13 Shaping Processes for Plastics

Plastics can be shaped into a wide variety of products, such as molded parts, extruded sections, films and sheets, insulation coatings on electrical wires, and fibers for textiles. In addition, plastics are often the principal ingredient in other materials, such as paints and varnishes, adhesives, and various polymer matrix composites. This chapter considers the technologies by which these products are shaped, postponing paints and varnishes, adhesives, and composites until later chapters. Many plastic-shaping processes can be adapted to polymer matrix composites and rubbers (Chapter 14).

The commercial and technological importance of these shaping processes derives from the growing importance of the materials being processed. Applications of plastics have increased at a much faster rate than either metals or ceramics during the last 50 years. Indeed, many parts previously made of metals are today being made of plastics and plastic composites. The same is true of glass; plastic containers have been largely substituted for glass bottles and jars in product packaging. The total volume of polymers (plastics and rubbers) now exceeds that of metals. There are several reasons why the plastic-shaping processes are important:

➢ The variety of shaping processes, and the ease with which polymers can be processed, allows an almost unlimited variety of part geometries to be formed.

➢ Many plastic parts are formed by molding, which is a *net shape* process. Further shaping is generally not needed.

➢ Although heating is usually required to form plastics, less energy is required than for metals because the processing temperatures are much lower.

➢ Because lower temperatures are used in processing, handling of the product is simplified during production. Because many plastic processing methods are

one-step operations (e.g., molding), the amount of product handling required is substantially reduced compared with metals.

➤ Finishing by painting or plating is not required (except in unusual circumstances) for plastics.

As discussed in Chapter 8, the two types of plastics are ***thermoplastics*** and ***thermosets***. The difference is that thermosets undergo a curing process during heating and shaping, which causes a permanent chemical change (***cross-linking***) in their molecular structure. Once they have been cured, they cannot be melted through reheating. By contrast, thermoplastics do not cure, and their chemical structure remains basically unchanged upon reheating even though they transform from solid to fluid. Of the two types, thermoplastics are by far the more important type commercially, comprising more than 80% of the total plastics tonnage.

Plastic-shaping processes can be classified as follows according to the resulting product geometry: (1) continuous extruded products with constant cross section other than sheets, films, and filaments; (2) continuous sheets and films; (3) continuous filaments (fibers); (4) molded parts that are mostly solid; (5) hollow molded parts with relatively thin walls; (6) discrete parts made of formed sheets and films; (7) castings; and (8) foamed products. This chapter examines each of these categories. The most important processes commercially are those associated with thermoplastics; the two processes of greatest significance are extrusion and injection molding. A brief history of plastic-shaping processes is presented in Historical Note 13.1.

Coverage of the plastic-shaping processes begins by examining the properties of polymer melts, because nearly all of the thermoplastic shaping processes share the common step of heating the plastic so that it flows.

Historical Note 13.1   *Plastic shaping processes*

Equipment for shaping plastics evolved largely from rubber processing technology. Noteworthy among the early contributors was Edwin Chaffee, an American who developed a two-roll steam-heated mill for mixing additives into rubber around 1835 (Section 14.5.2). He was also responsible for a similar device called a calender, which consists of a series of heated rolls for coating rubber onto cloth (Section 13.3). Both machines are still used today for plastics as well as rubbers.

The first extruders, dating from around 1845 in England, were ram-driven machines for extruding rubber and coating rubber onto electrical wire. The trouble with ram-type extruders is that they operate in an intermittent fashion. An extruder that could operate continuously, especially for wire and cable coating, was highly desirable. Although several individuals worked with varying degrees of success on a screw-type extruder (Section 13.2.1), Mathew Gray in England is credited with the invention; his patent is dated 1879. As thermoplastics were subsequently developed, these screw extruders, originally designed for rubber, were adapted. An extrusion machine specifically designed for thermoplastics was introduced in 1935.

