Plastics & Composite Materials: Forming & Shaping

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Chapter 19
Plastics

• Can be molded, cast, formed, machined
  – In a few operations
  – Easily
  – Rapidly
• Can be joined
• Can be coated
• Can be shaped into discrete products
• Can be produced as materials (sheets, plates, rods, and tubing) for later manufacture into discrete parts
Some Plastics Terminology

• *Thermoplastic* (TP) – Polymers that can be shaped when heated and regain original hardness & strength upon cooling
  – Have a linear or branched structure (weak secondary bonds)
  – Process is reversible
  – Acrylics, cellulosics, nylons, polyethylenes, polyvinyl chloride

• *Thermoset* (TS) – Polymers that become permanently set when heated
  – Have a cross-linked structure (strong secondary bonds)
  – Process is irreversible
  – Epoxy, polyester, urethane, phenolics, silicones

• *Elastomer* (Rubber) – Elastic; low elastic modulus
  – Tires, footwear, gaskets, flooring, weatherstripping, hoses
Plastics

• Generally shipped to plants as pellets, granules, powders
  – TP then melted prior to shaping
  – TS are liquid plastics that cure into final form

• Increasing quantities of recycled plastics
  – Lower product quality
### TABLE 19.1  General Characteristics of Forming and Shaping Processes for Plastics and Composite Materials

<table>
<thead>
<tr>
<th>Process</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion</td>
<td>Continuous, uniformly solid or hollow, and complex cross sections; high production rates; relatively low tooling costs; wide tolerances</td>
</tr>
<tr>
<td>Injection molding</td>
<td>Complex shapes of various sizes; thin walls; very high production rates; costly tooling; good dimensional accuracy</td>
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<tr>
<td>Structural foam molding</td>
<td>Large parts with high stiffness-to-weight ratio; less expensive tooling than in injection molding; low production rates</td>
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<tr>
<td>Blow molding</td>
<td>Hollow, thin walled parts and bottles of various sizes; high production rates; relatively low tooling costs</td>
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<tr>
<td>Rotational molding</td>
<td>Large, hollow items of relatively simple shape; relatively low tooling costs; relatively low production rates</td>
</tr>
<tr>
<td>Thermoforming</td>
<td>Shallow or relatively deep cavities; low tooling costs; medium production rates</td>
</tr>
<tr>
<td>Compression molding</td>
<td>Parts similar to impression-die forging; expensive tooling; medium production rates</td>
</tr>
<tr>
<td>Transfer molding</td>
<td>More complex parts than compression molding; higher production rates; high tooling costs; some scrap loss</td>
</tr>
<tr>
<td>Casting</td>
<td>Simple or intricate shapes made with rigid or flexible low-cost molds; low production rates</td>
</tr>
<tr>
<td>Processing of composite materials</td>
<td>Long cycle times; expensive operation; tooling costs depend on process</td>
</tr>
</tbody>
</table>
FIGURE 19.1 Outline of forming and shaping processes for plastics, elastomers, and composite materials. 

(TP = Thermoplastic; TS = Thermoset; E = Elastomer.)
FIGURE 19.2  (a) Schematic illustration of a typical screw extruder.  
(b) Geometry of an extruder screw.  
Complex shapes can be extruded with relatively simple and inexpensive dies.
FIGURE 19.3  Common extrusion die geometries: (a) coat-hanger die for extruding sheet; (b) round die for producing rods; and (c) nonuniform recovery of the part after it exits the die.

FIGURE 19.4 Extrusion of tubes.
(a) Extrusion using a spider die (see also Fig. 15.8) and pressurized air.
(b) Coextrusion for producing a bottle.
FIGURE 19.5  (a) Schematic illustration of the production of thin film and plastic bags from tube—first produced by an extruder and then blown by air. (b) A blown-film operation. This process is well developed, producing inexpensive and very large quantities of plastic film and shopping bags. *Source:* (b)Courtesy of Wind Moeller & Hoelscher Corp.
FIGURE 19.6 The melt-spinning process for producing polymer fibers. The fibers are used in a variety of applications, including fabrics and as reinforcements for composite materials. In the stretching box the right roll rotates faster than the left roll.
FIGURE 19.7  Schematic illustration of injection molding with (a) a plunger and (b) a reciprocating rotating screw.
FIGURE 19.8 Sequence of operations in the injection molding of a part with a reciprocating screw. This process is used widely for numerous consumer and commercial products, such as toys, containers, knobs, and electrical equipment (see Fig. 19.9).

