific knowledge. There are now formal two- and four-year plastics technology programs available. However, graduates of these programs still experience considerable on-the-job training. In addition to these programs, video training packages; compact disc, read-only memory (CD-ROM) interactive packages; and consultants are available as training resources. Most chemical company suppliers also provide training for use of their products. Companies are encouraged to take advantage of available training packages.

The type of training selected must meet the needs of the employee and the company. The first step is to determine the employee’s needs. Furthermore, any successful training program must also meet the company requirements. Defining the goals and objectives of the training is done by those responsible for the employee’s work. The employee is then assessed to determine his current level of soft-skill proficiency and provide training opportunities.

### TRAINING METHODS

- **Support life/career planning.** Employees must be “retooled” for the coming years. However, this retooling must build, not detract, from their self-esteem and give them confidence and hope for the future.

- **Avoid broad generalizations about the work processes.** Because much of the plastics industry work is specialized both by functions and products, continual training is essential.

- **Emphasize the importance of listening and other interpersonal “soft” skills.** Effective performance relies on an employee being technically competent but also interpersonally proficient. Since the emphasis on training has traditionally emphasized technical competency, soft-skill development is often overlooked. Communication skills are particularly important.

- **Extend collaborative planning and decision making.** The broad involvement of employees in diverse positions and experience can lead to improved planning and decision making. Properly structured, collaborative planning and decision making can result in synergistic outcomes that improve management and enhance the participant’s role.

- **Combine technical and interpersonal training.** When training is highly compartmentalized, its broad benefits may be lost. The challenge is to provide opportunities for applying newly learned soft skills in technical situations.

### TABLE 19-1—continued

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Focus</th>
<th>Action Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support life/career planning</td>
<td>Employees must be “retooled” for the coming years. However, this retooling must build, not detract, from their self-esteem and give them confidence and hope for the future.</td>
<td>• Design programs to assist employees in constructing life plans to promote interpersonal proficiency and technical competency.</td>
</tr>
<tr>
<td>Avoid broad generalizations about the work processes.</td>
<td>Because much of the plastics industry work is specialized both by functions and products, continual training is essential.</td>
<td>• When possible, design training for specific work processes.</td>
</tr>
<tr>
<td>Emphasize the importance of listening and other interpersonal “soft” skills.</td>
<td>Effective performance relies on an employee being technically competent but also interpersonally proficient. Since the emphasis on training has traditionally emphasized technical competency, soft-skill development is often overlooked. Communication skills are particularly important.</td>
<td>• Utilize uniquenesses in work processes as much as similarities in designing training programs.</td>
</tr>
<tr>
<td>Extend collaborative planning and decision making.</td>
<td>The broad involvement of employees in diverse positions and experience can lead to improved planning and decision making. Properly structured, collaborative planning and decision making can result in synergistic outcomes that improve management and enhance the participant’s role.</td>
<td>• Assess the relevance of an array of soft skills for different work processes.</td>
</tr>
<tr>
<td>Combine technical and interpersonal training.</td>
<td>When training is highly compartmentalized, its broad benefits may be lost. The challenge is to provide opportunities for applying newly learned soft skills in technical situations.</td>
<td>• Establish an effective means of determining an employee’s soft-skill level.</td>
</tr>
</tbody>
</table>

- **Weight, part size, volume of parts produced, and the type of polymer used.** Methods vary from fabrication to molding, and from extrusion to calendering. Depending on forming method, the parts may also be finished.

- **Finishing can range from degating and deflashing to cutting, welding, painting, metallizing, or printing.** Most of these finishing processes may be applied to any plastic part. There are also several methods of decorating plastics. These include hot stamping, pad printing, silk screening, painting, printing, metallizing, and plating. Each has its application depending on size, shape, material, and process speed.

- **Understanding safety issues is important to all who work in the plastics industry.** Workers must recognize decomposition products that may be released from the process. Protecting employees from hazardous situations is a vital part of the training. Employees must also know the importance of good housekeeping in preventing accidents. Most polymers are shipped as pellets, which are slippery if spilled. Some materials cannot be mixed at processing temperature, or an explosion may result. Hazardous-marking icon recognition is essential, and employees must have access to material safety data sheets.
quantify the employee’s understanding. When the capabilities are compared to the requirements, a detailed training plan is written. This plan can be tailored to an individual or applied to an entire work group.

An appropriate training environment is essential. Good lighting and minimal background noise is important. Video-based training works well in a classroom-type setting for a group, or it can be conducted as one-on-one or self study. Some CD interactive training programs are designed for self study. Home study can be effective if the materials are carefully selected and the information is reviewed with a knowledgeable trainer. Most programs are supplemented with hands-on training for maximum effectiveness. This training is done at the workstation as long as the product is not required in the production schedule. This portion of the training is best done on a one-on-one basis with the instructor present.

The skills learned in any program must be practiced so they become embedded and familiar. Newly learned skills also build the employee’s interest in his work and the desire to learn more. If training remains positive, it inspires further discussion in the workplace, therefore furthering the training. The training can be used as a benchmark for determining advancement, but job-specific knowledge requirements dictate that it is only a part of the advancement
criteria. It is best to avoid making training mandatory, because many will resent the program. The communication that occurs during a training workshop develops a team within the workforce. After-hours training of a work group can be very effective.

Whatever training method is used, the student is tested to ensure the success of that training. While positive feedback is essential, negative feedback from testing highlights its weak points and improves future sessions.

**PERSONNEL SKILLS**

**MOTIVATION**
Management’s goal is to motivate employees to peak performance. It has been said that management does the work through others. It is imperative that management learn the skills to motivate and influence others. They must understand that motivation must come from within the employee (intrinsic motivation) rather than from an external source (extrinsic motivation).

Specific management skills include:
- Proven motivational principles and their application.
- Separation of performance and the performer.
- How to criticize the performance but praise the performer.
- How to praise in public and reprimand privately.
- How to manage time effectively.
- How to involve employees through their own enthusiasm.

**LEADERSHIP**
Effective managers know that leadership does not require a magnetic personality or a special gift for making friends. These individuals have mastered a set of leadership practices that enables them to raise employee performance standards, focus on employees’ strengths, and create for employees a sense of challenge and the satisfaction of achievement.

**PLANNING AND ORGANIZATION**
All organizations conduct planning. Preparing an annual budget, for example, represents planning. The use of formal planning systems encourages systematic forward thinking, leads to better coordination of efforts, and promotes performance that can be objectively measured.

**TIME MANAGEMENT**
Efficient managers rely on time management. These managers make the best use of time—their own, their coworkers’, their superiors’, and their subordinates’. They have learned to prioritize and turn time into a manageable resource. Time control is a habit—that is, a group of practices that can be learned.

Management in the plastics industry must focus on the following areas:
- Learning prioritization methods.
- Designing a personal priority system.
- Keeping a time log.
- Differentiating between managing and doing.
- Minimizing meetings that create few actions.
- Conquering procrastination.
- Saying no when appropriate.

**DELEGATION**
Good management requires effective delegation. A common complaint is the lack of time to complete tasks. Many believe that getting the job done right means doing it yourself. These points highlight an inability to prioritize and delegate.

Delegation multiplies employee effectiveness, develops subordinates for increased responsibility, and prevents employees from becoming frustrated and demoralized. The following is required for effective delegation:
- Select employees who deserve authority.
- Continually improve communication methods.
- Give decision-making power to appropriate individuals.
- Design interesting work.
- Encourage employees to take more responsibility.

**COMMUNICATION**
Management requires the ability to communicate with impact. Good communication motivates people. Whether writing a report, conducting a meeting, or conferring with a coworker, a manager must express himself or herself clearly and convincingly. Effective managers are sensitive to the needs of others. They understand how to maximize the use of nonverbal communication. Furthermore, they listen effectively and know how to make employees listen to them.

Plastics industry management requires training in the following areas:
- All types of personal communication, including nonverbal communication.
- Listening.
- Typical barriers to communication.
- Organizational communication.
- Developing a plan for effective communication.

**MEASURING PERFORMANCE**
Management must measure performance. This measurement is often a demanding and misunderstood responsibility. Because of management’s inherent power, the evaluations must be fair, must guarantee respect of the employee, and must preserve each employee’s dignity and sense of self-worth.

**DECISION MAKING**
Making the right decisions is critical to management success. Proper decisions involve defining a given problem in detail, focusing on the root cause, objectively analyzing the facts, developing alternate approaches, and choosing the best solution.

The following steps promote good decision making:
- Differentiate between routine and strategic decisions.
- Know when not to make a decision.
- Define and analyze the problem using the critical factor method.
- Define the unknowns.
- Develop alternative solutions.
- Know how to sell a decision.
- Know how to use group participation in the decision.
- Know how to use feedback.

**Focusing on Value-added Activities**
Effective managers know exactly what they want to accomplish. When objectives and goals are established, energies are mobilized...
for specific performance. Instead of splintering their efforts, efficient managers concentrate on results-producing activities.

The items support that follow this focus:
- Develop methods that set goals, and relate these goals to priorities.
- Know how to transfer objectives into action plans.
- Learn about the Pareto principle.

TEAM BUILDING AND EMPOWERMENT
Good management requires building and managing effective teams and empowering individuals. A cohesive team, composed of dedicated and talented individuals working toward a common goal and helping other team members, obtains results.

Plastics industry management must be familiar with the following items:
- Recognizing a team.
- Understanding empowerment.
- Requirements for teams and empowerment implementation.
- Fostering team design principles.
- Recognizing team versus group communications.
- Developing trust.
- Establishing rules for team leadership.
- Understanding fellowship.
- The importance of feedback.

OPERATIONS MANAGEMENT
Operations management, once considered minimally important, has taken on strategic proportions for executives in practically every organization. Even small organizations must now struggle to maintain their competitiveness.

In the past, most executives busied themselves with advanced product design, facility planning, financial areas, or marketing. Now decisions relating to operations and inventory planning and control are prominent strategic decisions.

Indeed, visionary organizations increase operational strategies, and in doing so, leap past competitors. To survive in the 1990s and beyond, organizations must balance departmental activities so that each department complements the others. One way to achieve this interaction between departments is the “chaining” of operations; this results in a steady flow of material.

Conventional American philosophy has changed little through the years. The fact remains on increasing production rates. The assumption that inventory items must be readily available at all times to maintain the flow of material remains strong. We must change this paradigm of operations to planning, prevention, and inventory control. While planning and prevention are important to quality, it is beyond the scope of this section, which focuses on inventory. There are two types of inventory control: pull and push. A pull system initiates operation as a reaction to present demand. A push system drives operation in anticipation of future demand. Each of the approaches has its strengths and weaknesses.

Both systems can coexist and complement each other. Pull systems are effective in disciplining operations. Push systems require great precision in material planning and coordination, often with computer assistance. Pull systems are less expensive and require no extensive computerization. A pull system is a combination of production and inventory control, always involving the interaction between lead time and inventory level. Because the inventory level triggers operations, pull systems do not recognize future events. As a consequence, a hybrid system is used to recognize the advantages of both systems.

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Just-in-time Method
After years of exposure to the just-in-time (JIT) concept, the plastics industry has generally failed to grasp the inventory scheduling and management system, its application, and its effect on an organization's profitability.

The focus has been on the obvious, reduction of inventory, rather than on the holistic approach of JIT. This approach covers not only inventory reduction but the improvement of material flow, decreased product development time, increased productivity, decreased nonconformances, and decreased expenditures.

An organization realizes the full potential of JIT when management recognizes that this philosophy applies to the full cycle of procurement (not only purchasing), operations, and delivery. True JIT is built on commitment to quality and continual improvement in the organization.

The most important prerequisite for implementing JIT is repetitiveness. If a process is repetitive, JIT principles often apply. The second prerequisite is time. If time is a condition for performance and indeed a constraint on the process, then JIT is of interest. A third prerequisite is when performance objectives are zero defects and exact compliance with schedule.

The operational emphasis of JIT requires minimizing the distances that parts must travel. Components must arrive at extremely precise times, and storage is based on the points of use. Proximity, then, is important. The JIT ideal is for all material to be in use as work-in-process elements.

Quality at the source is emphasized in conjunction with prevention. Where inventory is concerned, less is better, and the ideal lot size is one, just enough to complete the next operation. Balanced operations are more important than fast operation rates, and excess stock is considered a waste of money, time, and space.

Inventory generally equals money, and it hides manufacturing problems. It also hides waste as part of non-value-added work such as storing, hauling, lifting, inspecting, and counting (sorting). All of these add cost but not value.3,4,5 Suppliers must comply with ever-tightening demands from major industries for cost reduction, high quality, and fast delivery.

To do so, forecasts are required well in advance with built-in mechanisms that quickly accommodate changes. Flexible production systems support these demands.

One misconception of JIT plastics manufacturing is that it forces suppliers to hold, and therefore finance, the upcoming material inventory. In fact, a supplier and customer must increase com-
munications regarding each other's needs; delivery lead times are therefore better controlled. Both parties become more responsive.

To examine a JIT system, the kanban method is presented here. Kanban is a method of achieving just-in-time production and scheduling. It means card and is sometimes referred to as the pull system. Furthermore, it is the most common system in the plastics industry for scheduling and controlling inventory.

Toyota Motor Co. of Japan pioneered the technique under Vice President Taiichi Ohno. Ohno's ideas about JIT, however, were inspired by the American supermarket, where shelves were replenished as emptied. Since space for each item was limited, more items were brought in only when needed.

Kanban is now universally accepted in Japan as a method to maximize profits by minimizing costs and inventory. Suppliers ship parts directly to assembly plants, where side-unloading trucks deliver parts directly to designated lines without counting or sorting.

How kanban works. The primary components of the kanban system are as follows:

- Kanban authorization cards—move and production.
- Standard containers.
- Work centers (or cells)—a machine, assembly line, or single work table.
- Withdrawal and production posts.
- Input areas.
- Output areas.

Every kanban system uses a marker such as a card, flag, light, hand signal, or voice command. In a two-card system, a move kanban indicates that a container can be passed on to the next work center. A production kanban notifies the work center to produce one container of parts. Withdrawal and production areas exist side by side on the shop floor.

Every work center has a withdrawal and production area. The withdrawal system is responsible for obtaining more stock, raw material, or parts from the previous work cell or machine. When the material container is empty, a move kanban is placed on that container, allowing it to retrieve more stock. When refilled, its move card is removed and replaced with a production card, and the container is returned to its correct work cell. The move card that was removed from the container is placed on the previous work cell's container, allowing that work cell to obtain more stock. Thus, each cell interacts with the preceding work center.

At the production area, a finished or full container awaits a move card. That container goes no farther down the line unless authorized, or “pulled” from the next downstream work center. When that work center sends up an empty rack, it is signaling that more stock is needed for its operations. The full and empty containers then switch contents and cards, thus authorizing the middle work center to make more parts, and allowing the downstream work center to have more stock for its operations.

A kanban system may also be a single card, a combination of push and pull. In some domestic plants, long die change times, low uptime of high-speed transfer presses, complex product designs, and an untrained workforce make a dual-card system difficult, because dies cannot be changed over quickly enough to justify small-lot production runs. The customer’s assembly plants can pull subassemblies from stamping plants, while the metal assembly lines within the stamping plant have material pushed on them from their adjoining pressrooms.

For the Japanese industry, the dual-card system works well, but the Japanese culture itself may be primarily responsible for the success of this system.

To counter some of the difficulties associated with the dual-card system, the Synchro MRP was created by Yamaha Motors for a high-volume manufacturing company with a broad product line. The master part schedule is developed, and then material requirements planning establishes the work cell production schedules. A computer prints out Synchro I cards, similar to move kanban cards, and Synchro II cards, similar to production cards.

Micro-kanban is the addition of a JIT kanban system to an established material requirement planning (MRP) system. A centralized computer calculates the parts required for the assembly line and downloads these data to a field computer on the line, similar to an electric kanban. These computer-kanban systems are more complicated than the simple, paperless kanban methods.

Factors affecting kanban implementation. Kanban requires intense discipline. Management commitment is essential to adopting the new philosophy and educating workers about why the change (sometimes a culture change) is necessary for survival.

Understanding JIT theory is imperative, since simply copying the method from another company does not guarantee success. Kanban also requires a stable, in-control process, where quality, quantity, and cycle time are predictable. The kanban system itself is not critical to improving performance. It is only one part of an overall manufacturing philosophy intended to reduce inventory investment, increase productivity, and improve customer service.

The three problem areas concerning kanban are: identification of flow lines, flow line loading problems, and operational control problems.

Flow line identification streamlines the operation from a functional layout, where several operators work together simultaneously at a variety of jobs. Flow line loading problems are overcome by allocating even work loads to each flow line to avoid bottlenecks. The operational control issue is overcome by determining the number of kanbans in a given process, considering the machine reliability and the uncertainty of demand.

To receive the full benefits from a pull inventory system such as kanban, a steady demand is recommended. As the number of kanbans and hence the inventory is reduced to near the feasible minimum, the system becomes more sensitive to demand variability. Incremental improvement in system performance is made by lowering the inventory level and increasing the process reliability.

Kanban versus traditional inventory systems. Traditional inventory management systems rely on the push system, where material is pushed on the following work cell or customer regardless of need. For efficiency and savings to accumulate, time, understanding and effort are strong requirements; these three items suggest a hybrid system.

One such hybrid system, the material requirement planning system, is a successful push technique. MRP can adequately serve material coordination, material planning, and purchasing. A computer-driven control system, MRP breaks the manufacturing operation into discrete parts. It projects demand, the time necessary to meet the demand, and the material required to meet that demand.

With MRP, the system is told the appropriate lead time to manufacture a part, component, or assembly. As a consequence, MRP orders only the required parts, not a preset lot based on safety stock. MRP mandates build to scheduled delivery of final product, not to a fixed inventory position.

Calculations for MRP start with the end items shipped and proceed back through bills of material, releasing orders according to predetermined quantity and timing. The most appealing feature of this inventory approach is its capacity to work through bills of material by which parts and subassemblies become the final product.
The MRP system works well for complex material coordination between several locations and suppliers, however if the end product is a complex one, a two-tier system is usually most effective. First, supplier channels are established based on forecasts, and then logistics coordination based on real time is defined. So, where the MRP system accepts the current values of planning parameters, such as lead time and lot size, the kanban system reduces lead times, minimizes lot size, and reduces scrap to cut costs.

Some barriers to successful implementation of MRP are:

- The cost of the computer system, including appropriate training and implementation.
- The lead time requirement may not be available.
- Use of the central computer becomes cumbersome, and the system becomes inflexible as complexity is added.

Another JIT hybrid is material requirement planning II (MRP II). This system is more precise than the basic MRP. It, too, initiates production of various components, releases orders, and offsets inventory reductions. MRP II grasps the final product by its parts, orders the parts delivery to the operators, maintains inventory positions in all stages of production, and determines what is added to existing inventories.

This complex system analyzes capacity and resource loading similarly to capacity planning. Load released by the MRP system is analyzed. If the load exceeds the capacity of the work center, the system indicates that the work will not be completed within the time allowed. Therefore, a human planner must find ways to cure problems diagnosed by the computer. MRP II is an advanced management system incorporating all available resources.

MRP II is considered a closed-loop system. The loop includes the following:

- Strategic business planning.
- Sales and production planning.
- Master production scheduling.
- Material requirements planning.
- Capacity requirements planning.

Like MRP, MRP II is related to kanban in two ways. It is a mechanical system for controlling production, and it occurs on a total system level.

Even though similarities exist, there are also some misconceptions. Kanban is a minimum stock order system, not a zero-stock system, because no stock is ordered until a time requirement is reached.

Drawbacks to the MRP II method include the complexity of the computer system. MRP II is also criticized because it is transaction oriented and data-entering time is high. Inaccurate inventory data may lead to the mismanagement of the master schedule and production plan.

MRP II programs often promise manufacturing more precision than they deliver, require unnecessary information, and demand more formal discipline than the shop floor needs. Kanban, on the other hand, can help make production more consistent and predictable.

With all the shortcomings of JIT, kanban, MRP, and MRP II, the advantages of implementing an inventory system are overwhelming.

First, levels of production, income, prices, wages, and interest rates are joined in a system that has stability over time. Second, future changes in economic magnitudes will result from present operating causes or may be deduced from present symptoms. Third, the nature of those causes and symptoms, and the future consequences, are determined by studying past relevant experiences.

These logical steps are also the basic assumptions that underlie business forecasting, economic theory, and statistics. The future quality professional must develop three strategies to optimize an organization: deterministic, symptomatic, and systematic.

**Deterministic Strategy**

The deterministic strategy assumes that the present has a close causal relationship with the future. The term deterministic, however, does not imply a fixed or irreversible relationship between the present and future. In the real economic and quality world, completely fixed relationships do not exist. Deterministic techniques, however, are used to forecast, not predict, particular elements. They are often combined with other methods to forecast general business and certain quality conditions.

The deterministic technique, which is important for short-run forecasting, assumes that economic magnitudes and relationships change slowly. Therefore, with the latest information, existing conditions and trends are expected to continue for some time. This technique is a bit simple, but it is important in businesses setting weekly or monthly production schedules, ordering raw materials, and setting prices.

In the deterministic method, many important factors bearing on the economic or quality future are determined in advance. These factors are expected to remain virtually stable or change at a predictable rate through the forecast period. The factors may also be elements that affect economic and quality developments during the forecast period. They may also limit other, more variable types of economic or quality activity.

Certain immediate facts are regarded as causes or early phases of future economic activities. For instance, residential and industrial building contracts precede construction, and coal and ore shipping precedes steel production.

In either of these cases, there is a causal connection between the initial and later process stages. Construction work may be delayed or accelerated, consumers may change their inclination to spend, and businesses may delay capital spending plans. Nevertheless, a fairly close relationship between the initial and later stages of an economic process usually exists to forecast on the basis of advance information.

**Symptomatic Approach**

The symptomatic approach to forecasting relies on the general sequence of events in a business cycle remaining sufficiently consistent to enable forecasting by following the “leading indicators.” The importance of the symptomatic approach is its concentration on spotting turning points in business activity.