Injection molding machines for plastics were adaptations of equipment designed for metal die casting (Historical Note 11.2). Around 1872, John Hyatt, an important figure in the development of plastics (Historical Note 8.1), patented a molding machine specifically for plastics. It was a plunger-type machine (Section 13.6.3). The injection molding machine in its modern form was introduced in 1921, with semiautomatic controls added in 1937. Ram-type machines were the standard in the plastic molding industry for many decades, until the superiority of the reciprocating screw machine, developed by William Willert in the United States in 1952, became obvious.

3.1 Properties of Polymer Melts

To shape a thermoplastic polymer it must be heated so that it softens to the consistency of a liquid. In this form, it is called a *polymer melt*. Polymer melts exhibit several unique properties and characteristics, considered in this section.

Viscosity   Because of its high molecular weight, a polymer melt is a thick fluid with high viscosity. As the term is defined in Section 3.4, *viscosity* is a fluid property that relates the shear stress experienced during flow of the fluid to the rate of shear. Viscosity is important in polymer processing because most of the shaping methods involve flow of the polymer melt through small channels or die openings. The flow rates are often large, thus leading to high rates of shear; and the shear stresses increase with shear rate, so that significant pressures are required to accomplish the processes.

Figure 13.1 shows viscosity as a function of shear rate for two types of fluids. For a *Newtonian fluid* (which includes most simple fluids such as water and oil), viscosity is a constant at a given temperature; it does not change with shear rate. The relationship between shear stress and shear strain is proportional, with viscosity as the constant of proportionality:

$$\tau = \eta\dot{\gamma} \quad \text{or} \quad \eta = \frac{\tau}{\dot{\gamma}} \tag{13.1}$$

where τ = shear stress, Pa (lb/in²); η = coefficient of shear viscosity, Ns/m², or Pa-s (lb-sec/in²); and $\dot{\gamma}$ = shear rate, 1/s (1/sec). However, for a polymer melt, viscosity decreases with shear rate, indicating that the fluid becomes thinner at higher rates of shear. This behavior is called *pseudoplasticity* and can be modeled to a reasonable approximation by the expression

$$\tau = k(\dot{\gamma})^n \tag{13.2}$$

where k = a constant corresponding to the viscosity coefficient and n = flow behavior index. For $n = 1$, the equation reduces to the previous Equation (13.1) for a Newtonian fluid, and k becomes η. For a polymer melt, values of n are less than 1.

In addition to the effect of shear rate (fluid flow rate), viscosity of a polymer melt is also affected by temperature. Like most fluids, the value decreases with increasing temperature. This is shown in Figure 13.2 for several common
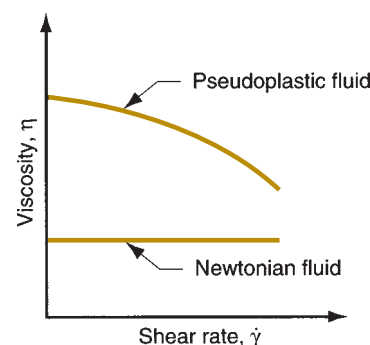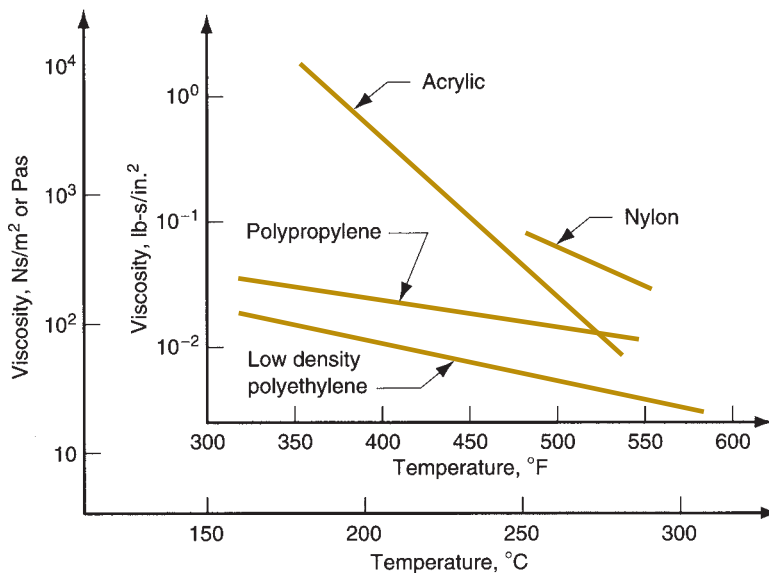

FIGURE 13.1   Viscosity relationships for Newtonian fluid and typical polymer melt.