Rotating and reciprocating screw

1. Build up polymer in front of sprue bushing; pressure pushes the screw backwards. When sufficient polymer has built up, rotation stops.

2. When the mold is ready, the screw is pushed forward by a hydraulic cylinder, filling the sprue bushing, sprue, and mold cavity with polymer. The screw begins rotating again to build up more polymer.

3. After polymer is solidified/cured, the mold opens, and ejector pins remove the molded part.
FIGURE 19.9 Typical products made by injection molding, including examples of insert molding.

Source: (a) Courtesy of Plainfield Molding, Inc. (b) Courtesy of Rayco Mold and Mfg. LLC.
FIGURE 19.10  Illustration of mold features for injection molding.
(a) Two-plate mold with important features identified.
(b) Schematic illustration of the features in a mold.
Source: Courtesy of Tooling Molds West, Inc.
FIGURE 19.11 Types of molds used in injection molding:
(a) two-plate mold; (b) three-plate mold; and (c) hot-runner mold.
Injection Molding

• High rate production process
• Permits good dimensional control
• Versatile process can produce complex shapes
• Reduce defects by:
  – Good mold design
  – Control of material flow in die cavity
Injection Molding: Sources of Defects

- Weld lines (similar to cold shut in metal casting)
- Unfilled die cavity if have premature solidification due to narrow runners
- Form flash if dies do not mate properly
- Sink marks form at thick sections due to uneven cooling causing local shrinkage

Avoid defects by:
- Temperature control
- Proper pressures
- Simulate processes using computer software
FIGURE 19.12 A 2.2-MN (250-ton) injection-molding machine. The tonnage is the force applied to keep the dies closed during the injection of molten plastic into the mold cavities and hold it there until the parts are cool and stiff enough to be removed from the die. Source: Courtesy of Cincinnati Milacron, Plastics Machinery Division.
FIGURE 19.13 Schematic illustration of the reaction-injection molding process. Typical parts made are automotive-body panels, water skis, and thermal insulation for refrigerators and freezers.
FIGURE 19.14  Schematic illustrations of (a) the extrusion blow-molding process for making plastic beverage bottles; (b) the injection blow-molding process; and (c) a three-station injection blow-molding machine for making plastic bottles.
FIGURE 19.15 The rotational molding (rotomolding or rotocasting) process. Trash cans, buckets, and plastic footballs can be made by this process.
FIGURE 19.16  Various thermoforming processes for a thermoplastic sheet. These processes commonly are used in making advertising signs, cookie and candy trays, panels for shower stalls, and packaging.
Thermoforming

Process Capabilities

- Parts with openings cannot be formed
- A combination of drawing & stretching
  - Requires material capable of high, uniform, elongation, i.e. thermoplastics
- Molds usually Aluminum (ductile, low strength)
- Molds have small through holes to aid vacuum forming

Defects

- Tearing of sheet during forming
- Non-uniform wall thickness
- Improperly filled molds
- Poor part definition
- Lack of surface details
FIGURE 19.17 Types of compression molding—a process similar to forging: (a) positive, (b) semipositive, and (c) flash, in which the flash is later trimmed off. (d) Die design for making a compression-molded part with external undercuts.
FIGURE 19.18  Sequence of operations in transfer molding for thermosetting plastics. This process is suitable particularly for intricate parts with varying wall thickness.
FIGURE 19.19  Schematic illustration of (a) casting, (b) potting, and (c) encapsulation processes for plastics and electrical assemblies, where the surrounding plastic serves as a dielectric.
Foam Molding

• The raw material is expandable polystyrene beads, possess a cellular structure
• The beads may be small (for cups, etc.), medium, large (for building blocks, cut)
• Polystyrene beads placed in mold with blowing agent (e.g. nitrogen) and exposed to heat (usually steam)
• Beads expand (up to 50 times) to take shape of cavity
• Control expansion by temperature & time
FIGURE 19.20 Schematic illustration of calendering. Sheets produced by this process subsequently are used in thermoforming. The process also is used in the production of various elastomer and rubber products.
Reinforced Plastics