Business analysts have long sought a set of indicators that lead general business developments. The debate over which indicators are the most reliable continues today.

The National Bureau of Economic Research has conducted detailed analyses of business cycles by screening time series with forecasting values. Nevertheless, the interpretation of the indicators is subject to numerous uncertainties. The main uncertainties are to:

- Determine whether a series change is a temporary dip, a rise, or really represents a trend reversal.
- Relate the significance of the changes in each series to the others, since virtually all of the series are somewhat variable.
- Obtain the current data for each series.
Each series in the leading group reaches its turning point from two to ten months before business cycle turns. Each series in the lagging group follows turns in the business cycle by two to seven months. The variability of lead and lag times is a hazard for the forecaster.

Another innovation in the leading indicator approach is an explicit scoring plan to help select an indicator evaluation. Six selection criteria are:
- Economic significance.
- Statistical adequacy.
- Historical conformity to business cycles.
- Cyclical timing record.
- Smoothness.
- Promptness of publication.

Systematic Forecasting

Systematic forecasting uses advanced econometric models to determine cause/effect relationships among factors. These factors hold true for the past; however, for the present and future, they define truth based on statistical confidence. The use of systematic methods for forecasting requires vast amounts of theoretical training, technical skill, and social and political insights.

By using systematic forecasting, the quality professional can use economic, accounting, statistical, mathematical, and consumer behavior data to help redefine customer demands.

The plant engineer of the plastic manufacturing/processing operation rarely has the opportunity to lay out a new plant. When given such a luxury, the task of creating an efficient operation is easier and more satisfying than working with pre-existing conditions that require compromise. The ultimate goal for a new facility is to lay out the most efficient operation under the given circumstances.

PLANT REQUIREMENTS

The requirements of a plastic manufacturing/processing plant are similar to those for any manufacturing facility. One of the first steps necessary when laying out a new plant or enhancing an existing facility is to conduct a fact-finding mission. A detailed listing of all equipment necessary to meet the forecasted production is prepared. The following issues are also addressed:
- Method and quantity of raw material received.
- Flow of material through the facility.
- Handling, packing, storing, and shipping of the finished product.
- Promptness of publication.
- Smoothness.
- Statistical adequacy.
- Historical conformity to business cycles.
- Cyclical timing record.

Once these items are established, the required manpower of the operation is projected. At this point, the size of the facility is calculated, with future growth in mind. The percentage of the facility that is dedicated to each department is also determined. Good facility design promotes a smooth, unidirectional, uninterrupted material and/or work flow through the facility, with the necessary service and support operations concentrated around it in a practical manner.

CONFORMANCE TO NEEDS

The manufacturing area must conform to the needs of the product being manufactured. The common plastic manufacturing processes and their respective area requirements are described in the following sections. Although several processes are described here, later sections focus only on injection molding and extrusion.

Injection Molding

This is the process in which molten plastic flows in a barrel, generally around an intermittently rotating screw. The molten plastic is advanced to the front of the barrel, where it is injected by the screw (or by a plunger) into the mold. Upon plastic solidification in the mold, the part is ejected. This process is most common with thermoplastic materials, but is also used with thermoset materials.

Extrusion

In extrusion, molten plastic is in a barrel, flowing around a continuously rotating screw. The material is forced through a die and cooled by air or water, and the solidified shape is stored on spools or cut to length. Used with thermoplastic resins, plastic sheets, films, and bags are made by this process.

Compounding

Compounding is similar to extrusion, except that several ingredients are intimately mixed into a homogeneous mass.

Blow Molding

This process is used to make hollow products. A parison (tube-like plastic shape) is injection molded or extruded with the ends sealed. Air is then blown into one end of the parison to inflate it inside a mold, where it is shaped, cooled, and removed. This process uses thermoplastic materials.

Rotational Molding

Rotational molding consists of four material-related steps: loading, curing, cooling, and unloading. In the loading stage, liquid or powdered plastic is charged in a hollow mold. The mold halves are then clamped shut and moved into an oven, where the loaded mold spins biaxially. The oven heat penetrates the mold, causing the plastic to adhere to the mold surface. As the mold rotates while heating continues, the plastic is gradually distributed evenly on the mold cavity walls due to centrifugal force. When the parts have formed, the mold moves to a cooling chamber, where it continues to rotate while it cools, so the part does not sag from the mold surface. Finally, the mold is opened and the parts are removed. This process, using thermoplastic material, is used to produce large parts in small to medium production quantities.

Compression and Transfer Molding

These processes consist of placing premetered amounts of plastic into a mold. After closing the mold, the molten plastic is solidified under exposure to heat and pressure. Upon curing, the part is removed from the mold. This process primarily uses thermoset materials.

Cold Molding

The cold-molding process consists of metering various nonre- fractory (organic) or refractory (inorganic) compounds into a die
and compressing them in a punch press under a pressure of 2,000–12,000 psi (13,789–82,735 kPa). The compressed part is then cured in an oven. This process uses thermoset materials.

**Thermoforming**

Thermoforming consists of heating thermoplastic sheets to the softening temperature and forcing the hot and flexible material against the contours of a mold or cavity by mechanical means or with compressed air. Vacuum is also applied to the opposite side of the mold to assist the forming process. After the plastic is cooled, it retains the shape and detail of the mold.

**Cold Forming**

This process is similar to thermoforming, except that less heat and higher pressures are used, thus shortening the cycle time.

**Casting**

Casting consists of pouring liquid plastic into a mold or onto a flat surface and allowing it to cure. This process is used to produce slabs and rods with thermoplastic or thermoset materials.

**Calendering**

This process consists of blending thermoplastic materials with various additives to form a paste-like mass and then forcing it repeatedly through a series of nip rollers to produce a sheet of film. This process is typically used to make floor coverings.

**PRODUCT-HANDLING EQUIPMENT**

Once the quantity and type of primary process equipment are selected, product-handling equipment is considered. As much as 40% of injection molding processing cost can come from product handling. The product-handling equipment chosen must match the productivity of the prime plastic-processing equipment. Conveyors can be the in-press type, take-out type, or special stacking or orienting machines. Other considerations are automatic bulk handling systems, in-press grinders, parts removal robots, product-handling conveyers, automatic take-off equipment, parts and runner separation systems, and equipment for automatic part assembly. On long-run products, special systems are considered in which the mold or die, the primary plastic-processing machine, and the product-handling equipment are designed to function as a system.

**RAW MATERIAL STORAGE AND HANDLING**

Once the basic hardware is selected, efficient storage and handling of raw materials is the next major consideration. The design of the raw material system has a major impact on the plant's ability to achieve low manufacturing costs and good housekeeping. The raw material system must feature expansion requirements, with future automation and flexibility in mind. The system design is based on the number of different materials, annual volume of each raw material, number of different colors, number of primary plastic-processing machines, and average production run length.

The purchase of raw materials in bulk quantities, by truck or rail car, usually provides major cost savings. If the annual consumption of a single raw material exceeds one million pounds, a silo system for bulk storage is usually justified by the savings in raw material costs. In some cases, the use of a rail car itself for bulk storage is less costly than silos. Raw materials are loaded and unloaded from silos or large bulk containers by an air blower or a bulk storage is less costly than silos. Raw materials are loaded and unloaded from silos or large bulk containers by an air blower.

**SUPPORT AREAS**

Offices, lounges, reception areas, cafeterias, first aid rooms, warehouses, locker rooms, and rest rooms are considered support areas. These areas require careful planning when preparing plant layouts.

**BUILDINGS**

After the detailed facility layout is completed, engineering specifications and statements of requirements are prepared. Site
selection, zoning, ordinances, building structure, insulation, sprinkler and fire protection systems, voice and data communication systems, water supply systems, sanitary and storm sewer systems, plant safety and security systems, loading docks, access roads, walkways, and parking lots require specification, review, and approval before starting construction.8

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**Fig. 19-4** Air blower method of conveying raw materials.

**Fig. 19-5** Vacuum pump method of conveying raw materials.
Fig. 19-6 Combined air blower/vacuum pump method of conveying raw materials.

Fig. 19-7 Compressed air method of conveying raw materials.
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Fig. 19-8 Typical in-plant compounding system for an injection molder.

Fig. 19-9 Flow chart of typical injection molding operation. (Courtesy Husky of America, Inc.)
Surge bins may be required inside the plant between blenders and distribution panel.

Fig. 19-10 Plant layout showing central blending with a central vacuum system for distribution to each machine.
Fig. 19-11 Side-by-side machine layout in one or more parallel rows.

Fig. 19-12 Machine layout parallel to aisles.
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Fig. 19-13 Machine layout at an angle to aisles.

SAFETY

In any plastic manufacturing/processing facility, safety concerns are placed in the following categories:

- The manufactured product.
- The manufacturing process.
- The environment.
- The life cycle of the product.

In most plastic manufacturing/processing facilities, the plant engineer and his organization play a key role in implementing safety. All manufacturers and plastic processors have a responsibility for the safety of their employees, as well as for the community in which they operate. For that reason, regulations, systems, action plans, enforcement plans, and follow-up plans are required. Since most plastics industry materials are considered chemicals, they fall under strict safety guidelines. Therefore, it is good practice for a plastic-processing organization to set up a safety team or committee. These individuals should concentrate on the following topics:

- Accident prevention.
- Loss prevention.
- Protection of humans and the environment.

EFFECTIVE SAFETY PROGRAM

An effective safety program is approached in the same manner as that used to increase production and efficiency, reduce costs, and eliminate waste. Efficient production methods and safety cannot be separated. Satisfactory personnel relations are maintained with a sincere interest in accident prevention on the part of both management and employees.

SAFETY TEAM/COMMITTEE

The effective executor of all accident and loss prevention programs and the administrator of all safety issues pertaining to the successful operation of a plastic manufacturing/processing operation is the safety team/committee. Its members include workers, managers, and professionals of the organization, each with a broad understanding of all aspects of the organization and having decision-making power. Their mission must include the following items:

- Establish an accident prevention program, safety inspection procedures, listing of the areas and inspected equipment, and frequency of inspections and recording methods. Establish
procedures to obtain, analyze, save, and display material safety data sheets on all substances used, as required by law.
• Establish the safety rules and procedures pertaining to the facility, the dress code, and the areas that require wearing compulsary protective equipment.
• Establish preparedness, prevention, and contingency plans.
• Organize safety and loss prevention training programs at all levels. Involve the expertise of all departments in the organization. Set up recordkeeping for lost time, accidents, and their costs.
• Establish a safety suggestion program, with recognition for good ideas.
• Establish an in-house fire brigade and first aid team.
• Establish a regulatory agency compliance coordination system.

DIRECT ACCIDENT COSTS
It is essential to understand the cost of injuries. As soon as someone is injured, costs generally accumulate. Direct and indirect accident cost accounting is required. Investing in safe work methods and equipment can prevent needless injuries and save a large amount of capital. Descriptions of various injuries and their consequences are as follows:

• With a minor injury, there is a loss of production time and the cost of treatment incurred, either at the facility or off the premises.
• With a serious injury, the individual may be at home or in a hospital for an extended period. Continuing medical treatment or surgery may be required.
• Compensation payments to the injured person vary, often according to state-established rates. Payments may continue until the individual can return to work.
• The employer is responsible for the cost of first aid, medical treatments, and compensation benefits, either directly, through an insurance carrier, or through a self-insurance plan.

The following indirect consequences are normally uninsured; these costs are generally difficult to estimate but can be high:

• Time lost due to assisting the injured employee.
• Investigating and reporting the circumstances of the accident.
• Rearranging production schedules.
• Overtime wages paid to replace lost production.
• Transferring, hiring, or training a substitute person.
• Material that is damaged by accident or by a substitute employee.

Other costs include:

• Public liability claims.
• Cost of renting replacement equipment or a facility.
• Clean-up costs of accidental releases or spills.
• Loss of canceled contracts by customers due to missed deliveries.

The majority of these consequences interfere with smooth, continuous manufacturing operations. The indirect or “hidden” costs may be four to ten times higher than the direct costs.

SAFETY SURVEY
A successful accident prevention program requires a highly detailed survey to determine the potential safety hazards, needs for corrective actions, frequency of inspections, method of enforcement, and proper recordkeeping. The following areas should be included:

• The total facility, inside and outdoors, including grounds, walkways, driveways, and parking lots.
• The various manufacturing processes, machinery, and auxiliary and service equipment for proper guarding, shielding, lock-out provisions, warning signs, and operating and warning instructions. Safeguarding features for molding machines include:
  1. Interlocked safety gates at the mold front, rear, and top, equipped with at least one electrical switch and one hydraulic or pneumatic valve to prevent the machine from operating when the gate is open. If a power-operated gate is used, the exposed leading edge must feature a pressure-sensitive switch or equivalent device to stop the gate if it is bumped.
  2. Fixed guards covering the mold areas not protected by interlocked guards, other machinery moving part hazards, and purging area.
  3. Mechanical safety device that prevents clamp closing when the safety gate is open.
  4. Ergonomically designed controls including the emergency stop.
  5. Guarded material feed openings.
  7. Enclosed electrical wiring and high-voltage connections.
  8. Guarded injection barrel heater bands and other hot surfaces.
  9. Warning and caution signs/labels.
  10. Administrative controls including operator training, maintenance, repairs, personal protective equipment, instruction manuals, and hand tools.

• Ergonomic considerations such as proper seating and sit/stand workstation heights, and avoidance of workstation setups that promote repetitive-motion injuries such as carpal tunnel syndrome.

SAFETY HANDBOOK
Safety rules and procedures pertaining to behavior in the facility are communicated effectively by publishing a condensed handbook containing all such directives. The content is explained to each employee in an appropriate training session. These handbooks are revised and updated as necessary and re-issued with a revision number clearly identified. In addition to covering general issues of plant behavior in these booklets, special attention is given to typical plastic manufacturing/processing industry issues, such as the need for eye, face, and breathing protection in the areas of plastic pellet granulation, mixing, and feeding; face, hand, and arm protection with heat-resistant protectors for use near hot machinery and when purging material from barrels and melting chambers; and safety shoes for those involved in changing, hauling, and handling heavy tools, dies, machines, and containers.

PREPAREDNESS, PREVENTION, AND CONTINGENCY PLAN
Completed contingency plans, generally bound as booklets with each section clearly marked for quick reference in case of emergency, are distributed to all members of the safety team/committee, the in-house fire brigade and first aid teams, and the fire departments and ambulance squads of the local community. The booklet is also displayed near bulletin boards along with a binder of all the material safety data sheets. The guide covers all materials used in the facility, as required by OSHA, and is made available to the employees in compliance with the Emergency Planning and Community Right-to-Know Act.

This preparedness, prevention, and contingency (PPC) plan is a guidance document only. It is not used to override or contradict the
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knowledge and experience of qualified personnel on the scene, such as fire marshals, trained emergency personnel, or other professionals familiar with emergency procedures.

A PPC plan should cover the following areas:

- The location of the plastic manufacturing/processing plant, with a United States Geological Survey (USGS) area map attached showing the surface water course and direction of flow.
- Site plan of property boundary and elevations.
- Site plan of exit locations and emergency direct telephone lines.
- Site plan of fire-fighting equipment, risers, shut-offs, and locations of the various “spill kits.”
- Site plan of distribution and disconnects of electrical mains, natural gas, water, waste water system, and drain lines.
- Site plan indicating the locations, list, and inventory of the average quantities of all stored and waste materials and their compatibility.
- Description of industrial activity.
- Organizational structure, duties, and responsibilities for implementation of the PPC plan, with the telephone numbers of all members involved in the implementation.
- List of safety procedures established to prevent spills, leaks, fires and explosions, and accidental releases to the atmosphere.
- Housekeeping, security, inspection, monitoring, prevention programs, and communication and alarm systems.
- List of agencies to be notified in any emergency.
- Arrangements with emergency response contractors.
- List of local emergency response agencies.
- Copy of plant first aid procedures and list of first aid team members.
- Copy of plant emergency evacuation procedure and list of emergency evacuation team members.
- Copy of plant safety team/committee procedures and list of team/committee members.
- Chemical hazard communication program.

PROPER HANDLING METHODS

In a well organized and loss prevention program, all employees are trained in the potential hazards associated with careless handling of materials or equipment. This training is repeated and updated at regular intervals. Employees must recognize the different plastic resins, some of them similar in appearance, that are capable of creating violent reactions when mixed.

The safety and loss prevention training program must also focus on safety issues pertaining to plastic processing. This includes hot-part handling, purging or cleaning melting chambers, handling of purging while cooling, and provisions to intercept and control “run-away” heats in melting chambers, which can result in explosive “blow-backs.” The key to successful safety suggestion programs is to involve all employees and reinforce their involvement by promptly evaluating and addressing their suggestions. This works best when the safety team/committee commits and adheres to a fixed time for all investigations. Good suggestions with potential for substantial savings should be rewarded by recognition, and perhaps financially. Prenumbered safety suggestion forms placed at highly frequented locations can enhance such efforts. In many cases, the analysis of suggestions may be so complex that it requires the mutual input of several professionals. It is the safety team/committee’s responsibility to coordinate this effort in a timely manner.

FIRE BRIGADE AND FIRST AID TEAM

When establishing an in-house fire brigade and first aid team, every operating shift requires coverage. The team members should include certified fire fighters and health providers. These are the team leaders, passing on their experience to other team members. Regular meetings provide review of the pertinent items covered under the PPC plan. Emergency training sessions, concentrating on safe equipment shutdown, evacuation procedures, and spill prevention, are essential. The fire brigade and first aid teams should invite members of the local fire department, emergency, and ambulance squads to these meetings and provide them with copies of the PPC plan.

RULES AND REGULATIONS

The plastic manufacturing/processing industry is dealing with a broad spectrum of thermoplastic and thermoset resins, compounds, and mixtures. There are many more materials used to make the end product, such as oils, lubricants, solvents, cleaners, paints, rust inhibitors, freeze protectors, and various gases. Many of these materials are highly regulated by federal, state, and local authorities. Due to the broad range of materials most plastic manufacturersprocessors deal with, and the many complex regulatory agency requirements, a task force is required to monitor the plant’s adherence to the myriad regulations. It must also establish procedures to track and report to the proper authorities any extremely hazardous substances from the source of acquisition, through storage and use within the facility, to off-premises disposition. The task force must strictly follow pertinent procedures outlined in the PPC plan.

In summary:

- Do not acquire, store, manufacture, or ship a product unless all applicable safety implications are known.
- Do not start up a facility until all safety aspects are satisfied.

EQUIPMENT SELECTION AND MATERIAL HANDLING

In a plastic-processing facility, the plant equipment and machinery generally fall into three groups:

- Primary plastic production/conversion equipment.
- Auxiliary equipment.
- Service equipment.

The plastic process engineer selects the necessary primary and auxiliary production machinery to best meet the needs of the manufacturing process. Those specifications and requirements are then reviewed by the plant and facility engineer to ascertain that the selected equipment is the most efficient, that it satisfies the needs and expectations of the manufacturing process, that all necessary options were selected in advance, and that they meet the requirements involved in installing, powering up, operating, servicing, and maintaining the plant.

From a plant engineering standpoint, the following issues are addressed at this point:

- Size of the equipment.
- Location, accessibility, and serviceability.
* Material handling and recycling.
* Plastic process changes.
* Mechanical, electrical, and building services.
* Process- and production-monitoring systems.
* Safety and environmental considerations.
* Reducing maintenance costs.

**SERVICE EQUIPMENT**

Equipment is chosen to supply all plant services. Reliable supplies of power, water, and air are essential. Other considerations include plant lighting; ventilation; air conditioning; compressed air supply; oil, gas, or water heating and circulating units; chillers; water treatment; cooling towers; hoists, cranes, and lifting equipment; and electrical substations. Expansion plans would include extra capacity in the electrical substation, cooling tower, silos, and plant services distribution system. This equipment is best located near permanent walls that would not be disturbed during a future expansion.

Service lines require accessibility for maintenance. Current schematic and installation drawings are essential. Services can be distributed by tunnels, trenches, or overhead conduits. The service tunnel is recommended for new plants with multiple machines, because it is the most efficient. Service trenches are best for existing plants and for operations of less than ten machines. Overall installation is the least expensive alternative with the most flexibility.

**MISCELLANEOUS EQUIPMENT**

Secondary and service equipment near the primary plastic-processing machinery requires careful planning. This equipment includes machines for secondary operations, grinders, dryers, printers, labelers, packing equipment, robots, part removers, conveyers, and machines performing sub- and final assemblies. These items require space, accessibility, electrical power, compressed air, and connections with other equipment.

**SIZE OF EQUIPMENT**

Several items are considered when equipment is brought into the plant:

- The method of hauling the equipment/machinery to the plant location.
- Proof of adequate insurance for a contract hauler and rigger.
- Availability of proper loading docks.
- Ample doorways.
- Free movement of the equipment through narrow aisles and near other equipment.
- Method and type of rigging equipment used and environmental issues associated with this equipment.
- Floor strength at the selected location, as well as in the transit areas, where equipment is transported.

**Location, Accessibility and Serviceability**

Accessibility of the machinery/equipment for service and replacement of components is essential. Interferences can result in long repairs and downtime.

**SAFETY AND ENVIRONMENTAL CONSIDERATIONS**

Safety and emergency preparedness are addressed in earlier sections. The following additional issues should be considered in the equipment selection process:

- The equipment manufacturer’s ability to demonstrate a history of service technician availability on a timely basis and an ample supply of critical and otherwise long-lead-time spare parts.
- Cost and delivery time comparisons of competitive equipment, quoted against similar specifications or statements of requirements.

**MATERIAL HANDLING AND RECYCLING**

Raw materials supplied for conversion to the primary plastic equipment/machinery take many forms. Furthermore, the method of its introduction to the production equipment can vary from full automation to full manual feed. Flexibility is important. Only when equipment is surely dedicated to a single process can its design focus on more specific objectives.