FIGURE 13.2 Viscosity as a function of temperatures for selected polymers at a shear rate of 10^3 s^{-1}. (Data compiled from [12].)

polymers at a shear rate of 10^3 s^{-1}, which is approximately the same as the rates encountered in injection molding and high speed extrusion. Thus, the viscosity of a polymer melt decreases with increasing values of shear rate and temperature. Equation (13.2) can be applied, except that k depends on temperature as shown in Figure 13.2.

Viscoelasticity   Another property possessed by polymer melts is viscoelasticity, which was discussed in the context of solid polymers in Section 3.5. However, liquid polymers exhibit it also. A good example is ***die swell*** in extrusion, in which the hot plastic expands when exiting the die opening. The phenomenon, illustrated in Figure 13.3, can be explained by noting that the polymer was contained in a much larger cross section before entering the narrow die channel. In effect, the extruded material "remembers" its former shape and attempts to return to it after leaving the die orifice. More technically, the compressive stresses acting on the material as it enters the small die opening do not relax immediately. When the material subsequently exits the orifice and the restriction is removed, the unrelaxed stresses cause the cross section to expand.
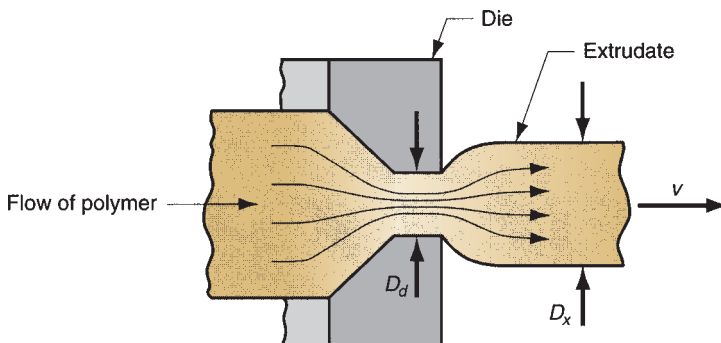

FIGURE 13.3   Die swell, a manifestation of viscoelasticity in polymer melts, as depicted here on exiting an extrusion die.

Die swell can be most easily measured for a circular cross section by means of the *swell ratio*, defined as

$$r_s = \frac{D_x}{D_d} \qquad (13.3)$$

where r_s = swell ratio; D_x = diameter of the extruded cross section, mm (in); and D_d = diameter of the die orifice, mm (in). The amount of die swell depends on the time the polymer melt spends in the die channel. Increasing the time in the channel, by means of a longer channel, reduces die swell.

3.2 Extrusion

Extrusion is one of the fundamental shaping processes, for metals and ceramics as well as polymers. *Extrusion* is a compression process in which material is forced to flow through a die orifice to provide long continuous product whose cross-sectional shape is determined by the shape of the orifice. As a polymer shaping process, it is widely used for thermoplastics and elastomers (but rarely for thermosets) to mass produce items such as tubing, pipes, hose, structural shapes (such as window and door moldings), sheet and film, continuous filaments, and coated electrical wire and cable. For these types of products, extrusion is carried out as a continuous process; the *extrudate* (extruded product) is subsequently cut into desired lengths. This section covers the basic extrusion process, and several subsequent sections examine processes based on extrusion.