- Are also known as polymer-matrix composites (PMC) and fibre-reinforced plastics (FRP)
- Consist of fibres in a polymer matrix
Common fibres are:
  - Glass, Carbon, Conductive graphite, Ceramic, Polymer, Boron
Matrix
- Support fibres in place; transfer stresses to fibres
- Physically protect fibres
- Reduce propagation of cracks in the composite
- Usually TP or TS
FIGURE 19.21 Reinforced-plastic components for a Honda motorcycle. The parts shown are front and rear forks, a rear swing arm, a wheel, and brake disks.
FIGURE 19.22  (a) Manufacturing process for polymer-matrix composite tape. (b) Boron epoxy prepreg tape. These tapes are then used in making reinforced plastic parts and components with high strength-to-weight and stiffness-to-weight ratios, particularly important for aircraft and aerospace applications and sports equipment. Source: (a) After T. W. Chou, R.L. McCullough, and R.B. Pipes. (b) Courtesy of Avco Specialty Materials/ Textron.
FIGURE 19.23  (a) Single-ply layup of boron-epoxy tape for the horizontal stabilizer for an F-14 fighter aircraft. (b) A 10-axis computer-numerical-controlled tape-laying system. This machine is capable of laying up 75- and 150-mm (3- and 6-in.) wide tapes on contours of up to ±30° and at speeds of up to 0.5 m/s (1.7 ft/s).

Source: (a) Courtesy of Grumman Aircraft Corporation. (b) Courtesy of The Ingersoll Milling Machine Company.
FIGURE 19.24 Schematic illustration of the manufacturing process for producing fiber-reinforced plastic sheets. The sheet still is viscous at this stage and later can be shaped into various products. Source: After T.-W. Chou, R.L. McCullough, and R.B. Pipes.
FIGURE 19.25  Schematic illustration of (a) vacuum-bag forming and (b) pressure-bag forming. These processes are used in making discrete reinforced plastic parts. Source: After T.H. Meister.
FIGURE 19.26 Manual methods of processing reinforced plastics: (a) hand layup and (b) spray layup. Note that, even though the process is slow, only one mold is required. The figures show a female mold, but male molds are used as well. These methods also are called *open-mold processing*. (c) A boat hull being made by these processes.

*Source:* Courtesy of Genmar Holdings, Inc.
FIGURE 19.27  (a) Schematic illustration of the filament-winding process; (b) fiberglass being wound over aluminum liners for slide-raft inflation vessels for the Boeing 767 aircraft. The products made by this process have a high strength-to-weight ratio and also serve as lightweight pressure vessels. *Source:* Courtesy of Brunswick Corporation.
The major components of fiberglass ladders (used especially by electricians) are made by this process. They are available in different colors, but are heavier because of the presence of glass fibers.

*Source: Courtesy of Strongwell Corporation.*
Quality Issues In Processing Reinforced Plastics

• Major quality concern is occurrence of internal voids and gaps between successive layers of material
  – Volatile gasses can develop during processing; trapped gasses cause porosity
  – Remove voids by roller (pressure) &/or vacuum

• Microcracks:
  – Caused by Improper curing
  – During transport and handling

• Can detect internal defects by ultrasonic tests
FIGURE 19.29  A Head Protector™ tennis racquet. Source: Courtesy of Head Sport AG.
FIGURE 19.30  (a) The composite Head Protector™ racquet immediately after molding; (b) a completed Head Protector™ racquet, highlighting the incorporation of piezoelectric Intellifibers™. Source: Courtesy of Head Sport AG.
Composites

• A combination of two or more chemically distinct and insoluble phases with a recognizable interface, in such a manner that its properties and structural performance are superior to those of the constituents acting independently

• Metal-matrix Composites

• Ceramic-matrix Composites
Metal-matrix Composites

• Advantages of metal matrix over polymer matrix:
  – Higher elastic modulus
  – Higher toughness
  – Higher ductility
  – Higher resistance to elevated temperatures

• Limitations:
  – Higher density
  – Greater difficulty processing parts
Metal-matrix Composites (MMC)

• Matrix materials:
  – Aluminum
  – Aluminum-lithium alloy
  – Magnesium
  – Copper
  – Titanium
  – Superalloys

• Fibre materials
  – Graphite
  – Aluminum oxide
  – Silicon Carbide
  – Boron
  – Molybdenum
  – Tungsten
MMC Manufacturing Processes

Liquid-phase processing

• Cast together the liquid-matrix material (e.g. Al, Ti) and the solid reinforcement (Graphite, Aluminum oxide, Silicon carbide)

• Conventional casting process, or

• Pressure-infiltration casting
  – Pressurized gas is used to force the liquid metal-matrix into a preform
High temperature vacuum transfer of alloys for pressure infiltration of ceramic and carbon fiber preforms. Metal Matrix Cast Composites, Inc.
MMC Manufacturing Processes