Plastic raw materials commonly take the following forms:

- Pellets.
- Flakes and fillers.
- Plastic sheet, flat, or in rolls; thermoplastic or thermoset.
- Powder.
- Liquid or paste.

**Pellets**

Pellets are supplied by resin compounders or manufacturers in various sizes. A common size is 0.125–0.375 in. diameter × 0.25–0.5 in. long (3.2–9.5 mm diameter × 6.4–12.7 mm long). Pellets are packaged in 5 lb (2.3 kg) containers to 2200 lb (1012 kg) gaylords or shipped bulk by truck or rail and stored in silos at the processor’s premises.

The majority of pelletized plastics are thermoform (remeltable), and therefore the plastic runners, which deliver the material to the finished product but are not part of it, are reground, mixed with virgin resin, and reused.

Plastic pellets, therefore, can be supplied to the hopper of the primary plastic production/conversion equipment by hand loading, elevator loading, or most popularly, vacuum feeding the hopper. This is done from a central location or from individual vacuum loaders near the hopper of each machine. Vacuum for individual vacuum loaders is generated by a small pump mounted on the top of the loader hopper, or with a venturi-type compressed-air-operated vacuum generator. Each is equipped with high- and low-limit switches to control the amount of resin in the loader hopper, with cleanable air filters, and blow-off to release the air from the loader hopper. A suction tube, with controllable air input ports, is placed in the pellet-filled container to convey the resin.

The loader hopper is generally installed on the top of the machine hopper, and a paddle-type switch located in the machine hopper controls the resin level in that hopper, which is filled from the loader hopper via a flapper or similar valve. When resin is fed from a central location, the type of equipment used for the individual plastic-processing machines is similar, except no individual vacuum generators are used; a central vacuum generator can supply ample resin flow through individual tubes placed in a loader hopper at each plastic-processing machine.

The pellet delivery system from a central location is popular in extrusion and injection molding operations, where the change of resin or color pellets is infrequent, because the necessary cleaning of long feed tubes at the resin or color change is time consuming. Construction of feed tube systems is critical when moisture-sensitive or hygroscopic resin pellets are used. Pellets cannot remain in these tube feed systems for more than 1–2 hours, especially in facilities without humidity control. Newer resin pellet feed systems provide a controlled amount of compressed air blast in each feed tube after applying the vacuum to remove residual resin pellets from the tube system.
Granulating Runners, Sprues and Gates

The sprues, runners, and gates made of thermoplastic resins are often reprocessed. This is done by granulating or size-reducing the material. Granulators come in various sizes and configurations. An upright construction feeds material through the loading chamber on the top through various flapper arrangements to prevent re-grind resin pellets from escaping through the top; others can be side fed, or of low-profile construction, with an auger screw feeder. The granulation or part reduction is achieved by numerous rotary cutting knives turning past a stationary cutting knife. The rotary knives can be parallel with the stationary knife, but an angular displacement between the stationary and the rotary knives provides a scissor-cutting action, which is more desirable for chopping small, thin parts, runners, and sprues.

The chopped granules are forced through a removable screen. Various screen sizes are available depending on the desired size of the granules. As a rule, the finer the screen size, the more powder that is generated and mixed with the granules. The reground granules are then removed manually, via drawers or by use of vacuum, and conveyed to the desired location. When moving plastic resin, considerable static electricity can be generated in the resin and on the liners, especially in dry atmospheric conditions. Highly charged plastic particles cling to each other and eventually hinder the flow, causing undesired build-up of resin. Sudden discharge can cause sparks and shocks and act as a fire hazard. For prevention, all such equipment must be solidly grounded; in some cases, static eliminators are used.

The regrinding or size reduction of plastic is generally done either by the source, where it is generated, or remotely in a central location. When done at the source, there is less handling involved, and it is easier to re-feed into the process, but the equipment may use valuable floor space, may add noise (despite the availability of noise-damped construction), and has the potential for dust contamination.

Mixing Regrind

Mixing regrind with virgin resin is done by measuring the proper proportions and using tumblers or mixers, or by hand-mixing small quantities. The regrind can also be fed with virgin resin in desired proportions, by vacuum loaders, with proportioning switches used to feed both into the loader hopper. This type of loading is less accurate, because it is influenced by the density and electrostatic charges of the resins, the differences in these characteristics between the virgin and the regrind resin, and the difference in the length of the conveying tubes. The virgin and regrind resin may be layered in the loader hopper as it arrives because of the time setting of the proportioning switch. Due to the viscosity variation between some virgin and regrind resins, such layering can also cause undesirable process variations. A more accurate method of mixing and feeding the regrind to the process is to use a variable-speed auger feeder. This is a process of feeding and mixing a precisely metered amount of regrind into the flow of the virgin resin while it is consumed by the plastic-processing machine.

Colorants are introduced to the plastic processing as concentrates in pellet forms, regrind, powder mixed with pellets, or liquids. They can be handled in the same manner as previously described. However, when liquid colorants are used, they are dosed precisely with the plastic used in the process; they are introduced either into the machine hopper or, more commonly, into the melt, just before introduction to the die or mold.

Thermset materials are delivered to the primary production/conversion equipment in different forms. They are premetered as powder or compound, introduced into the mold/die before conversion to the final shape, and then cured under pressure and heat. Certain thermoset rubbers, after being calendered with the desired additives, are cut into strips and fed through the hoppers of injection molding machines. These calendered thermoset rubbers, however, have a limited shelf life and warmer ambient temperatures reduce shelf life.

Removal of Finished Product

While the finished product can be removed in many ways from the primary production/conversion equipment, special consideration should be given to flexibility in product output, method of handling secondary operations, packaging, product identification, intermediate and final component count, and interfacing with existing production and quality control procedures. Certain plastic primary production/conversion processes require high speed; for example, part removal, cutting, spooling, counting, and performing secondary operations. Processes that are not properly designed for quick changeover can be cumbersome to set up, start up, or tear down. Since global competitiveness today dictates the need for minimum inventory and short delivery times, it is essential to design flexible, quick-changeover-type manufacturing processes or a continuous improvement program to achieve these goals.

Secondary Operations and Packing

In the modern competitive world, the secondary and packaging operations are combined with the primary production/conversion manufacturing process; this is done for time and cost-saving purposes and for logistical reasons.

To optimize these conditions, the most efficient primary production/conversion process development is required, knowing that no more improvements are possible at this time and under the given circumstances. After ascertaining these facts, the maximum number of secondary operations are planned concurrently with the primary process. In the plastics industry, the “cell” or “workstation” principle is the most cost-efficient manufacturing method; finished products are manufactured faster than with earlier methods. Components manufactured at various locations are made in batches and moved to the next operation level, with many product-staging stations located throughout the manufacturing process. When rearranging the manufacturing process to cell or workstation operation, it is important to recognize that most primary plastic production/conversion equipment is more complex than metalworking or similar machines.

Storing, Shipping, and Identifying Finished Product

It is important to identify, track, count, ship, and monitor the quality of components or products, throughout the manufacturing process, and on to the customer. In some primary plastic production/conversion processes, there is a tool, die, or mold involved; it demands a certain layout of components manufactured in that stage. This condition offers the benefit of having the components properly oriented. Full advantage is taken of this orientation in the manufacturing process to accommodate handling the components through all the subsequent manufacturing steps, including packaging.

Special care and consideration are important for the postmanufacturing requirements of certain products, such as cooling before packaging, meeting “clean room” requirements before sealing products, and where required, including additives with the packaging.

Whether the finished plastic product is a component, a completed assembly, fiber, filament, plastic pellet or powder, liquid in various viscosity forms, paste, compounded or calendered in rolls, or
in the form of extruded shapes, the material is counted, measured or weighed, packed, identified, often date coded and bar coded, stacked, and palletized to meet the customer's requirements. Furthermore, exporters must familiarize themselves with environmental regulations pertaining to the compatibility of packing materials.

Robotics
Robots are used in many ways in the plastic-processing industry. They range from simple pick-and-place units to servo-motor-driven, multiaxis machines, sometimes with complex arm-end tooling, to perform single to multiple operations in various steps. Most robots are used with primary plastic production/conversion equipment, and most frequently with injection molding machines. The most common types that serve injection molding machines are sprue pickers, part sweepers, shot pickers, and variations of these units. These areas are generally served by the following robot types: machine-mounted, top entry; machine-mounted, side entry; and floor-mounted.

Robotic motions are achieved by fluid power, mechanics (robots connected to the movable platen), and servo motors. Sprue runners or parts are removed via grippers (pushers or vacuum) individually or on end-of-arm tools. With the exception of floor-mounted robots, these units are installed on the stationary platen of the molding machine. They retract full shots or runners and sprues from the mold, transferring them to a location within their reach.

Secondary Functions. Robots, generally used to retrieve sprues or shots from the mold, can perform secondary operations or degating in transit to the unloading station. They can also retrieve shots or parts from the unloading station, after certain operations are performed there, and move the parts to subsequent unloading stations.

Selecting Robots. Injection molding robots perform best if chosen with the following features:

- Proper travel to reach the pick-up and unloading area.
- Appropriate speeds of the up/down and in/out motions to permit entering the split line of the mold and to retrieve shots or parts without slowing the process.
- Sturdiness of construction, to eliminate unnecessary shaking and vibration.
- Repeatability in picking up and unloading parts or shots.
- Compatibility with the signals and commands of the molding machine or other associated machinery to which it is attached or which it serves.
- User friendliness, facilitating teaching and enabling the operator to retain commands pertaining to each job.

PLASTIC PROCESS CHANGES
In the modern competitive world, production runs have become shorter. This condition requires reducing the time required to change over production, processes, tooling, and all auxiliary equipment.

Flexibility is the key factor in all plant engineering efforts, whether laying out new facilities or processes, acquiring equipment, or instituting a program of continuous improvement. It is best implemented by making the interchangeability of various plastic materials, colors, tools, dies, fixtures, and auxiliary equipment as safe, simple, and easy as possible.

Cleaning Equipment
Primary process equipment is satisfactorily cleaned by using the proper purging compound and strictly adhering to the material manufacturer's recommended purging method. If the purging is unsatisfactory, equipment disassembly may be necessary for thorough physical cleaning. In most cases, this is done under heated conditions, using protective equipment. Availability of proper hoists, lifts, and holding and cleaning fixtures greatly reduces the cleaning time. When electrical or fluid-heating media are involved, all heat sources must have quick disconnects. The use of proper hoists, balancers, and adjustable-height die carts (all on wheels) with locking features can reduce changeover times.

When dies, screws, barrels, adapters, and plungers are cleaned in injection molding machines or extruders, copper wire brushes attached to cleaning rods for barrels and copper scrapers for screws are effective in cleaning the equipment at near-processing temperatures. In some instances, however, when degraded material is adhered to screws, it must be scraped off when cold.

Changing Molds
Injection mold changes are time consuming. The mold is lifted between the platens, centered to the stationary platen, and leveled and clamped to the stationary and moving platens of the molding machine, and the supply and return coolant lines are connected through a manifold system to the mold-cooling media. When molds of certain similar sizes run in the same injection machines, quick mold-change devices are installed on the stationary and moving platens of these machines to readily accept all molds so equipped. With the motion of a locking bar, the mold halves are firmly locked in place, saving the time normally needed to secure the mold with clamps. Similarly, the supply and return coolant lines are attached via quick-disconnect manifolds, reducing hook-up time and potential human errors.

When many similar molds are frequently interchanged, automatic mold changers may be appropriate. These units can remove the mold from the molding machine and place it in an allocated bin, thereafter retrieving the next scheduled mold from its storage bin, moving and installing it quickly to the same molding machine. Such systems, while extremely efficient, require much technical preparatory work with elaborate tool-handling systems, preferably capable of servicing numerous machines. The mold storage racks, with dedicated locations for each mold, are located near the injection molding machines served for ease of mold handling.

All overhead hoists used in the plastic industry require accurate pushbutton controls, with all motions clearly marked on them. The use of chains or pullers on hoists is strictly not recommended, due to the potential of damaging equipment under the hoists.

Cleaning of plastic material in hoppers, granulators, material feeders, dryers, service tubes, hoses, and conveyers is done for each material or color change. When such changes become frequent, these activities become time consuming and expensive. In selecting, specifying, and installing this equipment, cleaning accessibility is an important issue.

MECHANICAL, ELECTRICAL, AND BUILDING SERVICES
The plant engineer of the plastic manufacturing facility is responsible for supplying the proper mechanical, electrical, and building services to all machinery and processes. She/he must also assure that these services are reliable. Therefore, the plant engineer must know the connected and the actual electrical power load, the availability and quality of the power supply, the process coolant, the compressed air, and various gas or fuel requirements, and understand the components that comprise the utility bills. Additionally, many plastic-processing machines generate noise and release heat and fumes into the atmosphere; these must be reduced, filtered, exhausted, or cooled. Proper illumination, hoists

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Financial Considerations

or cranes, vacuum generators, drains, service trenches, safety gates, and warning signs are essential.

PROCESS- AND PRODUCTION-MONITORING SYSTEMS

Every plastic manufacturing process is monitored and controlled by temperature controllers; timers; counters; and various pressure, position, and level controllers. This instrumentation enables the process to operate within established parameters. When excursions, deviations, or interruptions occur, the process falls out of control; it may be readjusted by corrective actions applied manually or by feedback systems.

Unless such conditions are monitored and recorded on a time basis, the establishment of trends and corrective actions cannot be implemented. There are many commercial systems available, with various capabilities, to chart the exceptional conditions of the important process parameters versus time. These are valuable tools for monitoring the quality of the products and the process.

Successful production control, planning, and production management require an accurate feedback system that is capable of reporting, on an ongoing basis, the production quality. This is done by piece count of parts produced within a certain time period, by the number of parts packed and shipped, by weight, or by volume. The system selected must offer timely and accurate information, with straightforward and self-explanatory directions.

REDUCING MAINTENANCE COSTS

The successful plant engineering/maintenance organization is essentially an independent business that operates at cost, within an established budget, and absorbs the budgeted charges for loss of income caused by defective plant equipment. There are several ways that the maintenance organization can profit the business it serves:

• By reducing the downtime of scheduled plant equipment.
• By reducing the department’s operating costs by improving operating efficiencies.
• By better equipment selection, stricter specifications, and more detailed statements of requirements when acquiring new equipment or rebuilding existing equipment.
• By recognizing that the lowest initial cost may not be the least expensive alternative in the long run.

Financial Considerations

Financial considerations pertaining to a plant engineering/maintenance organization are value added. As a result, plant engineering functions are analyzed based on the size, cyclical nature, and complexity of the business when considering which functions will be done in-house and which are contracted services.

Plastic manufacturing/process machinery is typically complex, requiring expertise in mechanics, fluid power, electrical and industrial electronics, and software logic. In many cases, this equipment has highly specialized, nonstandard options and features. It is therefore good practice to train the in-house technical staff, when appropriate, so they can expediently service such equipment.

However, in most plastic manufacturing/process facilities there is considerable general purpose equipment. This equipment, also requiring preventive maintenance, is a good candidate for contractual services.

Sound budgeting and optimization of spare parts inventory is not possible without reliable prior cost history. This history serves as a baseline from which to reduce expenditures.

Therefore, the key to good budgeting is the proper collection and categorization of expenditures, but overcomplication is best avoided. The best method captures and identifies 70–80% of expenditures.

In a good cost collection system, the production equipment that supports the bulk of the business is identified individually with history information such as age and initial cost. Accompanying breakdowns, nature and time to repair, and cost of parts and labor are essential additions to this history. Support and auxiliary equipment is grouped by its function or frequency of use, and the costs are similarly collected. A similar approach is used for general purpose equipment and buildings and grounds. When maintenance employees account for their time against such a cost collection system, this information can be retrieved and posted appropriately with reasonable accuracy. This information is identified regularly for the following reasons:

• To identify troublesome equipment or components.
• To identify the need for preventive maintenance frequency and activity changes.
• For better inventory control.

Cost of Repair Personnel

For continuous improvement in service and costs, a multishift plastic manufacturing/processing operation must consider several options:

• To staff all shifts with repair personnel.
• To do repair work only on certain shifts.
• To depend on a call-in system, with repair personnel compensated for standby or home-availability duty.
• To shut down the defective operation until maintenance personnel are present.

Other factors to consider include:

• The income loss as a result of equipment downtime.
• The potential frequencies of breakdowns occurring on shifts without available maintenance personnel.
• The cost of manning a shift with maintenance personnel.
• The quantity and type of work that is assigned to maintenance personnel when they are not involved in major equipment repairs.
• Maintenance supervision or the lack of it on off shifts.

To establish a successful, cost efficient preventive maintenance program can be challenging. Equipment manufacturers’ recommendations are analyzed and compared to experience gained within the facility or through past experience with similar equipment. In laying out a preventive maintenance plan, preliminary time and material estimates are assigned. These are later revised as experience is gained.
The repetitive nature of the plastic-processing industry lends itself to computer automation. Improvement of tasks ranging from part costing, production management, and statistical process control/statistical quality control (SPC/SQC) to inventory control can be realized through automation. This has led to many products addressing potential applications in plastic part manufacturing. This section provides a discussion of how computer systems automate plastic manufacturing management tasks (see Table 19-2).

Each framework section is expanded to cover approaches typically used by systems analysts for each type of automation. System architecture is defined in terms of input-process-output (IPO), and their cost justifications are developed. A special attempt is made to demonstrate how to avoid common garbage in, garbage output (GIGO) results from any systems. Garbage is meaningless information and usually confuses the interpreted data instead of making it easier to understand.

Before considering a computer system, an engineer should have a clear idea of management’s expectations. These expectations are readily developed by clarifying the type and method of data entry and the corresponding outputs. Any computer system can be analyzed by defining its basic IPO operations. Manufacturing systems for plastics processing have evolved with three types of IPO designs. Engineering efforts are effectively focused if management’s expectations match one of these designs. System characteristics of each design are listed in Table 19-2.

Some plant management systems are designed around a central computer, which collects data from multiple stations and produces centralized reports. Other systems use personal computer (PC) network architectures to distribute data to many users via workstations. Finally, there is a class of systems, using PC capability, that is embedded in newer, microprocessor-based machine and process controls. The characteristics of each type are not necessarily exclusive, but represent the typical application. Users of existing systems may use this framework to satisfy their expectations; those responsible for implementing new systems can use the framework as a guide in choosing appropriate equipment. These three designs can be combined in any order to create medium- and large-scale systems.

### PRODUCTION MANAGEMENT SYSTEMS

Central systems recognize that most phases of plastic part fabrication (plastication, filling, packing, and curing) are usually done by a single machine. In the 1970s, techniques to better manage a plastic fabrication facility emerged by automatically tracking a machine’s cycle. Management reports were then prepared to compare cycle performance with an expected manufacturing standard. Since production planning is often centered around a cycle standard, real-time feedback of execution represented an opportunity for dramatic improvement in management’s control.

#### Inputs

A central system has a mechanism that senses the completion of a machine cycle and reports it via a plant network. A mold-open signal, available in most presses, represents a classic source of cycle data. However, since cycles are repetitive, most discrete cycle phases can serve as the input source. An electrical input, such as a limit switch, photocell, or relay contact, creates an automatic input for the system. At this point, the input is converted to serial data that is sent over the network. Original designs had one such device per machine. Since this data conversion is relatively simple, costs are reduced by having one such device serve a group of machines. This works effectively in collecting cycle counts; however, if collecting manually entered data is required, removing the data entry point from the machine makes effective operation more difficult.

If only one machine is sending information to a computer, that computer’s RS-232 port is adequate for a maximum distance of 50 ft (15 m). Normally, the central computer is monitoring multiple machines over much longer distances; this necessitates using a networking scheme. Ethernet, Token Ring, and ARCnet with wire cables are common choices for office automation. However, industrial environments are susceptible to more electrical interference than that witnessed in an office. Therefore, a plant network often uses an RS-485 architecture or fiberoptic cables. RS-485 is a multiple-node connection standard based on current rather than voltage. Current is less susceptible to induced noise; this avoids use of the more expensive fiberoptic cables.

Processing data. The power of these systems increases as more production standards are applied to the cycle occurrence information. This information is used in at least four areas:

- Production run control.
- Efficiency management.
- Manufacturing resources management.
- Scheduling/execution management.

Overruns and underruns have serious economic impacts for a plastic processor. Unlike the printing industry, plastic production runs are not usually acceptable if they vary from the specified amount. Overproduction must be inventoried, regrounded, or sold at a discount. Even worse, underruns require the absorption of a second set-up. Cycle reporting offers an exact method to control this. Each cycle produces a set number of pieces (in molding, for example, it is the number of cavities). This, and the amount scheduled for manufacture, are the production coefficients. Each cycle occurrence is multiplied by the units per cycle, and this value is subtracted from the amount left to produce. A real-time “balance remaining” result; management uses this as a guide to control the production run’s length.

Cycle efficiency. Daily reports of yesterday’s results are informative, but they are a day too late. Managing efficiency requires...
instantly knowing if the plant is running to standard, and real-time cycle reporting again offers an exact control method. Here the standard cycle time is compared to the actual cycle time. A timer in the system calculates the length of each cycle and includes this information when reporting. The standard cycle time is commonly derived from part-costing data and then corrected for historical performance. The ratio of standard cycle time to actual cycle time, usually reported as a percentage, is the cycle efficiency. This number is a measure of the last cycle recorded; it is a rapid indicator of current production efficiency change. A useful variation is for the central computer to recognize when a node is not sending cycle data and is therefore not running.

Standard cycle weight. Just as standard cycle time is derived from part costing (corrected for historical performance), a standard cycle weight is similarly determined. Multiplying the standard cycle weight by the cycles executed estimates the amount of material consumed. Standard cycle weight multiplied by cycles remaining estimates the amount of material required to finish a run. These estimates are used as the basis for a simple inventory control system, or they are combined with a master schedule in the more sophisticated MRP or MRP II approaches. The difference is that MRP II plans for all manufacturing resources, while MRP strictly focuses on materials. The automatic cycle inputs, "clicks," are only indicators of machinery movement. For accurate inventory control, the real part weight is determined by the machine node with electronic weighing.