- **Solid-phase processing**
- Uses powder-metallurgy techniques
- Cold & hot isostatic pressing

- Figure 17.13
MMC Manufacturing Processes

• **Two-phase (liquid-solid) processing**
  – Combines techniques of
    • rheocasting,
    • spray atomization,
    • deposition
Ceramic-matrix Composites (CMC)

- Have resistance to high temperatures and corrosive environments
- Ceramics are strong & stiff but lack toughness
- Matrix materials include:
  - Silicon carbide
  - Silicon nitride
  - Aluminum oxide
  - Mullite (compound of aluminum, silicon, oxygen)
- Fibre materials include:
  - Carbon
  - Aluminum oxide
CMC Processes

- **Slurry infiltration**
  - Pass fibers through a slurry containing particles of the ceramic matrix, carrier liquid, organic binder
  - Wind the fibres infiltrated by the slurry onto a drum and dry
  - Stack the slurry impregnated fibres in a desired shape
  - Consolidate the matrix by hot pressing in a graphite die at high temperature
CMC Processes

• Chemical-synthesis

• Chemical-vapour Infiltration
Design Considerations
in forming and shaping of plastics

• Material selection considerations
  – Service requirements
  – Long-term effects on properties
    • Dimensional stability & wear
  – End of useful life disposal
Design Guidelines

• Plastics manufacturing capability competitive with metals (volume, speed, complex shapes); consider part properties appropriate to application
• Plastics have lower stiffness and strength than metals; consider design modifications, use of reinforced plastics
• Part requirements (shape, thickness, tolerances) can influence process selection
• Avoid large variations in cross-section area and thickness, abrupt change in geometry
• Select shapes, material, properly for improved stiffness
• Consider physical properties; avoid distortion, warping
• Consider work hardening and residual stresses
• Consider directional strength of reinforced plastics
FIGURE 19.31 Examples of design modifications to eliminate or minimize distortion in plastic parts: (a) suggested design changes to minimize distortion; (b) stiffening the bottoms of thin plastic containers by doming—a technique similar to the process used to shape the bottoms of aluminum beverage cans; and (c) design change in a rib to minimize pull-in (sink mark) caused by shrinkage during the cooling of thick sections in molded parts.
TABLE 19.2 Comparative Production Characteristics of Various Molding Methods

<table>
<thead>
<tr>
<th>Molding method</th>
<th>Equipment and tooling cost</th>
<th>Production rate</th>
<th>Economical production quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion</td>
<td>M–L</td>
<td>VH–H</td>
<td>VH</td>
</tr>
<tr>
<td>Injection molding</td>
<td>VH</td>
<td>VH</td>
<td>VH</td>
</tr>
<tr>
<td>Rotational molding</td>
<td>M</td>
<td>M–L</td>
<td>M</td>
</tr>
<tr>
<td>Blow molding</td>
<td>M</td>
<td>H–M</td>
<td>H</td>
</tr>
<tr>
<td>Compression molding</td>
<td>H–M</td>
<td>M</td>
<td>H–M</td>
</tr>
<tr>
<td>Transfer molding</td>
<td>H</td>
<td>M</td>
<td>VH</td>
</tr>
<tr>
<td>Thermoforming</td>
<td>M–L</td>
<td>M–L</td>
<td>H–M</td>
</tr>
<tr>
<td>Casting</td>
<td>M–L</td>
<td>M–L</td>
<td>L</td>
</tr>
<tr>
<td>Centrifugal casting</td>
<td>H–M</td>
<td>M–L</td>
<td>M–L</td>
</tr>
<tr>
<td>Pultrusion</td>
<td>H–M</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Filament winding</td>
<td>H–M</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Spray layup and hand layup</td>
<td>L–VL</td>
<td>L–VL</td>
<td>L</td>
</tr>
</tbody>
</table>

VH = very high; H = high; M = medium; L = low; VL = very low.
Summary

• TP shaped by many processes including extrusion, molding, casting, thermoforming
  – Raw material in form of granules, pellets, powder
  – TP can stretch; produce complex, deep shapes
• TS generally molded or cast
• TS better dimensional accuracy than TP
• Fibre-reinforced plastics (stronger) produced by a variety of methods
• Design of plastic parts must consider low strength and stiffness, other physical properties
• MMC and CMC processes continue development
• Consider economics, comparing with metals: machinery, dies, cycle times, production rate, volume