Adding intelligence. Although computer systems often plan production, systems to help fulfill that plan are relatively new. Several computer approaches were tried in the plastics industry, with varying degrees of effectiveness. A simple approach uses a spreadsheet that allows a scheduler to estimate job completions based on standard cycle times. A more refined approach continuously adjusts for cycle efficiency. When MRP/MRP II systems are used, schedules are often taken from the current state of the master plan. Development work is ongoing in this area to create "intelligent scheduling" or expert "management execution systems." To use these systems, a database of both machine and mold (die) characteristics is developed. An intelligent matching of molds to machines for a given production requirement is dynamically created. Text-based. The text-based form of an electronic plant management display creates a single line for each processing node. An indication of the type of production running, plus key run-control and efficiency figures, are shown. Various color arrangements are used to highlight run-control or efficiency problems. For example, running at 100% cycle efficiency may be green, running below 100% could be yellow, and a machine that is down could be indicated in red. Since it is important for this type of information to reach plant supervision, passive remote displays are frequently installed where they are visible to a shift leader. As graphical user interface (GUI) computers have become popular, many of these text-based screens now display icons that change color and/or shape to indicate a status change.

Printed plant management reporting has not developed in such a uniform manner, with most installations requiring uniquely formatted reports. In each area that data are processed, there are a variety of reports that classify results by machine, shift, mold, or material. Reporting systems need flexibility to create a custom report for each plant's management. An important aspect of the report is that it can summarize total productivity, and in subsequent details, it must provide clues to the location of manufacturing problems.

Determining return on investment for a central system. The argument that real-time information eliminates waste can be justified by determining an increase in total productivity. Total throughput for a fixed set of resources is evaluated to determine if the system has indeed increased the utilization of the fixed resources, thereby providing a benefit.

This task is difficult to initiate after a system is in place. A cleaner approach to system justification is to develop an enhanced set of productivity metrics before a central system is installed. Such metrics can include average efficiency based on standard hours (as previously described), equipment utilization, statistics (such as mean time between failures), processing-related metrics (such as mean time between alarms), average set-up time per job change, and work-in-process values. Once these metrics are developed, "before" and "after" plant performance is evaluated. These metrics then provide a basis for long-term continuous improvement. Management can establish productivity goals and use the central system as its instrument to measure progress.

Garbage inputs and the central plant computer system. There is an exactness to the design of a basic centralized plant management system. Two critical inputs provide the core information necessary for the automated system. These are the production standard, which in plastics is normally the standard cycle, and the productivity measurement, typically cycle time. Ensuring that these two inputs are correct virtually guarantees accurate system performance. Unfortunately, many users find that their systems are not effective; obtaining accurate standards and cycle information is more difficult than it appears.

The first encountered difficulty is that the completion of a machine cycle in plastic manufacturing does not necessarily represent the production of good parts. There are maintenance cycles, set-up cycles, and cycles that make inferior parts. Simple systems permit production counts that are manually corrected by an operator, a supervisor. Production count corrections are made on the machine, where a machine attendant recognizes that bad cycles have occurred, or it can occur at the central station, where the part inspection results adjust the balance-remaining figure. A large motivation in developing multiuser workstation systems was the desire to use statistical control techniques to qualify each cycle so that the machine node can report not simply that a cycle had occurred, but rather that a good or bad cycle had occurred. Systems...
that count parts and not cycles, such as weighing or photo cell systems, also attempt to better address the issue of automatically determining if a machine cycle is good or bad.

Another problem has developed for the most successful central system users. Continuous improvement goals cannot be indefinitely raised. There are physical limitations that prevent processes from becoming faster or more reliable. Neither part costing nor historical performance are necessarily indicators that a process limit has been reached. Management must benchmark its production capabilities. Process simulation software includes data-developed internally. Each family of plastic materials has specific processing equipment providers, and the other is to remain in contact with material distributors. Both of these groups will suggest the cycle times that are possible with their technologies. An improvement in processing technology can be theoretically justified, and then accurately determined, by a processor with a central system.

Benchmarking technology for plastic processors can also be developed internally. Each family of plastic materials has specific processing capabilities. Process simulation software includes databases with this information. When combined with machine and mold characteristics, simulation software can produce a process-based theoretical cycle time for a given set of material, machines, and molds. If the plant’s standards are significantly lower than the limits indicated by an accurate simulation system, an area for rapid improvement is identified. This methodology of improvement can be extended by improving the quality of the simulation techniques and its inputs.

**PROCESS MANAGEMENT SYSTEMS**

As process management has become prevalent, computerized systems were developed to automate tasks related to this discipline. One aspect of process management is its sharing of information among all groups associated with production. To implement systems that fulfill the needs of multiple departments, common data are made available for any requester. Low-cost PC networks are an effective platform for delivering this type of service to multiple users in a plastic production facility; these networks are connected to a central computer. Data collected from the plant floor and filed at the central computer, which now acts as a data server, provide a common resource that various departments can access. Since these needs are far more encompassing than production management, the shared and collected data are more comprehensive than the production-control-only systems. These systems take on features of a computer-integrated manufacturing (CIM) system; they are often referred to as CIM systems.

**Inputs**

Defining and collecting the information that relates to productivity and quality are essential to process management. From a computerization standpoint, this represents two forms of data that are entered into the system: measurements and transactions (events).

Measurements. Measurements are a straightforward extension of the work done by a machine node. In process management, however, there is interest not only in the results of the process, but in all of the factors that are causes in the process. By collecting data from all relevant causes and applying rules of statistical control and analysis, managers gain an understanding of the process and measure its results. They manufacture not only to produce parts, but also to learn how to better produce parts. This is not a simple task, because the parameters that affect plastic processing are highly interactive. At a minimum, the total process is broken into the following primary subprocesses:

- Plastication. Heating the plastic so it can flow.
- Filling. Flowing the plastic into or through a mold (die).
- Packing. Causing the plastic to conform to the required shape.
- Curing. Resolidifying the plastic into its new shape.

Times, pressures, and temperatures associated with each subprocess can be gathered by the machine node if adequate sensors and conditioning electronics are added. It is sometimes impractical to directly measure a primary parameter. Secondary parameters, which vary directly with primary parameters, are often substituted.

Table 19-3 lists examples of secondary parameters that are often more cost effective to measure.

An example of indirect measurement is pressure sensing. There is perhaps no better way to characterize a plastic-molding process than to monitor its in-cavity melt pressure performance. However, in production, this requires a sensor mounted during set-up into every mold (or built into every mold). This problem is compounded in multicavity molds. Table 19-3 lists two popular alternatives. There is no single parameter/sensor set that has gained universal acceptance in monitoring a plastic process. A secondary parameter may be appropriate for one material, while using another material in the same process yields data that are useless for process management. Another consideration is that not only must the parameter accurately analyze the process, an appropriate response alarm is also needed. Here the secondary parameters, which usually more directly reflect machine control settings, provide superior information because there is a clear adjustment for alarms.

Transactions. Each discrete production event that occurs is recorded as a transaction, occurring at a certain place and a certain time. While detailed parametric data are crucial for process analysis, actual management is more quickly performed with transaction data. Each occurrence of a parameter that is out of specification creates a transaction. Starting a new job is a transaction; a machine going down is a transaction. Changing the lot of processed material is a transaction. These transactions, sometimes called events, are difficult to collect automatically. As greater levels of automation are achieved, improved control systems report transactions through their serial communication facilities. Unfortunately, many nonautomated systems exist that cannot sense and report transactions automatically. Therefore, many machine nodes have been expanded to include bar code or keyboard entry capability to collect transactions. Floor personnel are then trained to enter coded information, which is collected by the central computer and analyzed by software available in the multiuser network.

**Analyzing Process Management Data**

An important step in working with a wide variety of process management data is to convert measurements to transactions by developing limits. Management can then focus on analyzing these transactions. At least one multiuser workstation must have the capability of analyzing data to establish upper and lower limits.

**TABLE 19-3**

<table>
<thead>
<tr>
<th>Primary Parameter</th>
<th>Secondary Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melt temperature</td>
<td>Plastication time and pressure</td>
</tr>
<tr>
<td>Plastic cavity pressure</td>
<td>Plastic nozzle pressure</td>
</tr>
<tr>
<td>Plastic nozzle pressure</td>
<td>Hydraulic pressure</td>
</tr>
<tr>
<td>Mold temperature</td>
<td>Conditioning fluid temperature</td>
</tr>
</tbody>
</table>
Three popular methodologies are used successfully in producing meaningful limits in plastic production. Managers use statistical control limits, process specification limits, and equipment capability benchmarks to provide these meaningful conversions.

Statistical control limits. Statistical control limits isolate the occurrence of something abnormal. These are often called "special causes" by those familiar with Deming’s terminology. A process has normal, or common, causes that create a standard level of process variation. Anything that exceeds this standard level of variance is an abnormal, or special, cause. Processes that are in statistical control are managed so they run without the occurrence of these special causes. When an alarm condition occurs, the appropriate response is to identify and remove the special cause, thereby allowing normal production to resume.

There are problems in implementing these techniques in plastic manufacturing. Determining practical process control limits for each mold and press combination has proven time consuming and expensive. The process often changes significantly each time a different part is produced. This can demand the dynamic development of control limits at the beginning of each production run. While this is a natural application for precontrol, it makes the more common statistical control techniques, such as X-bar and R charting, difficult. There is also widespread industry disagreement on the process parameters required to produce consistent parts. Plastic processors establish control limits based on process limit spreads of from 2–8 sigma (standard deviations). In addition, it is difficult for plastic processors to establish the appropriate statistical ground rules for isolating those special causes that affect plastic part quality.

An alternative approach to establishing process control limits is to use an absolute approach (that is, a plus/minus fixed temperature, time, or pressure) rather than to rely on a relative (sigma) approach. This absolute method recognizes that there exists a process function, such as that illustrated in Fig. 19-14, that describes a theoretical relationship between a monitored process parameter and a part specification. Since the part has a specific tolerance, a corresponding specific process tolerance, which only produces parts to specification, should also exist. If the process drifts outside of these limits, those parts are removed from production, and the process is corrected. While conceptually simple, the theoretical functions necessary to transform part specifications to process specifications are relatively complex. The typical approach to determining specification limits is an empirical one. Information is taken from the beginning of a production run. Rules are applied that compare the recorded range of parameter activity to the occurrence of parts that meet specifications. Process specification limits are then determined and applied to the rest of the production run.

An opportunity exists to integrate computer-aided engineering (CAE) systems with process management systems at this point. If the process has been designed with engineering analysis software, there is a theoretical basis for establishing process specification limits that produce good parts. Advanced users of both system types can take advantage of this by using the CAE results for specification limits.

Industrial experiments, and their associated techniques, can provide another theoretical approach to developing process specification limits. Computer programs can provide a design-of-experiments (DOE) method; this process minimizes the number of tests that are run to analyze an operation. These programs can also assist in developing the process function, as shown earlier in Fig. 19-14, once test results are known. Extremely simplified experimental designs, exclusive to plastic molding, known as molding area diagrams, are also present in industry literature. These techniques provide the mold with an area of processing parameter values that produce good parts.

Collecting performance data. A third approach to developing parameter limits is to disregard any consideration of the parts and use collected data to benchmark the consistency of machine performance. Plastic processors recognize that it is unrealistic to achieve consistency in plastic parts as long as there are inconsistencies in the processing equipment. Several published efforts document the establishment of equipment performance benchmarks. This benchmarking process requires collecting performance data of a significant population of machines that are producing good parts. Benchmarks extracted from these data indicate a best-to-worst consistency for a given type of machine. Maintenance departments can then apply the data collected by machine monitors to specific machinery benchmarks. Changes in equipment performance are then detected before they affect part quality. Management can also assign critical production only to machinery that is well maintained. However, since this approach does not consider the manufactured part, it is only used in conjunction with one of the other two methods to assure quality.

One advantage of the multiuser workstation architecture is that different departments can analyze the same set of data in different ways to convert the data into transactions. For example, a quality department may use process control limits, an engineering group may use process specification limits, while the maintenance department may evaluate machinery benchmarks. The same measurements produce different events for each group.

Assimilating the wide variety of manufacturing transactions that are collected is a daunting task. However, statistical control techniques appropriate for attribute analysis are applied to produce powerful analyses of transactional data. Departments on the multiuser network can access those transactions that relate to their responsibilities and use tools, such as Pareto charts, to focus efforts in appropriate directions. Transactional data also make linking floor data to higher-level systems, such as MES and MRP, very systematic. As process management techniques mature, less emphasis is placed on working with measurement information, and more emphasis is focused on using transactional data.

Multiuser Outputs

The multiuser architecture offers a rich set of video and printed outputs. Instead of passive displays, active terminals are available throughout the system to display current plant status and to allow dynamic analysis of current information. Various workstations are configured to provide different departments with specific displays and reports that best suit their needs. This is done by producing custom user interfaces for each department, or more elegantly, by using
a common icon-oriented executive information system that allows “drilling down” to any level of detail. Drilling down refers to a database technique where a summary figure is first displayed; the details behind each figure are displayed by selecting it and requesting the system to expand (drill down). In a similar fashion, an open data architecture allows many different network applications to produce a variety of reports from a single manufacturing database.

Return on the investment of a multiuser system. Unlike central or embedded computer systems, multiuser management computer systems cannot be justified with conventional accounting techniques. The expected payback from these systems is that all departments can increase their understanding of the manufacturing process, and with this understanding, work “smarter.” More commonly, upper management simply chooses to implement these systems or a quality-demanding customer requires this type of system. If a financial justification is required, the simplest approach is to highlight the system aspects that reflect the characteristics of a central or embedded computer system and to calculate its return based on this system as if it were one of those types. As activity-based costing develops in manufacturing, the accounting techniques needed to quantify the financial impact of superior process management may emerge.

Garbage collecting with multiuser system architecture. Process management systems are susceptible to processing garbage in or out. While they attempt to correctly quantify cycles so that the production count is not susceptible to the same error that simple cycle counters suffer, there remain specific problems to anticipate in maintaining the integrity of measurements and transactions. The quality of measurement data is especially critical if specifications are chosen to create specification limits rather than statistical control limits. With statistical control methods, measurement error is a common cause that is anticipated in the system variances. Therefore, statistical control methods create limits that only alarm when a special cause, whose variance is even greater than measurement error, occurs. However, in the case of specification limits, there is no compensation for measurement error. Because of this, the total measurement error created by sensors, signal conditioners, and conversion circuits must total some amount that is insignificant to the accurate repeatability of the process. Systems adequate for use in statistical process control are often applied unsuccessfully when used with process specification limits.

The transactions required to accurately control the process include many items that are typically entered manually. It is difficult to achieve high accuracy in manual entries unless there is some immediate benefit to those making those entries. Systems reporting only to management have little benefit for the floor personnel; therefore, the quality of their manual entries is often suspect.

Misusing system outputs. The largest failing of these systems is the misuse of their outputs. Good outputs are often wasted by the lack of automated responses. Manufacturing engineers have defined at least seven classes of manufacturing waste, from slow cycles to long set-up times. A most interesting type is the waste of waiting. The interesting aspect of this waste is that it is extremely visible; therefore, management has no tolerance for it.

A notable example of this is allowing assembly-line problems to stop the entire line. When a manual line can run without being shut down, that line is considered ready for full automation. Process management systems offer the same opportunities to stop plastic part production as soon as problems are detected. Early users found that since there was considerable waste created in trying to restart a plastic system, complete stoppages were not as easy as handling in assembly lines. However, a second response of automatically diverting product production (creating a visible waste) could be done without expensive restarts. The percentage of process management system users who will automatically stop or divert production is quite small. Instead, process abnormalities are frequently left in a report form only. During installation, these reports show productivity improvements as a result of the new system’s operation. However, since waste is not being converted into a visible waste, frequently the reports improve only because the wastes move into other forms. Over time, the reports of the process management system become less valuable as waste hides in manners that cannot be indicated on those reports.

PROCESS CONTROL SYSTEMS

The computer communication revolution has stretched from the office, across the plant floor, and into the very control structure of the processing equipment. The computer content of processing equipment has steadily grown for years. Solid-state sequence controls have replaced older relay circuits. Microprocessors were added to enable multiple-process control functions. Finally, the data collection nodes previously discussed are now common. These “islands of automation” distributed across the machinery are integrated by newly developed communication and integration schemes. As the integration becomes more complete, the primary control level of embedded computers will move from machine control to cell control.

Integrating Cell Inputs

Architectures for cell systems used in plastic part manufacturing have developed slowly. One factor that has slowed technology development is that computerization of machine control functions has safety implications. If there are problems in the control data, a malfunction may result in a damaging, or even fatal, incident. The large liability exposure that machinery and control manufacturers must face causes them to move cautiously.

Two strategies exist in developing a unified, PC-controlled machinery cell. The results are analogous to a stereo component system versus a single integrated music system. The argument for keeping sequence controls, process controls, and monitoring terminals separate is that certain custom components provide a higher level of quality. These components are integrated by allowing one of them to act as the cell’s master controller. The argument for the completely integrated single-component system is that it is less expensive, and the user interface is always contained in one area. Economics favor single-component, integrated controls in new equipment and the integration of separate components in upgrading existing machinery.

The Society of the Plastics Industry (SPI) created a common protocol to enable computer communications between a cell control and various auxiliaries. (A second phase of this protocol, which would enable communication of the central computer with the various molding machines, will soon be available.) The objective of this effort is to create an “Esperanto” computer communication protocol that is not favorable to any specific equipment supplier. With it, plastic processors could build cells from SPI-compliant devices from various suppliers. Fully integrating multiple components would be a much simpler task.

As an alternative to using an industry-specific protocol, such as SPI’s, cell architecture can be based on control protocols developed by sequence control manufacturers. Each major supplier has such a protocol, with a large number of auxiliary suppliers that offer compliance to the proprietary protocol. The issue of control integration is rapidly becoming important.
CHAPTER 19
COMPUTERS AS MANAGEMENT TOOLS

Processing Cell Control Data

A primary reason to develop a cell is to create superior plastic-processing capability. In addition to coordinating the movement of work through the processing center, advanced cell controls provide an aspect of superior process control. For example, in injection molding, superior ram control can provide improvements in plastication, fill, and pack. In blow molding, improved parison programming can result in more precise control over part weights. A much-desired byproduct in developing plastic-processing cells is that, as plastic parts are produced on faster and steadier equipment, the parts automatically improve in quality.

Prompted control strategies. In addition to automated (closed-loop) process control strategies, cell controls can enable prompted control strategies. In these methodologies, an operator is prompted by the computer to make corrections to an aspect of the process that is not economically feasible to automate. The importance of the prompt is that it occurs before the process reaches a limit, and that the process can continue running without producing defective parts. Statistical precontrol is one method used to implement prompted controls at the cell level. In this technique, precontrol limits are placed inside the specification limits, and statistical rules are used to determine when data outside of these precontrol limits (but still inside specification) represent the process drifting. The cell control warns the operator of the potential problem and may also provide a graphic analysis of the machine’s performance so that an adjustment can be made.

Self-optimization. Self-optimization is another potential cell control feature. Computer algorithms exist that can seek an optimal setting for a group of inputs based on a certain goal. This goal can be a single item, such as minimum part weight or cycle time, or it can be a form of Taguchi loss function with many parameters. Automatic measurements of each cycle’s results are returned to the cell controller, and minor adjustments are made to the set-up to seek an optimum result. These algorithms are proven in other industries. The challenge is to make them viable in plastics, where it is often difficult to determine quality immediately at the processing site.

Cell Reporting

There is virtually no paper reporting from embedded computers in plastic-processing equipment. The machine-terminal function of the computer reports data to a central computer if it is networked to one with information that is to be printed. The primary outputs are to the processing equipment itself, in the case of a closed loop, and to the floor attendants, in the case of prompted control. Prompted screens focus personnel on immediate process management issues. They also assist by displaying the type of historical and analytical information that is available on the multiuser network displays. An important aspect of this on-machine analysis capability is the resulting improvement in the manual entry of transaction data. As previously mentioned, when there is no benefit to the person entering data, there is often a loss of input. However, where on-machine PC’s provide immediate analytical information to the floor personnel, there is a data entry benefit to them and, therefore, enhanced motivation to ensure that all significant information is correctly presented to the system.

Justification of Cell Controllers

This architecture is the most expensive on a per-machine basis. However, it is also the easiest to justify. From its infancy, the plastics industry has recognized the economic benefit of improving the process. Cost accounting systems are oriented toward determining the value of purchasing equipment that reduces part costs. Value added is easily determined by comparing the cost of parts produced per time period in an older process versus a new one. The value of this increase is divided into the cost of the cell to determine a specific payback period.

Garbage Control

The embedded PC has processing capabilities that often advance faster than the mechanical characteristics of the equipment it is controlling. Balancing advanced computer algorithms to the capabilities of the mechanisms attached to them is a critical issue in the design and implementation of cell controls. For example, increasing the resolution of pressure control by a factor of ten is a simple matter for a computer programmer. The data fields are simply expanded to include an additional digit. However, making the hydraulic or mechanical system (that controls the pressure) operate ten times more accurately is more complex.

CONCLUSIONS

The framework that was developed here to define the characteristics of various plant management computer systems is in many respects arbitrary. A review of central computer systems reveals a need for the part-qualification data and the distributed reporting of multiple workstation systems. These systems have limited functions without extending their capabilities by embedding computers in the process equipment. While embedded controllers run well in a stand-alone mode, it is difficult to manage a large plant with information reported across the floor, and networking to a central computer becomes attractive. One architectural style inevitably creates needs addressed by the next. The final evolution of these systems is complete computer-integrated manufacturing (CIM).

References

Bibliography


Belt, B., "MRP and Kanban - A Possible Synergy?" *Production and Inventory Management* (1st Quarter, 1987).


Foster, L. W., *Modern Geometric Dimensioning and Tolerancing, with Workbook Section* (Ft. Washington, MD: National Tooling and Machining Association, 1982).


Stamatis, D. H., *ISO 9000: The Road to Quality Improvement* (Southgate, MI: Contemporary Consultants Co.)

PROFESSIONAL ORGANIZATIONS AND RESOURCES

Please note: any omissions are not intentional and information is subject to change.

UNITED STATES


American Mold Builders Association, 701 E. Irving Park Road, #207, Roselle, IL 60172, Phone: (708) 980-7667, Fax: (708) 980-9714. Promotes the development, welfare, and expansion of businesses engaged in the manufacture of molds and related tooling. Publications: AMBA Membership Directory, annual; quarterly News & Views.

American Plastics Council, 1275 K St. N.W., Suite 500, Washington, DC 20005, Phone: (202) 371-5319, (800) 243-5790, Fax: (202) 371-5679.

American Society of Electroplated Plastics, Inc., 1767 Business Center Drive, Suite 302, Reston, VA 22090, Phone: (703) 438-8292, Fax: (703) 438-3113. Firms engaged in the manufacture, sale, and/or development of equipment, materials, processes, or provision of services to the electroplating on plastics industry. Publications: ASEPN News and Views, quarterly; annual membership directory; Standards and Guidelines for Electroplated Plastics.

American Society for Plasticulture, P.O. Box 860238, St. Augustine, FL 32086, Phone: (904) 829-0754. Advances agriculture through the use of plastics. Conducts research and education programs. Affiliated with International Committee of Plastics in Agriculture. Publications: Agri-Plastics Report, bimonthly; Proceedings of National Congresses, periodic.


Association of the Nonwoven Fabrics Industry, 1001 Winstead Dr., Suite 460, Cary, NC 27513, Phone: (919) 677-0060, Fax: (919) 677-0211. Primary and secondary manufacturers and marketers of nonwoven fabrics; suppliers of raw materials; institutions and manufacturers of machinery. Funds research. Publications: IDEA Conference Papers, biennial; INDA-TEC: The International Nonwovens Technological Conference, annual.

Association of Rotational Molders, 2000 Spring Road, Suite 511, Oak Brook, IL 60521, Phone: (708) 571-0611, Fax: (708) 571-0616. Distributes technical literature and educational material about rotational molding. Annually conducts a technical conference and exhibition at which the latest developments in rotational molding are displayed. Publications: ARM Roster, annual; membership directory.

Center of Excellence for Composites Manufacturing Technology, 8401 Lakeview Parkway, Suite 200, Kenosha, WI 53142-7403, Phone: (414) 947-8900, Fax: (414) 947-8919.

Chemical Fabrics and Film Association, 1300 Summer Avenue, Cleveland, OH 44115, Phone: (216) 241-7333, Fax: (216) 241-0105. Manufacturers of chemically coated materials, supported and unsupported vinyl, and urethane materials. Publications: Chemical Fabrics and Film Association Directory, annual.

Composites Fabricators Association, 1735 N. Lynn St., Suite 950, Arlington, VA 22209, Phone: (703) 524-3332, Fax: (703) 524-2303. Companies engaged in the hand layup or sprayup of fiberglass in open molds or engaged in filament winding or resin transfer molding. Publications: Association Update, bimonthly; Fabrication News, monthly; Membership Directory/Buyers Guide, annual; News, monthly.

Composites Manufacturing Association of SME, Society of Manufacturing Engineers, One SME Drive, P.O. Box 930, Dearborn, MI 48121-0930, Phone: (313) 271-1500, Fax: (313) 271-2861. CMA/SME’s primary goal is to provide manufacturing professionals with information on processes and applications for composites design, tooling, assembly, producibility, supportability, and future trends in materials and hardware. Technical referral database, electronic bulletin board. Computer-Aided Process Selector software. Publications: Manufacturing Engineering, monthly; Composites Manufacturing, quarterly.

Decorative Laminate Products Association, 13924 Braddock Road, Suite 100, Centreville, VA 22020, Phone: (800) 684-3572, Fax: (703) 222-6180. Manufacturers of residential, commercial, and industrial goods using high-pressure decorative plastic laminate and solid surface materials. Publications: DLPA News, quarterly; annual membership directory.


International Cast Polymer Association (formerly the Cultured Marble Institute), 1735 N. Lynn St., Suite 950, Arlington, VA 22209, Phone: (703) 276-2644, Fax: (703) 524-2303. Promotes the merits of cast polymer products. Develops and promotes industry-wide standards of product quality and acceptability. Works to develop reliable industry-wide market data. Publications: Cast Polymer Connection, bimonthly; ICAP—Membership/ Product Directory, annual.

National Association for Plastic Container Recovery, 3770 Nations Bank Corporate Center, 100 N. Tryon St., Charlotte, NC 28202, Phone: (704) 358-8882, Fax: (704) 358-8769. Seeks to facilitate the economic recovery of PET plastic containers through collection, reclamation, and development of end-use markets. Provides technical, marketing, and promotional support for plastics recycling programs. Publications: Environmental Impact of Soft Drink Delivery Systems; PET Market List, three/year; PET...
Projects, quarterly; PET Recycling: A Model Solution, video; PET Tech, quarterly; Recycling PET: A Guidebook for Community Programs; Recycling Plastic Containers.

National Recycling Coalition, 1727 King St., 1st Fl., Alexandria, VA 22314, Phone: (703) 683-9025. Individuals and environmental, labor, and business organizations united to encourage the recovery, reuse, and conservation of materials and energy, and to make the benefits of recycling more widely known. Publications: Federal Legislation in 102nd Congress; Measurement Standards and Reporting Guidelines; Multifamily/Apartment Recycling; National Policy on Recycling; NRC Connection, bimonthly newsletter; Proceedings, annual; Rural and Small Town Recycling.


Plastics Institute of America, Inc., 277 Fairfield Rd., Suite 307, Fairfield, NJ 07004, Phone: (201) 808-5950, Fax: (201) 808-5953. Educational and research organization supported on a cooperative basis by companies in the plastics and allied industries. Publications: Catalog of Polymer Science, biennial; Proceedings of ConstructionPlas '92; Proceedings of FoodPlas Conferences, annual; Proceedings of RecyclingPlas Conferences, annual.

Plastics Molders & Manufacturers Group of SME, Society of Manufacturing Engineers, One SME Drive, P.O. Box 930, Dearborn, MI 48121-0930, Phone: (313) 271-1500, Fax: (313) 271-2861. Provides information on the process of building or molding products using plastic materials. Addresses concerns of SME's traditional metalworking members who must incorporate plastic components and environmental issues. Technical referral database, electronic bulletin board. Publications: Manufacturing Engineering, monthly.


Polymer Processing Institute, Stevens Institute of Technology, Castle Point, Hoboken, NJ 07030, (201) 216-5019. Facilitates academic-industry cooperation in polymer processing research and the advancement and rapid transfer of scientific knowledge in all aspects of polymer processing technology. Publications: Advances in Polymer Technology, quarterly; annual report.

Polyurethane Foam Association, P.O. Box 1459, Wayne, NJ 07470, Phone: (201) 633-9044, Fax: (201) 628-3086. Manufacturers of flexible polyurethane foam; suppliers of goods and services to the industry. Provides a forum for discussion of industry issues and makes current information available to members. Publications: INFORMATION, bimonthly, INTOUCH, quarterly. Semiannual technical and business meeting.

Society for the Advancement of Material and Process Engineering, P.O. Box 2459, Covina, CA 91722, Phone: (818) 331-0616, Fax: (818) 332-8929. Material and process engineers, scientists, and other professionals engaged in development of materials and processing technology in airframe, missile, aerospace, propulsion, electronics, life sciences, management, and related industries. Publications: SAMPE Journal, bimonthly; SAMPE Quarterly.

Society of Plastics Engineers, 14 Fairfield Drive, Brookfield, CT 06804-0403, Phone: (203) 775-0471, Fax: (203) 775-8490. Professional society of plastics scientists, engineers, educators, students, and others interested in the design, development, production, and utilization of plastics materials, products, and equipment. Conducts seminars. Publications: Journal of Vinyl Technology, quarterly; Plastics Engineering, monthly; Plastics Engineering Services, book; Polymer Composites, bimonthly; Polymer Engineering and Science, semimonthly.


Society of Vacuum Coaters, 440 Live Oak Loop, Albuquerque, NM 87122, Phone: (505) 856-7188, Fax: (505) 856-6716. For persons and groups interested in the vacuum coating process. Sponsors educational programs and equipment exhibits. Publications: annual membership directory; Products and Services Directory, annual; SVC Conference Proceedings, annual; SVC News Bulletin, quarterly.

Society for Women in Plastics, P.O. Box 775, Sterling Heights, MI 48311-0775, Phone: (313) 365-6060, Fax: (313) 365-8080. Women with education or employment experience in the field of plastics or related businesses. Promotes knowledge of the plastics industry. Conducts plants tours; operators speakers' bureau.

SPI Composites Institute, c/o Society of the Plastics Industry, 355 Lexington Avenue, New York, NY 10017, Phone: (212) 351-5410, Fax: (212) 370-1731. Molders and fabricators of glass and other fiber reinforced plastics; materials and equipment suppliers; consultants and users of fiberglass/composite products. Computer database. Publications: Annual Technical Conference Proceedings; Awards of Excellence; bimonthly CI on Composites; Industry Report, annual; Introduction to Composites; Literature Catalog; users guides, glossaries, and technical materials.

Technical Association of the Pulp and Paper Industry, Technology Park/Atlanta, P.O. Box 105113, Atlanta, GA 30348-5113, Phone: (404) 446-1400, (800) 332-8868, Fax: (404) 446-6947. Conducts conferences and develops testing methods for the pulp, packaging, converting, paper, nonwovens, and allied industries. Reference library with 2,200 books, periodicals, audiovisuals, monographs, archival material. Online and catalog computer service. Publications: Catalog; membership directory; proceedings; TAPPI Journal, monthly; also publishes test methods, technical information sheets, training aids, and home study courses.

ALGERIA

National Enterprise of Plastics and Rubber, Entreprise Nationale Des Plastiques Et Caoutchoucs, BP 452-453 Zone Industrielle, Setif 19000, Phone: (213) 590 81 57, Fax: (213) 590 06 65, Telex: 86040/86030.

ARGENTINA

Argentine Chamber of the Plastics Industry, Camara Argentina de la Industria Plastica, Jeronimo Salguero 1939/41, 1425 Buenos Aires, Phone: (54) 1-821 96 0, Fax: (54) 1-826 54 80, Telex: 9900.
AUSTRALIA

Plastics Industry Association, Inc., 41-43 Exhibition Street, Melbourne, Victoria 3000, Phone: (61) 3-654 2199, Fax: (61) 3-654 2384.

AUSTRIA

Austrian Chemical Industries Federation, Fachverband der Chemischen Industrie Österreichs, Wiedner Hauptstrasse 63, PO. Box 325, 1045 Vienna 4, Phone: (43) 1-50105 33, Fax: (43) 1-50206 280.

National Guild of Plastics Processors, Bundesinnung der Kunststoffverarbeiter, Wiedner Hauptstrasse 63, 1045 Vienna, Phone: (43) 1-50105 32, Fax: (43) 1-50206 291.

BELGIUM

European Plastics Converters, Av. de Cortenbergh 66, 1040 Brussels, Phone: (32) 2-732 4124, Fax: (32) 2-732 4218.

Plastics Manufacturers and Plastics Processors, 49 Square Marie-Louise, 1040 Brussels Phone: (32) 2-238 97 1, Fax: (32) 2-231 13 01, Telex: 23167.

Association of Plastics Manufacturers in Europe, Av. E. Van Nieuwenhuyse 4, Box 3, 1160 Brussels, Phone: (32) 2-675 32 9, Fax: (32) 2-675 3935.

European Organization of Reinforced Plastics/Composite Materials, Rue des Drapiers 21, 1050 Brussels, Phone: (32) 2-510 25 0, Fax: (32) 2-510 25 62.

European Association of Flexible Polyurethane Foam Blobs Manufacturers, c/o FIC Square Marie-Louise 49, 1040 Brussels, Phone: (32) 2-238 97 1, Fax: (32) 2-231 13 01, Telex: 23167.

Liaison Bureau of the Rubber Industries, Bureau de Liaison des Industries du Caoutchouc, 2, Avenue des Arts, 1040 Brussels, Phone: (32) 2-218 4940, Fax: (32) 2-218 6162.

Belgian Reinforced Plastics Association, Rue des Drapiers 21, 1050 Brussels, Phone: (32) 2-510 25 0, Fax: (32) 2-510 25 62.

Association of Belgian Plastics Converters (Fabrimetal Group 18), Rue des Drapiers 21, 1050 Brussels, Phone: (32) 2-510 25 0, Fax: (32) 2-510 25 62.

Belgian Association of Manufacturers of Technical Plastic Components, Rue des Drapiers 21, 1050 Brussels, Phone: (32) 2-510 25 0, Fax: (32) 2-510 25 62.

Belgian Association of Manufacturers of Extruded Thermoplastic Pipes, Rue des Drapiers 21, 1050 Brussels, Phone: (32) 2-510 25 0, Fax: (32) 2-510 25 62.

BOLIVIA

ANIPLAST c/o Plasmar, Casilla 942, La Paz, Fax: (591) 2-850 581.

BRAZIL

The Plastics Materials Association, Avenida Paulista 2439 8 andar, 01311 Sao Paulo SP, Phone: (55) 11-282 82 82, Fax: (55) 11-282 80 42, Telex: 1134101.

National Institute of Plastics, Instituto Nacional do Plastico, Avenida Paulista 1313 cj. 702, Sao Paulo SP, Phone: (55) 11-2896287, Fax: (55) 11-289 6287.

CANADA

Environment & Plastics Institute of Canada, 1262 Don Mills Road, Suite 104, Don Mills, Ontario M3B 2W7, Phone: (416) 449-3444, Fax: (416) 449-5685.

Society of the Plastics Industry of Canada, 1262 Don Mills Road, Suite 104, Don Mills, Ontario M3B 2W7, Phone: (416) 449-3444, Fax: (416) 449-5685.

CHILE

Chilean Plastics Association, Associacion Gremial de Industriales del Plastico, Casilla 14610, Avda Pedro de Valdivia 1481, Santiago, Phone: (56) 2-274 93 1, Fax: (56) 2-223 45 40, Telex: 340412.

COLOMBIA

Colombian Association of Plastics Industries, Associacion Colombiana de Industrias Plasticas, Calle 69 No 5-33, Santafe de Bogota, Phone: (57) 1-255 2139, Fax: (57) 1-255 2317.

COSTA RICA

Costa Rican Association of the Plastic Industry, Asociacion Costarricense de la Industria del Plastico, Apartado 8247, 1000 San Jose, Phone: (506) 55 09 61, Fax: (506) 55 09 61.

CYPRUS

The Cyprus Plastics Processory Association, P.O. Box 1455, Nicosia, Phone: (357) 2-449 500, Fax: (357) 2-367 939, Telex: 2077.

DENMARK

Plastics Industries of Denmark, Plastindustrien Danmark, Radhuspladsen 55, 1550 Copenhagen, Phone: (45) 331 33 022, Fax: (45) 339 10 898.

Rubber Fabricators Society, Gummifabrikantforeningen, Hestehaven, 5260 Odense 5, Phone: (45) 661 15 515, Fax: (45) 659 12 394, Telex: 59873.

ECUADOR

Ecuadorian Association of Plastics, Asociacion Ecuatoriana de Plasticos, c/o Polimalla SA, Via a Daule, km. 9.5, Casilla postal 10830, Guayaquil, Phone: (593) 4-253 850, Fax: (593) 4-253 850, Telex: 253 833, Telex: 253 834.

FINLAND

The Finnish Plastics Industries Federation, Suomen Muoviteollisuusliitto Etelaranta 10, 7th floor, PO. Box 4, 00131 Helsinki, Phone: (358) 0-17 28 4, Fax: (358) 0-17 11 64.

The Rubber Manufacturers’ Association of Finland, Kumiteollisuusyhdistys, Talleberginkatu 2B, 00180 Helsinki, Phone: (358) 0-6932 41, Fax: (358) 0-6946 289.

FRANCE

The French Plastics Industries Federation, 92038 Paris La Defense Cedex 72, Phone: (33) 1-47 17 63, Fax: (33) 1-47 17 63 60.
APPENDIX A

International Committee of Plastics in Agriculture, 65, rue de Prony, 75854 Paris Cedex 17, Phone: (33) 1-47 63 12, Fax: (33) 1-47 64 11 25.

National Syndicate of Rubber, Plastics and Associated Industries, Syndicat National du Caoutchouc, des Plastiques et des Industries qui s’y Rattachent, 60, rue Auber, 94408 Vitry sur Seine, Phone: (33) 49 60 57 5, Fax: (33) 45 21 03 50, Telex: 265 560.

Society for the Studies and Development of Rubber Industries, Société D’études et de Développement des Industries du Caoutchouc, 60, rue Auber, 94408 Vitry sur Seine Cedex, Phone: (33) 49 60 57 5, Fax: (33) 45 21 03 50, Telex: 265 560.

Laboratory of Research and Control of Rubber, Laboratoire de Recherche et de Controle du Caoutchouc, 60, rue Auber, 94408 Vitry sur Seine, Phone: (33) 49 60 57 5, Fax: (33) 46 60 70 66, Telex: 265 560.

National Institute of Professional Teaching of Rubber, Institut National de Formation et D’enseignement Professionnel de Recherche et de Controle du Caoutchouc, 60, rue Auber, 94408 Vitry sur Seine, Phone: (33) 49 60 57 5, Fax: (33) 49 60 70 66, Telex: 265 560.

European Manufacturing Association of Ruban Auto Adhesives, Association des Fabricants Européens de Ruban Auto-Adhésifs, 60, rue Auber, 94408 Vitry sur Seine, Phone: (33) 49 60 57 5, Fax: (33) 45 21 03 50, Telex: 265 560.

GERMANY

German Machinery and Plant Manufacturers Association, PO. Box 71 08 64, 60498 Frankfurt, Phone: (49) 69-660 38, Fax: (49) 69-660 38 40.

European Group of Manufacturers of Plastics Technical Parts, Am Hauptbahnhof 12, 60329 Frankfurt, Phone: (49) 69-27 105, Fax: (49) 69-23 98 36, Telex: 411122.

GREECE

Hellenic Plastics Industries Association, 66, Michalakopoulou, 115 28 Athens, Phone: (30) 1-77 94 51, Fax: (30) 1-77 94 518.

HONG KONG

Federation of Hong Kong Industries, Hankow Centre, 4th fl, 5-15 Hankow Rd, Tsim Sha Tsui, Kowloon, Hong Kong, Phone: (852) 723 08 18, Fax: (852) 721 34 94.

Hong Kong Plastics Manufacturers Association Ltd., 1/F, Flat B, Fo Yuen, 39-49 Wanchai Road, Wanchai, Hong Kong, Phone: (852) 574 22 30, Fax: (852) 574 28 43.

Hong Kong Plastics Material Suppliers Association Ltd., 1/F, 11 Lai Yip Street, Kwun Tong, Kowloon, Hong Kong, Phone: (852) 757 93 31, Fax: (852) 796 88 85.

The Chi Chau Plastics Manufacturers Association Co. Ltd., Rm 603, Fu Hing Bldg, 9-11 Jubilee Street, Hong Kong, Phone: (852) 545 03 84, Fax: (852) 545 05 39.

Hong Kong & Kowloon Plastic Products Merchants United Association Ltd., 13/F, 491 Nathan Road, Kowloon, Phone: (852) 384 01 71, Fax: (852) 781 01 07.

Hong Kong Plastics Technology Centre Co. Ltd., c/o Rm U 509, Hong Kong Polytechnic, Hung Hom, Kowloon, Phone: (852) 766 55 77, Fax: (852) 766 01 31.

HUNGARY

Plastics Industry Association, Muanyagipari Szakszovetseg, Erzsébet Királyne utja 1/c, P.O. Box 40, 1406 Budapest, Phone: (36) 1-142 07 5, Fax: (36) 1-142 09 80.

INDIA

The All India Plastics Manufacturers’ Association, Jehangir Bldg, 3rd floor, 133, Mahatma Gandhi Road, 400 023 Bombay, Phone: (91) 22-27 39 8, Fax: (91) 22-27 77 09.

Organization of Plastics Processors of India, Leo House, Ground Floor, 88-C, Old Prabhadevi Rd, Bombay 400 025, Maharashtra, Phone: (91) 22-43 05 1, Fax: c/o ID (91) 22-43 06 022.

Plastindia Foundation, 2, Leela Apt., 355 S.V. Rd, Vile Parle W, Bombay 400 056, Phone: (91) 22-837 05, Fax: (91) 22-837 59 09, Telex: 1179395.

INDONESIA

Indonesian Plastics Industry Association, Asosiasi Industri Plastik Indonesia, Jl. Kesatriaan I no 25, Matraman, Raya, Jakarta Timur 13150, Phone: (62) 21-858 32.

IRAQ

Iraqi Federation of Industries, Federal Bldg., Khullani Square, P.O. Box 5665, Baghdad, Phone: (964) 1-888 0091, Fax: (964) 1-888 2305, Telex: 212776.

ISRAEL

Society of Israel Plastics and Rubber Industry, 29 Hamered Street, P.O. Box 50022, 61500 Tel-Aviv, Phone: (972) 3-512 884, Fax: (972) 3-662 026.

ITALY

Italian Plastics and Rubber Processing Machinery and Mold Manufacturers’ Association, P.O. Box 24, 20090 Assago (MI), Phone: (39) 2-575 1270, Fax: (39) 2-575 12490, Telex: 341378.


National Union of the Plastics Processing Industry, Unione Nazionale Industrie Transformatrici Materie Plastiche, Via Petitti 16, 20149 Milano, Phone: (39) 2-392 1042, Fax: (39) 2-392 66548.

Assogomma, Via S. Vittore 36, 20123 Milano, Phone: (39) 2-498 8168, Fax: (39) 2-435 432.

Assoplast, c/o Federchimica, Via Accademia 33, 1-20131 Milano, Phone: (39) 2-268 101, Fax: (39) 2-268 10311, Telex: 332488.

JAPAN

The Japan Plastics Industry Federation, Tokyo Club Bldg, 3-2-6, Kasumi-gaseki, Chiyoda-ku, Tokyo 100, Phone: (81) 3-3580 077, Fax: (81) 3-3580 0775.

Plastic Waste Management Institute, Fukide Bldg, 1-13, 4 chome, Toranomon, Minato-ku, Tokyo 105, Phone: (81) 3-3437 225, Fax: (81) 3-3437 5270.

Japan PET Bottle Association, Fukide Bldg 1-13, 4 Cho-me, Toranomon, Minato-ku, Tokyo 105, Phone: (81) 3-3437 225, Fax: (81) 3-3437 1313.

Japan Expanded Polystyrene Recycling Association, Fax Bld 2-20, Kandasakuma-cho, Chiyoda-ku, Tokyo 101, Phone: (81) 3-3861 904, Fax: (81) 3-3861 0096.

Japan Polystyrene Foamed Sheet Industry Association, Tokon Bldg. 26 Higashikonya, Chiyoda-ku, Tokyo 101, Phone: (81) 3-3257 333, Fax: (81) 3-3257 3339.
KOREA

Korea Plastic Industry Corp., 146-2, Saangnim-dong, Chung-ku, Seoul 100-400, Phone: (82) 2-275 7991, Fax: (82) 2-277 5150, Telex: 26302.
Korea Reclaimed Plastic Industry Corp., 94-121, Youngdeungpo-dong, Youngdeungpo-ku, Seoul 150-020, Phone: (82) 2-677 0331, Fax: (82) 2-671 6136.

LEBANON

General Syndicate of Plastics Materials Processors, Syndicat General des Transformateurs des Matieres Plastiques, P.O. Box 11, 6635 Beirut, Phone: (961) 1-86 06 9, Fax: (961) 1-2124 781 532, Telex: 21760.

MALAYSIA

Malaysian Plastics Manufacturers Association, 37, Ground Floor, Jalan 20/14, Paramount Garden, 46300 Petaling Jaya, Phone: (60) 3-776 3027, Fax: (60) 3-776 8352.

MALTA

Malta Federation of Industry, Development House, St. Anne Street, Floriana, VLT 01, Phone: (356) 22 20 74, Fax: (356) 24 07 02.

MEXICO

National Association of Plastics Industries, Asociacion Nacional de Industrias del Plasticos A.C., Dr. Vertiz no 546, Col. Narvarte, Deleg. Benito Juarez, 03020 Mexico DF, Phone: (52) 5-566-7466, Fax: (52) 5-519-8526.
National Chamber of Processing Industries, Camara Nacional De La Industria De La Transformación, Phone: (52) 5-515 6356, Fax: (52) 5-277 4926.

NEW ZEALAND

The Plastics Institute of New Zealand, Level 4, Manukau City Centre, Auckland, Phone: (64) 9-262 3773, Fax: (64) 9-262 3850.
Composites Association of New Zealand, Inc., 5 Balmacewen Rd, P.O. Box 12-003, Dunedin, Phone: (64) 3-467 2514, Fax: (64) 3-467 2514.

THE NETHERLANDS

Union of the Metal and Electrotechnical Industry, Vereniging Metaal en Elektrotechn. Industrie, Boerhaavelaan 40, 2713 HX Zoetermeer, Phone: (31) 79-53 11 0, Fax: (31) 79-53 13 65, Telex: 32157.

SWITZERLAND

European Committee of Machinery Manufacturers for the Plastics and Rubber Industries, c/o VSM, Kirchenweg 4, 8032 Zurich.
Zurich, Phone: (41) 1-384 4844, Fax: (41) 1-384 4848, Telex: 816519.

Swiss Plastics Association, Kunstraumverband Schweiz, Schachenallee 29, 5000 Aarau, Phone: (41) 64-23 08 6, Fax: (41) 64-23 07 62.

Association of Swiss Rubber and Thermoplastic Industries, Verband Schweizerischer Gummi- und Thermoplast-Industrieller, Schachenallee 29, 5000 Aarau, Phone: (41) 64-23 09 7, Fax: (41) 64-23 07 62.

Union of Swiss Machine Manufacturers, Verein Schweizerischer Maschinen Industrieller, Kirchenweg 4, 8032 Zurich, Phone: (41) 1-384 4844, Fax: (41) 1-384 4848, Telex: 816519.

TAIWAN
Taiwan Plastics Industry Association, 8F, 162 Chang-An East Rd, Sec. 2, Taipei, Phone: (886) 2-771 911, Fax: (886) 2-731 5020.
Taiwan Association of Rubber Industries, 7, Ningpo East St., Taipei, Phone: (886) 2-351 226, Fax: (886) 2-341 2691.
Taiwan Synthetic Resins Manufacturers Association, 4F, 82 Chienkuan N. Rd, Sec. 2, Taipei, Phone: (886) 2-504 087, Fax: (886) 2-504 0883.
Taiwan Regional Association of Synthetic Leather Industries, 5F, 30 Nanking W. Rd, Taipei, Phone: (886) 2-559 020, Fax: (886) 2-559 8823.

THAILAND
The Thai Plastics Industries Association, 127/2 Payamai Road, Somdej Chaopraya, Klongsarn, Bangkok 10600, Phone: (66) 2-438 9457, Fax: (66) 2-437 2850.

Plastic Industry Club, The Federation of Thai Industries, 394/14 Samsen Road, Dusit, Bangkok 10300, Phone: (66) 2-2800 951, Fax: (66) 2-2800 958-9, Telex: 72202.

TUNISIA
The Syndicate Chamber of Plastic, Chambre Syndicale du Plastique, 17, rue Abderrahman El Zaziri, 1002 Tunis, Phone: (216) 1-791 882, Fax: (216) 1-790526.

TURKEY

Turkish Industrialists' Foundation for Research, Development and Education, Page-Turk Plastik Sanayicileri Arasirma Gelistirme ve Egitim Vakfi, 9-10, Kisim, S-1 C Blok, Daire 63, Alakoy/Istanbul, Phone: (90) 1-560 4397, Fax: (90) 1-560 6749.

UNITED KINGDOM
The British Plastics Federation, 6, Bath Place, Rivington Street, London EC24 3JE, Phone: (44) 71-457 500, Fax: (44) 71-457 5045.

The Institute of Materials, 1 Carlton House Terrace, London SW1Y 5DB, Phone: (44) 71-976 133, Fax: (44) 71-839 2078, Telex: 8814813.

Plastics Machinery Distributors Association Ltd., P.O. Box 1414, Dorchester, Dorset DT2 8YH, Phone: (44) 305-25 00, Fax: (44) 305-25 09 96.

British Rubber Manufacturers’ Association, 90 Tottenham Court Rd, London W1P OBR, Phone: (44) 71-580 279, Fax: (44) 71-631 5471.

European Resin Manufacturers’ Association, Queensway House 2, Queensway, Redhill/Surrey RH1 1QS, Phone: (44) 737-75 86, Fax: (44) 737-75 61 85, Telex: 948669.

British Independent Plastic Extruders Association, 89 Cornwall Street, GB-Birmingham B3 3BY, Phone: (44) 21-236 186, Fax: (44) 21-200 1389.

British Laminated Plastic Fabricators Association, 6, Bath Place, Rivington Street, London EC2A 3JE, Phone: (44) 71-457 500, Fax: (44) 71-457 5045.

Rubber Consultants, Brickendonbury, Hertford SG13 8NL, Phone: (44) 992-554 65, Fax: (44) 992-554 837.

URUGUAY
Uruguayan Association of Plastic Industries, Asociacion Uruguaya de Industrias del Plastico, Av. Libertador 1672, 11100 Montevideo, Phone: (59) 82-91 50 0, Fax: (59) 82-92 25 67.

VENEZUELA
Venezuelan Association of Plastics Industries, Asociacion Venezolana de Industrias Plasticas, Av. Principal, Urbanizacion, Macaracuy, Multicentro, Macaracuy, Caracas 1070, Phone: (58) 2-256 33 4, Fax: (58) 2-256 28 67, Telex: 21509.

Venezuelan Bureau of Small and Medium Plastic, Rubber, and Related Industries, Cavenpla-Camera Venezolana de la Pequena y Mediana Industria del Plastico, Gomas y Afines, Av. Principal de La Cooperativa, Qta. Maria Elisa, Detras de Malariologia, Maracay 2101, Estado Aragua, Phone: (58) 43-41 542, Fax: (58) 43-41 70 63.
GLOSSARY

absorptance The fraction of radiation retained by a specimen after exposure.
accelerated aging A process that increases the rate of environmental conditions and reduces the material's expected lifespan.
accelerated weathering Laboratory exposure to continuous or repeated outdoor conditions.
accumulator In blow molding and injection molding, an auxiliary ram extruder cylinder that provides fast parison delivery.
acrylics Polymers and copolymers with thermoplastic molecules in amorphous structure. They are usually transparent, tough, and resistant.
additive A substance combined with another substance, usually in small percentage, to enhance or improve certain characteristics.
adhesion The state in which two surfaces are held together by interfacial forces. The forces may be valence forces, or interlocking action, or both.
adhesion buildup An increase in peel adhesion value of an adhesive bond after it has been allowed to dwell on an applied surface.
adhesion to backing The bond produced by contact between an adhesive mass and its release liner or carrier.
adhesive A substance capable of holding materials together by surface attachment.
adhesive failure Rupture of an adhesive bond where the separation is at the adhesive-substrate interface.
adhesive transfer The adhesive transfer from one substrate to another substrate.
aftermixer A diverting device cut into a RIM mold runner that causes turbulence in the liquid reactants passing through it. Aftermixers are used when the reactants are difficult to mix completely in a relatively small impingement mixer.
air pocket Air trapped between the mold and plastic sheet.
allophanate linkage Branched linkage formed by the reaction of one hydroxyl (–OH) group with two isocyanate (–NCO) groups (–B&5). Allophanate linkages are analogous to urethane linkage. Some allophanate linkages are normally formed during a polyurethane polymerization, and excess isocyanate is used to compensate for this.
amine Organic nitrogen compounds used as curing agents when combined with epoxy resin.
amine linkage A “Y” linkage formed through a trivalent nitrogen atom. Amine linkage occurs when isocyanates react with polyols in the presence of water (or moisture in small quantities).
amorphous Random molecular arrangement; not having a crystalline structure.
amplifier A device that produces a magnified output reproduction of the essential features of its input.
anchorage Part of an insert that is molded inside a plastic part and is held fast by shrinkage of the plastic on the insert’s knurled surfaces.
angel’s hair Small slivers of plastic material that are shaved from the trimmed edge.
anisotropy The characteristic of exhibiting unequal physical properties (for example: strength, refraction, thermal conductivity) in different directions of a body of material.
arbiating Heating a formed shape to a temperature near but below its melting point, holding the temperature for a period of time, then slowly cooling. This relaxes stresses produced during formation of the object.
antifogger An additive that prevents or retards condensation of moisture on smooth surfaces.
antioxidants/antiozonants Additives that prevent or retard deterioration caused by exposure to oxygen or ozone.
antistats Additives that eliminate or lessen static electricity.
asynchronous operation A process in which one function is performed after another.
auto clave molding A method of forming or curing reinforced plastics that utilizes heat and pressure in a closed vessel.
“B” stage Same as gelation.
backbone The main portion of a molecular chain that is relatively nonreactive compared to the end groups attached to it.
back-drilled holes Holes larger than the vacuum hole itself drilled from the back surface to reduce air-flow resistance.
backing plate In injection molding a heavy steel plate that supports the cavity blocks, guide pins, and bushings.
backing sheet A thin metal support plate that backs up the steel rule die.
bag molding Applying uniform pressure to a flexible diaphragm or bag that covers the molded surface and forces it against the mold.
batch count A quantity of material produced or used at one operation.
biaxial deformation Stretching of the sheet in two directions.
biaxial orientation See orientation.
binder A resin or other material used to hold particles together.
- The binder is the continuous phase in a reinforced plastic that provides mechanical strength or ensures uniform consistency, solidification, or adhesion to a surface coating. Typical binder materials include resin, glue, gum, and casein.
- Blocking Undesired adhesion between touching layers of material that may develop under moderate pressure during storage or use.
- Blow molding A process using air pressure to form hollow articles by expanding a hot hollow plastic tube (parison) against the internal surfaces of a mold.
- Blow pin In blow molding, the tube through which air is injected into the parison.
- Blow ratio In blow molding, the ratio of the mold cavity diameter to the parison diameter.
blowing agent A substance added to plastics because it generates gases by chemical or thermal action. This blowing causes the plastic to expand, forming a foam.
blown-film extrusion Process of making plastic film where an extruded plastic tube is inflated by internal air pressure, cooled, collapsed, and wound onto rolls.
blushing The formation of a whitish discoloration appearing on plastic articles that are highly stressed, or where water absorption (especially in glass-reinforced polyesters) occurs. It appears most frequently in periods of high humidity.
branching In polymers, the growth of short molecular side chains in different directions from the long main chain.

The Contributors of this appendix are: Charles Alexander, Consultant, Alexander and Associates, Willowdale, Ontario, Canada; Al Dickerson, Engineering Manager, Carlisle Geauga Company; J. George Drobny, Senior Development Engineer, Chemfab Corporation; Ted Malinowsky, Research and Development Director, Norwood Coated Products; Stan Rosen, President, Mold Systems Corporation; Armand Winfield, Director, Training and Research Institute for Plastics, University of New Mexico.
The Reviewer of this appendix is: Plastics Molders and Manufacturers Group of SME, Society of Manufacturing Engineers.

The Contributors of this appendix are: Charles Alexander, Consultant, Alexander and Associates, Willowdale, Ontario, Canada; Al Dickerson, Engineering Manager, Carlisle Geauga Company; J. George Drobny, Senior Development Engineer, Chemfab Corporation; Ted Malinowsky, Research and Development Director, Norwood Coated Products; Stan Rosen, President, Mold Systems Corporation; Armand Winfield, Director, Training and Research Institute for Plastics, University of New Mexico.
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brittleness The tendency of a material to fracture without first undergoing significant plastic deformation.
bulk roll The full width roll as the product is removed from the coating machine.
calendering Producing sheets of thermoplastic material by passing it through a series of heated steel rollers.
calibration Ascertaining the errors of a measuring technique or instrument by comparing its readings to known values.
carrier Used to refer to the release liner, or other material that the adhesive is coated on.
casting The process of forming solid or hollow articles from fluid plastic mixtures or resins by pouring or injecting the fluid into a mold or against a substrate with little or no pressure, followed by solidification and removal of the formed object. To form a plastic material in a mold of a given shape and let it harden or cure without more than atmospheric pressure. The most common casting resins include polyesters, epoxies, and acrylics.
catalyst A substance, of small amount, that causes or accelerates a chemical reaction without itself undergoing any net change.
center bevel/double bevel/center face Steel rule blade with a double angle (wedge) geometry knife edge.
centrifugal casting A process in which resin is placed into a rotating container with heated walls. After the resin is melted, it conforms to the internal surface of the container.
chain drive Power source that drives the pin chain and sheet through the thermoformer. Sources include air or hydraulic cylinder driving a rack and pinion, servo motors, and hydraulic motors.
chain extenders Short chain diols that join disocyanates in a linear fashion to form crystalline “hard blocks” and, consequently, modify the properties of a polyurethane. Chain extenders have two hydroxyl (-OH) groups and do not cause branching in the hard block region. Nevertheless, chain extenders are sometimes called cross-linkers.
chain pitch The distance between centers of adjacent joint members.
chain rail Carries the plastic sheet through the thermoformer. The left and right side rails can be adjusted for different sheet widths and to compensate for material expansion and shrinkage during the forming operation.
chill mark Wrinkled surface of formed plastic that results from uneven cooling during the forming process.
chill roll A cored roll, usually temperature controlled by circulating water, used to cool extruded or cast film or sheet before winding or cutting.
chopped strand mat The most common type of reinforcement is chopped strand mat (CSM). It consists of strands of glass filaments chopped to about 0.5 in. (12.7 mm) long and held in a random pattern by a binding agent of polyester-resin powder or polyvinyl acetate emulsion.
chopper gunning The chopper gun will apply random patterns of short lengths of roving very similar to the pattern of CSM. The evenness and weight of each chopped-rolling application is determined entirely by the skill and concentration of the operator.
circuit The path for electric current in an electrical system.
class A finish A mirror-smooth finish. The finishes or part surfaces are usually compared to a standard test plaque that allows visual comparison.
closed cell foam Foam consisting of cells that are not interconnected.
closed loop control Uses feedback information from the sensor to properly regulate the system.
cm Centimeter.
coating techniques Spraying is most common. In air spraying, the liquid is atomized by an air stream. In airless spraying, which produces larger droplets, the liquid is forced through a nozzle at high speed without using air. Centrifugal sprayers atomize the liquid by spraying it against a rotating disk or bell.
corrosion coatings (paints) Solvent-borne coatings are solutions of polymers and additives. If they dry as the solvent evaporates, they are lacquers; if the coating oxidizes or polymerizes, they are varnishes; and if cross-linking or other reactions occur to form a new molecule, they are enamels. Water-borne coatings include solutions, colloids, and latexes of polymers in water; they pose fewer environmental problems than do solvent-borne coatings. Also environmentally friendly are high-solids and 100% solids coatings—liquid polymers, predominantly acrylics, that are fluid enough for application but cure when exposed to radiation or heat.
crocking A phenomenon that occurs when the release carrier is dried during coating. In subsequently regaining its equilibrium moisture content, the paper will “cockle” (take on a waffled or wrinkled appearance).
coextrusion The outputs of two or more extruders are brought together in a feedback to form a single multilayer stream that is fed into a die to produce a layered extrudate.
cohesive failure Bond failure within the adhesive “glue line” without any failure to either bonded surface.
cohesive strength The intrinsic strength of an adhesive.
cold flow Permanent distortion that takes place in polymeric materials under continuous load at room temperatures.
color stability The ability of a plastic compound to resist fading, darkening, or degradation when exposed to sunlight or ultraviolet light.
colorants/pigments Additives used to change the color of the plastic. They can be powder or a resin/color premix.
common cut A cut line shared by two adjacent parts.
compounding Mixing basic resins with all necessary materials before processing them into finished products.
compression molding A technique of thermoset molding in which the preheated molding compound is placed in a heated open mold cavity, the mold is closed under pressure causing the material to flow and completely fill the cavity, and pressure is held until the material has cured.
compressive strength The maximum compressive stress a material is capable of sustaining.
condensation polymerization A chemical reaction in which two or more molecules combine. Often, but not necessarily, accompanied by the separation of water or some other simple substance.
conduction Heat conduction is the exchange of heat from one body while in contact with another body at a lower temperature.
conformability The ability of an adhesive mass to make complete contact with the surface of an irregular object without creasing or folding.
confusion A phenomenon in which the film adhesive has a tendency to pick off or lift from the surface of the interliner upon which it was cast, during the unwinding process.
control system All of the electronic, mechanical, and electromechanical components used to operate a particular process.
convection Heat energy transfer by flowing fluids.
convergent Head tool type that directs the flow inward since the diameter of the parison is smaller than the internal flow diameter of the head.
copolymer A polymer formed by reaction of two chemically different monomers.
core The central tube on which the film is wound.
corona treatment Surface treatment of a web (for example, film) by exposing it to a high-voltage discharge. The main purpose is
to make a surface of an inert web receptive to inks, adhesives, or decorative coatings.
counter stroke Predetermined number of trimmed parts that are counted and then stacked into separate groups.
cream time The time when the mix takes on a creamy appearance. After polyurethane chemical systems are mixed, the chemical reaction that forms urethane linkages gives off heat. R-11, the expanding agent that foams the reacting mix to fill and pack the mold, starts to vaporize when the temperature of the mix reaches the boiling point of R-11 and dissolves in a viscous carrier. The initial formation of microscopic bubbles in the reacting mix causes a sudden change of color and the mix takes on a creamy appearance. If the reactants are thoroughly mixed at a specific temperature, the color change will occur at a specific time. The cream time is an important process parameter in making RIM parts. Generally the shot time (mold filling period) should be less than the cream time.
creep Same as cold flow.
cross direction/transverse direction Direction perpendicular to the flow of the web through the machine.
cross-link Intermolecular bonds between long-chain molecules that increase molecular size and weight, resulting in a change in the physical properties of the material.
cross-linker A compound that ties chains together to form branched chains or polymer networks. Short-chain triols tie hard blocks together. Long-chain triols tie soft blocks together. Either or both methods may be used to modify polymer properties.
cross-linking In polymer molecules, the setting up of chemical links between molecular chains. When extensive, it makes an infusible supermolecule from all the chains.
crystalline The form of a substance that is comprised predominantly of crystals.
crystalline polymer A solid having an orderly repetitive three-dimensional arrangement of atoms, a crystalline region uniformly dispersed in an amorphous, noncrystalline matrix. RIM polymers have crystalline hard blocks and amorphous soft blocks.
crystallinity A state of molecular structure in which molecular chains are uniform and compact resulting in solid crystals with definite geometric form.
cure To change the physical properties of a material, usually liquid to solid, by chemical reaction, heat, catalysts, or pressure.
cut sheet Usually heavy gage rectangular sheet 0.125 in. (3.18 mm) or thicker.
cut-in-place Forming and then cutting in the same mold.
cutting anvil Flat plate that the die cuts against.
cutting force Usually stated in pounds (kg) per linear inch (cm) of blade.
cycle A complete, repeating sequence of operations in a process or part of a process (for example, curing cycle).
data acquisition System takes the signals produced by transducers, flow meters, sensors, etc., and converts signals into a form that a computer can interpret, so that this information can be monitored, analyzed, and graphed.
daylight opening Clearance between the upper and lower moving press platens in the open position.
dead plate Support plate upon which the indexing material rests.
deflashing A method to remove excess, unwanted material from a finished or semifinished product.
deflection temperature The temperature at which a standard test bar deflects 0.010 in. (0.25 mm) under a stated load of either 66 or 264 psi (455 or 1.8 kPa).
degradation A deleterious change in the chemical structure, physical properties, or appearance of a material due to heat, light, oxygen, or weathering.
delamination Separation of layers in a laminate caused by failure of the adhesive bond.
denesting Separation of parts from one another. Part geometry, material properties, and surface treatments can affect the ease with which parts will separate from each other.
density Measure of mass per unit volume of a solid material, usually expressed in lb/ft³ (kg/cm³) at a temperature of 73.4 °F (23 °C).
depth of draw In thermoforming, the depth of the lowest point in the formed object relative to the clamped edge of the sheet.
die A tool, usually containing a cavity, into which plastic material is injected or pressed shaping the material to the desired form.
die nipping To put undercuts in a knife blade for the purpose of keeping the formed article attached to the sheet.
die set The assembly of the upper and lower die shoes (punch and die holders), usually including the guide pins, guide pin bushings, and heat blocks.
diisocyanate Chemical compound containing two isocyanate (-NCO) reactive end groups.
diol Dihydric alcohol; chemical compound containing two hydroxyl (-OH) groups.
dip coating Applying a coating by dipping the object to be coated into fluid resin or plastisol, then cooling.
dip molding A process similar to dip coating except that the coating is cured, cooled, and removed from the form.
directed chopped fibers Fibers chopped to lengths of 0.5–2 in. (12.7–50.8 mm) and directed and oriented to a pattern or preform screen by manual or automated methods.
directional Head tool type that directs the flow outward since the diameter of the parison relative to the clamped edge of the sheet.
downtime The period of time that an operation is not functioning as planned.
draft angle The angle of taper between the side of a mold and its vertical plane. This angle facilitates smooth ejection of parts from the mold.
drape forming Plastic sheet is heated and then placed over a male mold. Vacuum is drawn through holes in the male mold to complete the forming process.
draw ratio A measure of the degree of stretching during the orientation of a fiber or filament. It is expressed as the ratio of the cross-sectional area of the undrawn material to that of the drawn material.
dry-sublimation printing Dye is applied to the part's surface by heat-transfer printing. The heat and pressure vaporize the dyes, and they migrate into the plastic surface. The resulting image cannot be abraded off. Sometimes this is called thermostatic printing.
ductility Ability of a material to be stretched, pulled, or rolled into shape without destroying the integrity of the material.
dwell A pause in the application of pressure to a mold, made just before it is completely closed, to allow the escape of gas from the molding material.
edge preheat To soften both edges of a sheet prior to puncturing the sheet.

edge lifting The lifting of adhesive on the edge of a roll as it is unwound.

edge trim Material that is trimmed away from one or both sides of the sheet in the machine direction.

elasticity Ability of a material to return to its original size and shape after being deformed.

elastomer A material that at room temperature can be stretched repeatedly to at least twice its original length, and snaps back to the original length upon release of stress.

electrical interference Electrical noise induced upon the signal wires that obscures the wanted information signal.

electron beam (E-beam) A stream of electrons in an electron-optical system.

electron beam processing Cross-linking of polymeric materials or polymerization of reactive monomers resulting from their exposure to high energy electron beam. The electrons are accelerated by high voltage, typically 300 kV to 1 MV.

emulsion A uniform dispersion of globules or fine droplets of one liquid in another liquid. (See dispersion.)

encoder An electromechanical transducer that converts a motion into a digital signal that can sense the speed and/or position of a moving device.

epoxide Generic name for a group of thermosetting resins that originally included products made by the condensation of bisphenol and epichlorohydrin, but which now are also made by other means. Uncured epoxide resins are characterized as having two or more epoxide groups per molecule.

euromere Combinations of metals that are easily fused or will fuse at the lowest possible temperature. An alloy with a melting point lower than any other combination of the same components.

exotherm The temperature/time curve of a chemical reaction giving off heat, particularly the polymerization of casting resins.

exothermic reaction A reaction that gives off heat as it proceeds.

exothermic reaction A reaction that gives off heat as it proceeds.

extender A material added to a plastic compound used to reduce the amount of resin required per unit volume.

extruder A machine for producing continuous lengths of plastics that have constant cross sections. It is a tubular barrel that contains a rotating screw or ram which forces molten plastic through the barrel and into a die mold.

extruder barrel The cylinder housing of an extruder through which the plastic material moves.

extrusion The process of forming continuous shapes by forcing a molten plastic material through a die. Typical shapes extruded are hoses, tubes, flat films and sheets, jackets around electrical wires, parisons for blow molding, filaments and fibers, strands for pelleting, and webs for coating and laminating. Related term: coextrusion.

extrusion die A device, usually made of steel, having a specific shape or design geometry and used to impart the desired shape to a polymeric melt that is forced through it.

fascia Root definition—face. Fascia are the visible body parts on an automobile, including panel and trim parts, the parts that are fastened to the body structure to give it shape and its overall appearance.

female mold A hollow cavity shaped in the form of the finished part.

filament winding A process for fabricating a composite structure in which continuous reinforcements (filament, wire, etc.), either previously impregnated with a matrix material or impregnated during winding, are placed over a rotating and removable form. Winding is done in directions calculated to resist stress in specific directions.

filler A relatively inert substance added to a plastic to alter its physical, mechanical, thermal, electrical, or other properties, or to lower cost or density.

filler A rounded edge between molded planes at the inside or outside corners. Fillets facilitate the flow of polymers filling the mold, prevent edge defects as the polymer shrinks, and improve mold heat transfer in critical regions of the molding.

film A thin plastic web typically under 10 mils (250 microns) in thickness.

film casting Producing unsupported film or sheet by casting a fluid resin onto a temporary carrier, usually an endless belt or circular drum, cooling or drying, and removing from the carrier.

fisheye A fault in transparent or translucent plastics appearing as a small globular mass and caused by incomplete blending of the mass with surrounding material.

flags Projection from the end of a roll indicating where splices or other defects exist in the coating.

flammability rating Tests for the extent to which a material will support combustion. Six categories are ignitability, burning rate, heat evolution, smoke production, products of combustion, and endurance burning.

flash A thin fin of plastic projecting from a molded part caused by leaking at the mold parting line. Flash is any extra plastic attached to the molded part that must be trimmed off.

flexibility The ability of a material to be freely bent or flexed repeatedly without undergoing rupture.

flexography A rotary printing process employing flexible rubber or elastomeric printing plates adhered to a roll. The printing plates are inked by a screen roll that has been coated by a feed roll immersed in ink. Used to produce high-quality images on flexible films.

foaming agent See blowing agent.

foam casting (foam molding) A process with many variations, depending on the polymers used. In general, a fluid resin or prepolymer/catalyst system is foamed before or during molding by mechanical frothing, or by gas dissolved in the mixture or released from a low-boiling point liquid.

forged high die A heavy construction trimming die made from...
hardened tool steel. Often used in high volume production runs where durability and long life are required.

form-down Open end of part is facing upward. Formed part is below the sheet line.

form press Equipment that supports the upper and lower form tooling and provides sufficient holding force to form parts.

form tooling Upper and lower tooling that imparts the finished part shape to a plastic film material.

form-up Open end of part is facing downward. Formed part is above the sheet line.

forming ratio The ratio of the part height to depth. This gives an indication of what the final part wall thickness will be in relation to the starting sheet thickness.

front clamp bar Chilled bar mounted on the leading side of the mold that reciprocates in a vertical motion to and away from the sheet line. This keeps the sheet from pulling out of the pin chain and also keeps the sheet from webbing.

frothing A technique to make foam by introducing blowing agents or air bubbles into a liquid compound (prepolymer or latex).

gapping In filament winding, an unintentional space between two windings that would lie next to each other.

gate Restriction at the end of a mold runner that helps control the flow of molten resin into a mold cavity.

gel The initial jelly-like solid phase that develops during the formation of a resin from a liquid. This form has very low strength and does not flow like a liquid. It is soft and flexible and will rupture under its own weight unless externally supported.

gel coat Resin applied to the surface of a mold (after the mold-release agent) and gelled prior to layup. The gel coat becomes an integral part of the finished laminate and is usually used to improve surface appearance.

gelation Intermediate semisolid stage in the liquid-to-solid curing of thermosetting resins.

glass transition temperature Narrow range of temperature at which a plastic changes from a rigid state to a softened state.

glitter A gilded or silvered crushed mica flake used to add sparkle to transparent plastics. In today’s markets, where mica may be expensive or difficult to obtain, glitter is made from finely diced Mylar™ that has been vacuum plated with gold or silver.

gloss Ratio of light specularly reflected (at an angle 90˚ from its entry angle) from the surface to the total amount of light reflected.

guide Rail Bars in the stacker station on which trimmed parts are pushed off to next operation.

guide rods Round rods in the stacker magazine that keep the trimmed parts in position while being vertically upstacked.

hanger hole An elongated slot or triangular shaped hole opening in a trimmed plastic article. This hole is often used to display part shape to a plastic film material.

head The end section of a blow molding machine that forms the plastic into a tubular shape to form the parison.

heat flux The energy incident on a surface element per unit. For example, watts/ in.² or BTU/ft² hour.

heat of reaction Energy transferred in the form of heat in a chemical reaction. The reaction that produces urethane linkages gives off 25 kcal/mold and is therefore exothermic.

heat of transfer coefficient A measure of the effectiveness of energy transport between a flowing fluid and the solid surface.

heat-transfer labeling Highly detailed, single or multicolor images are printed on a carrier web by screen printing, gravure, flexography, offset, or metallization. A heated metal or silicone platen melts a release coating on the carrier and transfers the image to the plastic. Flat or slightly curved objects can be printed in this manner; for more curved objects, such as bottles, a fixture rolls the object along the platen.

heat sealing The process of joining two or more plastic films by simultaneous application of heat and pressure.

heat stabilizers Additives that increase the ability of a material to withstand the negative effects of heat exposure. They are used to increase the overall service temperature of the material.

heat transfer coefficient A measure of the effectiveness of energy transport between a flowing fluid and the solid surface.

death Die cutting Upper or lower cutting tool that is heated to reduce angel hair, cutting force, knife edge wear, and produces a smooth finish on trimmed edges.

heated water plate A flat plate mounted between the moving press platen and the form tooling base plate. Plate transfers heat to the mold during the forming process to provide a consistent mold temperature during and after the forming process.

heterogeneous Varying dispersion of materials.

high-pressure bump Event in the trimming operation where high pressure is applied to cut part(s) from the sheet.

hold The ability of an adhesive to resist slippage when subjected to shear; creep resistance.

homogeneous Uniformity.

homopolymer A polymer resulting from the polymerization of a single monomer.

hot stamping Engraving operation in which a web carrier that has an ink pigment or metal foil surface is stamped with heated metal dies onto a plastic surface. Also, pressing heated inked type against a plastic surface.

hydrocolloid A substance capable of forming a suspension or emulsion with a liquid (in this case, water) that will not settle out to a noticeable degree and will not readily diffuse through vegetable or animal membranes. Colloidal particles are usually of high molecular weight, ranging in diameter from about 10⁻⁶ to 5 × 10⁻¹⁵ cm.

hydroquinone C₆H₄ (OH)₂, a white crystalline material derived from aniline, used along with many of its derivatives as an inhibitor in unsaturated polyesters and in monomers such as vinyl acetate and acrylics. The hydroquinones are relatively colorless and require trace amounts of oxygen in the resin in order to be activated.

impact modifiers Additives used to enhance the material’s ability to withstand the force of impact.

impingement Collision of two streams at high pressure. In RIM machines, two or more streams of reactive material are passed through nozzles at high pressure and high velocity and are directed to collide with each other, causing them to mix.

impulse welding (sealing) Heat is applied by resistance elements rapidly with a subsequent rapid cooling.

in situ trimming/cut-in place Trimming that takes place while the formed article is still in the mold.

index Ratio of one reactant to the other reactant. For RIM polyurethanes, by convention, this is the ratio of -NCO to -OH. (A–B ratio) The fixed distance advances each cycle.

infra red That part of the electromagnetic spectrum between visible light and radar.
injection molding A molding process whereby heat-softened plastic is forced into a relatively cool mold cavity under pressure.

input/output This makes reference to the signals used to bring data into and out of a device.

insulator plate A thermal heat barrier mounted between the press platens and tooling.

interface The boundary or surface between two different, physically distinguishable media.

intimate contact A cooling liquid that is brought into direct contact with the formed part before it has been removed from the mold.

ISO Term used in this book to designate an isocyanate system (reactive disocyanate, plus other additives in the package). The term ISO is used by some machine manufacturers to label the isocyanate tank on a RIM machine.

isocyanate group The reactive end group—NCO.

isotropy The condition in which material properties are the same regardless of the direction in which they are measured.

jetting The spurting that occurs when RIM reactants flow through a mold gate at excessive velocity. This causes turbulence, which may result in part defects such as swirls, bubbles, lumps, and laminating interface surfaces inside the part. The problem can be corrected by reducing the reactant fill rate or making the gate area larger.

laminate (n) A product made by bonding together two or more layers of material, usually preformed layers joined by adhesives or by heat and pressure.

latches/stacking latch Hinged flaps that allow the trimmed parts to pass through in one direction only. Once past the latch, parts then rest on the opposite side until the next part is pushed through.

latex A stable dispersion of a polymeric substance (thermoplastic or elastomer) in an essentially aqueous medium.

lay-flat area The recessed area of the mold that accommodates the flash of excess plastic attached to the part.

linear inches Total inches of die blade that is brought into direct contact with the plastic each cycle.

linear thermal expansion Thermoplastic materials expand when heated and contract when cooled. The ratio of the change in linear dimensions to the original dimension is expressed in./in./˚ F or cm/cm/˚ C.

locating pins Hardened steel pins used with matching hole locations drilled into the opposing mold to force mold halves into alignment.

long center bevel/center face double bevel Steel rule blade with a four angle geometry knife edge.

lower clamp A plate cut out to the shape of the trimmed parts that allows the parts to pass through. The clamp holds the sheet against a fixed plate below the sheet line while a pusher separates the trimmed parts from the sheet.

lower mold Tooling half that can be either the male or female portion attached to the lower moving platen.

lubricant Any substance interposed between two surfaces in relative motion for the purpose of reducing the friction or wear between them.

machine direction The direction parallel to the flow of the web through the machine.

magazine Tooling that temporarily stores a predetermined amount of the trimmed parts for the next operation.

magazine mounting bars Supporting structure upon which the magazine rests.

magazine plate Flat plate cut out to the shape of the trimmed parts. The parts are pushed through this plate and then come to rest on the opposite side.

metal mold Female and male mold halves configured to the shape of the part and separated enough to accommodate the finished part’s wall thickness. Often used in the thermoforming of foam sheet.

material yield Describes how much plastic film at a given thickness can be extracted from a unit weight per volume of material.

matrix The resinous phase of a fiber-reinforced composite.

melamine Common name for melamine-formaldehyde, one of the amino plastics and compounds. It is an amino-type thermosetting resin made by the condensation of melamine (the amide of cyanuric acid) and formaldehyde. Alpha-cellulose-filled melamines are widely used in the dinnertime industry.

melt index Material is melted at a known temperature, and then extruded through a standard orifice. The units of measure are given in grams per 10 minutes. The melt index is strongly indicative of relative flow ability of various kinds of materials. The property measured by this test is basically melt viscosity or rate of shear. In general, the materials that are more resistant to flow are those with higher molecular weight.

melt temperature The temperature range at which a plastic material changes from a rubbery solid to a viscoelastic liquid.

melting point Temperature at which a solid changes to a liquid.

metallic finishes Electroless plating applies a metallic coating to nonconductive objects. A plastic object is immersed in a plating bath containing metal ions and a reducing agent. Electrolytic plating uses electric current to deposit material from a solution of metal salts onto a conductive object. A plastic object must first be rendered conductive by electroless plating.

metallizing A process by which a plastic is coated with a thin layer of metals.

methyl methacrylate A thermoplastics polymerization product of methacrylic acid esters used to make casting molding compounds. It has exceptionally good optical properties, and can be made in a wide range of transparent, translucent, and opaque colors. Clear, it can be used for embedding or for optical components. It is the only transparent material (plastics) with an outstanding weather resistance record since 1936.

micron A unit of linear measure equal to one millionth of a meter, or one thousandth of a millimeter.

migration The movement over a period of time of entities (electrons, ions, atoms, molecules, etc.), from one surface to another when the two surfaces are in direct contact.

mm 0.001 inches or one thousandth of an inch. One mil equals 25 microns.

mixing head, RIM Chamber in which chemical reactants are mixed by high-pressure impingement. A cleanout piston removes all materials from the mixing chamber following the shot by injecting them into the mold runner using a displacement piston. RIM mixers are designed to recycle reactants between shots.
mold perimeter clamp Heated material is clamped around the mold insert. A removable mold piece. Insert allows replacement of mold height. Overall dimension of the closed mold halves.
mold cavity Portion of the tooling from which the softened plastic takes its final shape.
mold extensions Adapter plates that mount to the sides of an existing mold base plate to increase the mold mounting surface area available in the machine or cross direction.
mold gap Space remaining between the male and female matched metal molds after closing. The plastic material under force from the press fills the gap completing the forming process.
mold height Overall dimension of the closed mold halves.
mold insert A removable mold piece. Insert allows replacement of a worn mold part, a change in vacuum hole size, and in mold lettering or graphics.
mold perimeter clamp Heated material is clamped around the perimeter prior to forming. This technique is often used to improve wall uniformity of the finished part.
mold radius Circular arcs machined into the mold tooling to form a film on the surface of a mold cavity, making it easier to remove a part after it has been molded. Mold releases should be easy to remove from the part surface so that paint finishes to be applied later will stick to the part surface.
mold release agent A lubricant used to coat a mold cavity to prevent adhesion of the molded piece when removed.
mold release, internal A material blended into a RIM chemical system that tends to migrate to the surface of a RIM part during the molding operation. This material forms a film that will prevent adhesion of the RIM polymer to the mold surface. Internal mold releases may be difficult to remove from the molded part and may interfere with subsequent painting operations.
mold seals Elastomeric material used to seal the adjoining surfaces between the upper and lower mold tooling halves during the molding operation. Entrained gas and some fillers perform this function.
mold shrinkage The fractional difference in dimensions, expressed in mils per inch (microns per mm), between the part and the mold cavity in which it was molded, both the mold and the molded part being at normal room temperature when measured.
mold spacing Measured center distance between multiple mold forms in the (X-Y) plane.
mold standoffs Spacers mounted between the mold plate and press moving platen.
mold temperature Temperature of the contact side of the mold surface ideal for forming a plastic material.
mold temperature control A device used to maintain a set temperature range ideal for the forming of a plastic material.
mold undercut Negative draft or taper that causes removal interference between the formed part and mold’s geometry. This condition can make stripping of part from the mold more difficult.
mold water manifold A multiple ported distribution block providing even flow of coolant to the mold inlet and outlet channels.
mold water plate Flat plate sandwiched between the moving press platen and the mold base plate. Coolant is pumped through the plate to assist in the removal of excess heat from the mold and also functions as a thermal heat barrier to keep heat from being transferred to the moving platen.
molding cycle The total time period between the start to finish of a single index.
monomer A single molecule that can react with like or unlike molecules to form a polymer, which is a long-chain molecule. Multiple cavities Mold with two or more mold impressions made in a single machine cycle.
nip unwind A power driven nip and idler roll that feeds out the desired linear units of material for the thermoformer’s next index.
notch sensitivity Measure of the ease with which a crack progresses through a material from an existing notch, crack, or sharp corner.
nucleating agent A chemical substance added to a crystallizable polymer that provides active centers for the growth of crystals as the melt is cooled.
nucleation Development of surfaces that facilitate the formation of gas bubbles that expand to produce a foamed product. Entrained gas and some fillers perform this function.
offset printing In offset printing, ink is transferred from a photo-imaged plate to a rubber blanket and then to an object’s surface. Sheets and webs are printed by this process, as are containers.
oligomer A polymer consisting of only a few monomer units (usually up to ten).
one-up mold Mold that produces one article at a time.
opacity The inability of a material to transmit light. It is measured by haze (light scattered within the material) and luminous transmittance (light passed through the material).
open-cell foam A foam with interconnecting cells (for example, sponge).
opent height Distance between the upper and lower moving platen surfaces at their maximum distance from sheet line.
opent-loop control A control device that has no self-correcting feedback information.
orientation Stretching a polymeric material to align the molecular chains in the direction of stretching, thus improving its physical properties.
packing Incorporating an expanding agent in the RIM chemical system that will expand to fill the mold volume after the shot, and applying internal pressure to the chemical reactant that presses the reactant against the sides of the cavity, improving the surface appearance of the molded part.
pad printing Pad printing is the easiest way to decorate objects that have compound curves or pronounced textures. An inked image is transferred from a photo-etched plate to a thick, soft silicone pad. The pad is then pressed against the plastic part. The pad can wrap itself as much as 180° around a small object, and ink coverage is excellent. One color is done at a time, but registration between colors is good enough to allow four-color process printing.
parison In blow molding, the hollow tube of plastic melt extruded from the die head, and expanded within the mold cavity by air pressure to produce the molded part.
parison swell The ratio of the diameter of the parison to the diameter of the die opening.
parting line The line or mark on a molded or cast article where the two halves of the mold met in closing.
pattern heating Selectively controlling the amount of heat applied to adjoining areas of the sheet.
peel adhesion The force required to pull a strip of two bonded substrates apart at a specified angle and speed.
perforated steel rule blade Blades with repeating high and low spots. Often used to keep the trimmed parts attached to the moving sheet for further processing downstream.
permeability The ease with which a gas, vapor, liquid, or solid passes through a material without being physically or chemically affected.

phenolic resin High-performance thermosetting plastics produced by the condensation reaction of phenol with an aldehyde.

PID control Proportional integrated derivative. A three-mode control action where the controller uses proportional gain, auto-reset (integral), and derivative rate action to control a process.

pigment General term for all colorants, organic or inorganic, natural or synthetic, which are insoluble in the medium in which they are used.

pin chain Special type roller chain with tooth-shaped side plates on every other pitch. The wedge-shaped teeth pierce the plastic material as it enters the infeed section of the thermoformer and carries the material through the various operations. The right and left strands of chain are used in matched sets.

pin hole A very small hole in a film or coating.

pinch bars Used on blow mold or the blow molder to close the parison during the blowing process.

pinch-off In blow molding, the raised edge around the cavity in the mold. It defines the edge of the part and separates the excess material as the mold is closed. The pinch edge needs to be sharp enough to facilitate trimming but not too sharp to cut the parison.

pipe Hollow cylinder of a plastic material in which wall thicknesses are usually small when compared to the diameter. The outside and inside walls of a pipe are essentially concentric.

plasma treatment A process of surface modification using a high-temperature plasma, improving bondability and wettability of the plastic surface. This process is more reliable and the changes are more durable than conventional corona treatment.

plastic A material that contains an essential ingredient of one or more organic polymeric substances of large molecular weight, is solid in its finished state and, at some stage in its manufacture or processing into finished articles, can be shaped by flow. The terms plastic, resin, and polymer are somewhat synonymous.

plasticity The property of a material that allows it to be repeatedly deformed without rupture.

plasticizer Substances that increase the flexibility of resins by reducing their normal intermolecular forces, thus permitting the macromolecules to slip past each other more freely.

plastisol A suspension of finely divided particles of vinyl chloride polymer or copolymer in a liquid plasticizer that remains liquid until it is heated to a specific temperature at which point it forms a homogeneous plastic mass. After cooling, it becomes more or less a flexible solid.

plug-assist forming A sheet thermoforming process in which a convex mold half presses softened sheet into a concave mold half, accomplishing most of the draw, then a vacuum draws the sheet further into the mold.

Poisson’s ratio Ratio of the lateral strain to longitudinal strain.

polyester A polymer formed by combining diols with dibasic acids to produce ester linkages. The -OH (hydroxyl) group reacts with a -COOH (acid) group to form -COO-, an ester linkage, and H-O-H (water).

polymer Natural or synthetic compound of a high molecular weight, formed by chains of chemically linked units, called monomers. These materials are made of many repeating groups of atoms or molecules linked in long chains that combine such elements as oxygen, hydrogen, nitrogen, carbon, silicon, fluorine, and sulfur.

polymerization A chemical reaction during which monomer units are linked together to form large molecules with molecular weights that are multiples of the molecular weights of the monomeric units. The degree of polymerization indicates the number of monomeric units in the polymer (typically several hundreds or more).

polyol A polymer, usually a polyether or polyester, that is terminated with -OH (hydroxyl) groups.

polyurethane A polymer formed by reacting diols (or polyols) with disiocyanates to form chains or networks through urethane linkages. All atoms in the two end groups (-OH and -NCO) are used to form the urethane linkage (-NHCOO-).

postcuring Accelerating the final curing of thermosetting resins in a curing oven after removal from the mold where partial cure has taken place.

postmold expansion Thermoformed parts expand after forming when removed from the mold.

preform A compressed shaped mass of plastic material or fibrous reinforcing material, or mixtures of both, mainly for convenience of handling. In composite material technology, the preform is a mat of chopped strands bonded together in an approximate shape of the end product. The preform gives added strength to the part.

preheating Heating of a compound prior to molding or casting. This facilitates the operation, reduces the cycle time, and improves the product.

prepolymer A polymer of relatively low molecular weight that can be further extended by additional polymerization during or after a forming process.

prepreg A thin sheet of fabric impregnated with a thermosetting resin partially cured (to B-stage) that can be stored at low temperatures around 0˚ F (–18˚ C) and can be cured further after lamination or winding.


pressure box Hollow mold half used for pressure forming.

pressure exhaust Pressurized air from the forming operation is vented to the atmosphere prior to mold open.

pressure forming A thermoforming process that uses air pressure to push the sheet against the mold, often used in conjunction with vacuum forming.

pressure sensitive adhesive An adhesive that in vehicle free form is aggressively and permanently tacky at room temperature and will bond firmly to a variety of untreated surfaces with only minimum finger pressure.

primer A coating applied to a surface to improve the adhesion, gloss, or durability of a subsequent coating.

product transfer Moves trimmed parts from one operation to the next.

programmable logic controller Abbreviated PLC. A type of microprocessor that uses structured logic, typically called ladder logic, to manipulate operations of a process.

programmed parison The change in the thickness of the parison wall as a result of the mandrel movement. This is needed to offset gravitational effects and to provide additional material in sections with lower blow ratios or heavier wall thickness requirements.

protrusion A substance promoting a chemical reaction initiated and sustained by radiation energy, particularly by electron beam.

puddling Visible continuous line marking surrounding the surface area of a formed part that did not make contact with mold surface.

pultrusion A continuous manufacturing technique for producing solid and tubular fiber-reinforced profiles with constant cross-section.

punch and die Matched male and female dies used to punch or blank formed articles from the sheet.
pusher plug Stacker's pusher plug is shaped to match that of the part. The pusher plug separates the trimmed part from the sheet and transfers it to the next operation in the stacker.
push-off To push trimmed parts away from the stacker magazine.
push-off to conveyor Trimmed parts are mechanically transferred from the stacker to a live conveyor belt for further processing.
push-off to plate Trimmed parts are mechanically transferred from the stacker to a fixed horizontal plate for temporary storage.
quenching Shock cooling thermoplastic materials from the molten state.
quick change tooling Devices and methods applied to reduce the time required to load and unload tools/molds from the press.
quick make ready Techniques used to bring the upper and lower die cutting surfaces into parallelism.
quick stick The ability of a pressure sensitive coated base material to adhere to a surface instantly using no pressure other than its own weight.
radiation Electromagnetic energy transfer.
rail jam Plastic sheet back fills in the chain rails resulting in stoppage of the thermoforming process.
reaction injection molding Low-pressure molding process using highly reactive liquid materials. Depending on requirements, the final product is either flexible solids or foams.
reaction rate The rate at which a reaction goes to completion. Some reactions may start rapidly and slow as the reaction proceeds. Catalysts speed up a reaction, and may favor one reaction over another when there are competing reactions.
rear clamp bar Cooled bar that clamps the material at sheet line prior to forming. The bar is positioned between the mold and the oven and is most often used to control material shift and folding.
reflectance The fraction of radiant energy that is reflected at the surface of a sheet.
reinforced plastic A plastic compound in which fibrous reinforcements are added before the forming operation, and that imparts strength properties greatly superior to those of the base resin. The reinforcements are usually fibers, rovings, or mats of glass, asbestos, metals, paper, sisal, cotton, or nylon. Resins most commonly used are polyesters, phenolics, aminos, silicones, and epoxies.
reinforced thermoplastic A reinforced plastic compound in which the bonding resin is a thermoplastic rather than a thermoset. The tensile strength of a thermoplastic can be at least doubled and immediately upon release of the stress, returns with force to its approximate original length.
rigidity The ability of an adhesive to resist exposure to varying conditions after application to the surface.
resistor A device that by design reduces electrical current flow.
rheology The science of the deformation and flow of matter.
rheostat A variable resistor.
rib A projection running across the back of a flat-molded part that imparts stiffness to the molding. Raised surfaces in the finished part used for reinforcement and strength.
rivet assist A continuous shaped ring that surrounds the entire perimeter of part to be formed. This technique can help control the material distribution during forming. Most often used with male molds.
rise-time curve The rate of foam polymerization and expansion between pouring a urethane mix and the completion of foaming.
roll fed Plastic film is unwound from a core and fed into the thermoformer.
rotational casting The process of forming hollow articles from fluid materials by rotating a mold containing a charge of the material about one or more axes at relatively low speeds until the charge is distributed on the inner walls of the mold by gravity and hardened by heating, cooling, or curing. Rotation about one axis is suitable for cylindrical objects. Rotation about two axes and/or rocking motions are employed for completely closed articles.
rotational injection molding A modified injection molding process applicable to hollow, symmetrical articles such as cups and beakers, in which the male half of the mold is rotated during the molding cycle until the material has hardened to a predetermined degree. The rotation produces multiaxial molecular orientation and increased crystal development in polymers such as polystyrene, resulting in improved toughness and stress-craze resistance.
rotational molding A process in which the product is made in a thin-walled mold with good heat transfer capabilities. The plastic material (liquid or powdered) is melted during the process and covers the interior surface of the mold which rotates simultaneously about two mutually perpendicular axes.
rubber A natural or synthetic material that at room temperature can be stretched repeatedly to at least twice its original length and immediately upon release of the stress, returns with force to its approximate original length.
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resistance to solvents, acids, chemicals, ultraviolet, etc.
reinforcement A strong, inert fibrous material incorporated in a plastic compound to improve its physical properties. Typical reinforcing materials are glass, silicon, boron, carbon, and graphite. To be effective, a reinforcement must form a strong bond with the resin.
release agent A material applied as a thin film to the surface of a mold cavity to prevent the molded piece from sticking to the mold.
release liner An impermeable paper or film that serves as a protector or carrier for an adhesive film or mass, and is easily removed from the film or mass prior to use.
resin Solid or pseudosolid material, often high in molecular weight, that exhibits a tendency to flow when subjected to stress, usually has a softening or melting range rather than a specific melting point, and usually fractures conchoidally.
resin-transfer molding After preformed reinforcement is placed in a heated mold, quick-curing resin is injected into the mold as it is being closed or after it is closed.
sensor A transducer that creates a useful signal when subjected to a change of state.
servo motor A motor that utilizes feedback loops for motor control.
sandwich heating Method of heating both sides of a plastic sheet at the same time.
screen printing A decorating stencil of taut woven screen is secured in a frame. Nonprinting areas of the screen are coated with a masking material. The screen is placed over the object to be printed and a squeegee forces ink through the uncoated areas of the screen.
sensitivity The minimum change in input signal to which an instrument can respond.
sensor A transducer that creates a useful signal when subjected to a change of state.
servo motor A motor that utilizes feedback loops for motor control.
set The maximum number of slit rolls that can be cut from a bulk roll.
set temperature Temperature at which the part may be removed from the mold. The deflection temperature is often used for this purpose.
setting temperature The temperature at which a formed article will retain its shape after being removed from the mold.
shearing time Period of time that a formed article remains in the mold for cooling.

shear adhesion The force required to pull an adhesive construction from a flat surface in a direction parallel to the surface.
shear modulus Ratio of shear stress to shear strain.
shear rate The overall velocity over the cross-section of a channel at which molten or fluid layers are gliding along each other or along the wall (in laminar flow).
shear stress The stress developing in a polymer melt when the layers in a cross-section are gliding along each other or along the wall of the channel (in laminar flow). Ratio of shear load to area resisting the load, measured in psi.
sheet fed Plastic film is in the form of sheets when fed into the thermoformer. Often used with material thicknesses that are not conducive to roll-fed thermoforming technology.
sheet line The entire assembly necessary to produce plastic sheet, including the extruder, die, polishing roll stand, cooling conveyor, pull rolls, winder, cutter, stacker, and all associated controls.
sheet orientation Direction of the plastic material’s grain with respect to the part being formed.
sheet shrinkage Linear reduction in the machine direction and cross direction dimensions of the sheet after heating and then cooling to room temperature.
sheet thickness/film gage Measured thickness of the unformed sheet.
shelf life The period of time during which a material, substance, product, or reagent can be stored under specified conditions and still remain suitable for use.
shrinkage The difference in size between a mold cavity and the molding made from that cavity, both being measured at the same room temperature.
shut height Distance between the upper and lower moving platen surfaces at their minimum distance from the sheet line.
side clamp bar Flat bars mounted on both sides of the mold that hold the sheet against the mold. This prevents the sheet from being pulled off the pin chain during the forming operation.
signal An electrical transmittance (either input or output) that conveys information.
single bevel/side bevel Steel rule blade with a single angle geometry knife edge.
sink mark A shallow depression or dimple on the surface of an injection molded part caused either by local internal shrinkage after the gate seals or by a short shot.
skeleton scrap Material left over after the formed parts have been removed from the sheet.
slip agent Additive that provides surface lubrication during and immediately following processing of the plastic material. It acts as an internal lubricant that will eventually migrate to the surface.
slit roll A roll of specified width and length, cut from a bulk roll.
soaking time Time required to bring the sheet to an equilibrium temperature throughout its mass.
software Computer programs designed to perform various tasks or functions.
solid-state relay A solid-state switching device that completes or interrupts a circuit electrically with no moving parts.
solvent A liquid used to dissolve other substances, thus forming solutions. The majority of solvents for polymers are organic liquids.
spreader plates Removable plates sandwiched between the press platen and the cutting tool mounting plate. The plate stack sets the height of the cutting tool in relation to sheet line.
specific heat Ratio of a material’s thermal capacity to that of water. Thermal capacity is the amount of heat required to raise the temperature one degree.
spattering A coating process whereby the coating material is deposited in the form of individual atoms. The source of the coating material is bombarded by gas ions, which cause individual atoms to be dislodged. They then move across a vacuum to the surface of the article to be coated.
stabilizer A chemical used in the formulation of some plastics to help maintain physical and chemical properties during processing and service life.
stacking lugs Forming alternating impressions in a part that keeps parts from interlocking together when stacked.
standard roller chain numbers Denotes the pitch of the chain given in 0.125 in. (3.18 mm) increments.
stand-off Risers mounted between the stacker moving platen and the pusher plug.
steel rule die A sharp-edged knife fashioned from thin steel that is flexible enough to be shaped to complex outlines when cutting several layers of sheeting.
steel rule thickness Wall thickness of steel rule blade. Thickness units are in point(s) with each point equal to 0.014 in. (0.36 mm).
stops Adjustments on the stacker to control the final position of the stacker moving platen when actuated.
string time Time at which a string forms when a splint is poked into a reacting polymerization mix and withdrawn. As polymerization proceeds in a polyurethane rise time test, the viscosity of the mix increases. When the polymerization reaches a certain point, a string forms when a splint is poked into the mix and withdrawn. This happens rather suddenly, and the time at which this occurs gives a second parameter indicating how a urethane polymer is polymerizing.
structured foam Expanded plastic materials having integral solid skins and porous cores that exhibit outstanding rigidity.
substrate The material on which another material such as adhesive or coating is deposited.
suction picking Method of transferring trimmed parts from the stacker by vacuum cups to next operation.
supported film (reinforced) A film adhesive internally reinforced with a thin, porous tissue or mat or other suitable material to build thickness and facilitate handling.
surface treatment Any treatment that renders a plastic surface more receptive to adhesives, paints, inks, lacquers, or lamination. Included are solvent cleaning, mechanical abrasion, chemical etching, flaming, corona discharge, and plasma etching.
surfactant A chemical compound that reduces the surface tension of a liquid in which it is dissolved, making it easier for the solution to wet solid surfaces and penetrate pores.
surge tank Vacuum tank between the vacuum pump system and the mold. This allows a faster vacuum pull and a more consistent level from cycle to cycle.
suspension A fluid in which fine solid particles are stably dispersed. (See dispersion.)
syntactic foam Lightweight material that contains cells formed by glass or plastic microballoon fillers instead of foaming.
tack The property of a pressure sensitive adhesive that causes it to adhere to a surface instantly without external pressure.

tack range The period of time during which an adhesive will remain useful after applying to the substrate.

tear tabs Perforated cuts in plastic articles to allow easy separation of the adjoining surfaces.

telescoping A sideways sliding of tape layers relative to each other such that the roll end becomes conical in shape.

temperature controller The hardware and software components of a system used to monitor and maintain a set temperature on the controlled device.

tensile strength Maximum stress that a material can withstand without breaking.

tenter frame A machine that stretches a temperature-conditioned film or sheet simultaneously in two perpendicular directions, thus imparting biaxial orientation.

thermal diffusivity Unsteady heat transfer in solid materials that is equal to its thermal conductivity divided by the product of heat capacity and density.

thermal spraying Metal wire or powder is fed into a spray gun, melted by a gas flame, and then atomized by compressed air.

thermistor A semiconductor whose resistance varies sharply and reproducibly with temperature, and is therefore useful for temperature measurement.

thermocouple A device that measures the temperature of a specific location on a closed circuit by gaging the electrical current passing through that circuit. The circuit can cover a large area, and the temperatures measured can be very high.

thermoforming The process of forming a thermoplastic sheet into a three-dimensional shape by clamping the sheet in a frame, heating it to render it soft and flowable, then applying differential pressure to make the sheet conform to the shape of a mold or die positioned below the frame.

thermoplastics Plastic materials that repeatedly become soft and moldable when heated, and change back to solids when cooled. When heated the linked chains of molecules can move relative to each other, allowing the mass to flow into a different shape. Included are such commonly known plastics materials as acrylics, celluloses, vinyls, polyethylene, nylon, etc.

thermosets Plastics are changed chemically during the process of heating and become irreversible solids when cooled. Processing develops cross-links between molecules forming complex networks that prevent relative movement between the chains at any temperature.

tilt Orient in a sloping position. Molds in RIM processing are tilted to facilitate the flow of liquid reactants during mold filling and the flow of foaming reactants as they expand to complete the filling of the mold cavity and to pack it.

timing parameters The time in which a function will be directed to activate or deactivate.

tooling Simple devices used in a manufacturing process. Examples in RIM technology are molds used to form the part itself, jigs to support the part before curing, fixtures to align parts for assembly, and templates used to align drills.

toughness Measure of the ability of a material to absorb mechanical energy without cracking or breaking.

transducer A device that transforms the value of a physical variable into an electrical signal, usually voltage or current.

transfer molding Thermosetting plastics are softened by heat and pressure in a transfer chamber, then forced at high pressure through sprues, runners, and gates into a closed mold for curing.

transmittance The ratio of light passed through a material compared to the light incident upon it.

trim heater plate An electrically heated plate located between the insulator plate and the trim tools base plate. Heat from the plate is transferred to the tool to improve cutting performance. (See heated die cutting.)

trim water plate Water-cooled plate mounted between the trim press platen and heated cutting die.

tripoli A light porous rock consisting of weathered chert and siliceous limestone that is used to make polishing compounds and abrasives.

two-level cut Knife blade that has been stepped (different height levels) to trim in more than one plane at a time.

ultrasonic welding A method of welding or sealing thermoplastics in which heating is accomplished by vibratory mechanical pressure at ultrasonic frequencies.

undercut A protuberance or indentation of a plastic part that forms a key that prevents removal of the part from the mold. When shape requirements dictate the use of an undercut, the mold must be designed to open to free the restriction and enable the part to be demolded.

up stack push-off Stack the trimmed parts vertically in a magazine and then push them horizontally away from the stacker magazine after a predetermined part count has been reached.

upper mold Tooling half that can be either the male or female portion attached to the upper moving plate.

user interface The hardware and software used to give an operator the tools necessary for adjusting and controlling the process.

UV stabilizers Chemical additives that selectively absorb ultraviolet rays.

vacuum cups Elastomer cups used in conjunction with vacuum to transfer parts from one operation to the next.

vacuum forming Method of sheet forming in which a thermoplastic sheet is clamped into a frame, heated, then drawn down over or into a mold by vacuum.

vacuum line Connecting the vacuum pump system to the mold.

vacuum tracking Grooves machined into the bottom surface of the form tooling for the purpose of distributing vacuum where required.

vent Small air passages cut into the surface of a mold to allow the air to escape from the mold as the molding material enters.

vent holes Vacuum holes machined into the form tooling for the purpose of removing air between the plastic sheet and the mold surface.

venting (1) In autoclave curing, turning off the vacuum source and venting the vacuum bag to the atmosphere, thus reducing pressure. (2) In injection molding, gases produced by the melt escape through vents in the mold.

vicat softening point The temperature at which a flat-ended needle of one square millimeter will penetrate a thermoplastic specimen to a depth of one millimeter under a specified load and uniform temperature rise.

virgin material A plastic material that has not been subjected to use or processing other than that required for its initial manufacture. It can be in the form of pellets, granules, powder, flock, or liquid.

viscosifier An additive increasing viscosity of a liquid system.

viscosity The bulk property of a fluid, semifluid, or semisolid substance that causes it to resist flow.

warpage Dimensional distortion in a plastic object after molding.

water absorption The ratio of the weight of water absorbed by a material compared to the weight of the dry material.
water baffle Partial barriers inserted into coolant lines and channels. The fluid turbulence created by these barriers improves the heat transfer between the adjoining higher temperature mold surface and the lower temperature coolant.

water line A hollow tubular-shaped passage that transports coolants to and from a mold.

water mark Visible continuous line marking surrounding the surface area of a formed part that did not make contact with mold surface.

water-white A low-viscosity, exceptionally clear unsaturated polyester or epoxy resin used in casting, embedding, or decorative laminating.

wavelength A measure of the nature of incident electromagnetic radiation.

web A continuous length of sheet material handled in roll form.

web puller/web chasers A mold insert of convex or concave features designed to pull material away from the mold form. The purpose is to control distribution of heated plastic material while forming. Often used to help reduce webbing of the finished part.

webbing Filaments or threads that sometimes form when adhesively bonded surfaces are separated.

weld line A line visible on a finished plastic part caused by the meeting of the two flow fronts of plastic material as they enter the mold.

wetout In composites fabrication, the condition whereby all spaces between reinforcing fibers are impregnated with surrounding resin.

wetting The ability of a liquid to adhere to a surface immediately on contact.

woven roving Bundles of fibrous glass filaments woven at right angles into a mat.

X-Y tooling adjustment Controlled movement of trim die.

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