13.2.1 PROCESS AND EQUIPMENT

In polymer extrusion, feedstock in pellet or powder form is fed into an extrusion barrel where it is heated and melted and forced to flow through a die opening by means of a rotating screw, as illustrated in Figure 13.4. The two main components of the extruder are the barrel and the screw. The die is not a component of the extruder; it is a special tool that must be fabricated for the particular profile to be produced.
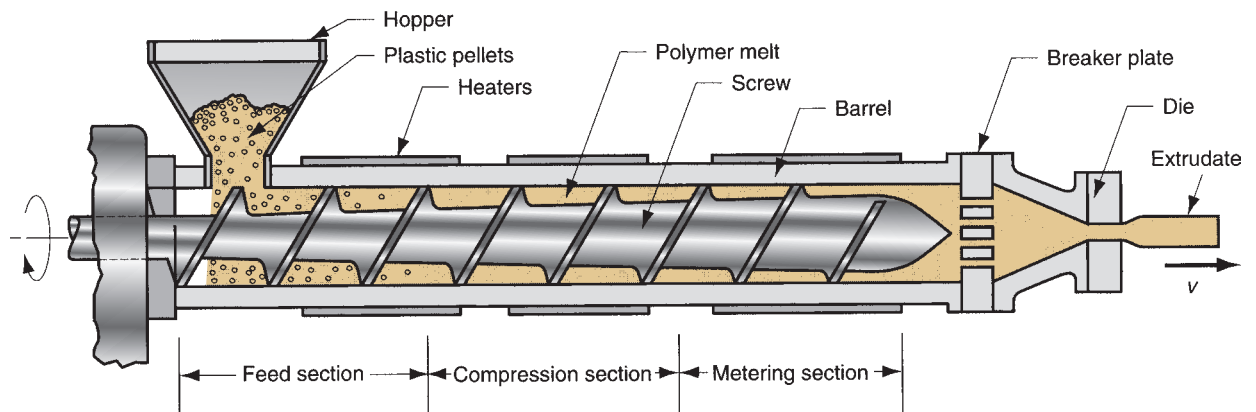

FIGURE 13.4   Components and features of a single-screw extruder for plastics and elastomers.

The internal diameter of the extruder barrel typically ranges from 25 to 150 mm (1.0–6.0 in). The barrel is long relative to its diameter, with L/D ratios usually between 10 and 30. The L/D ratio is reduced in Figure 13.4 for clarity of drawing. The higher ratios are used for thermoplastic materials, whereas lower L/D values are for elastomers. A hopper containing the feedstock is located at the end of the barrel opposite the die. The pellets are fed by gravity onto the rotating screw whose turning moves the material along the barrel. Electric heaters are used to initially melt the solid pellets; subsequent mixing and mechanical working of the material generate additional heat, which maintains the melt. In some cases, enough heat is supplied through the mixing and shearing action that external heating is not required. Indeed, in some cases the barrel must be externally cooled to prevent overheating of the polymer.

The material is conveyed through the barrel toward the die opening by the action of the extruder screw, which rotates at about 60 rev/min. The screw serves several functions and is divided into sections that correspond to these functions. The sections and functions are the (1) **feed section**, in which the stock is moved from the hopper port and preheated; (2) **compression section**, where the polymer is transformed into liquid consistency, air entrapped amongst the pellets is extracted from the melt, and the material is compressed; and (3) **metering section**, in which the melt is homogenized and sufficient pressure is developed to pump it through the die opening.

The operation of the screw is determined by its geometry and speed of rotation. Typical extruder screw geometry is depicted in Figure 13.5. The screw consists of spiraled "flights" (threads) with channels between them through which the polymer melt is moved. The channel has a width w_c and depth d_c. As the screw rotates, the flights push the material forward through the channel from the hopper end of the barrel toward the die. Although not discernible in the diagram, the flight diameter is smaller than the barrel diameter D by a very small clearance—around 0.05 mm (0.002 in). The function of the clearance is to limit leakage of the melt backward to the trailing channel. The flight land has a width w_f and is made of hardened steel to resist wear as it turns and rubs against the inside of the barrel. The screw has a pitch
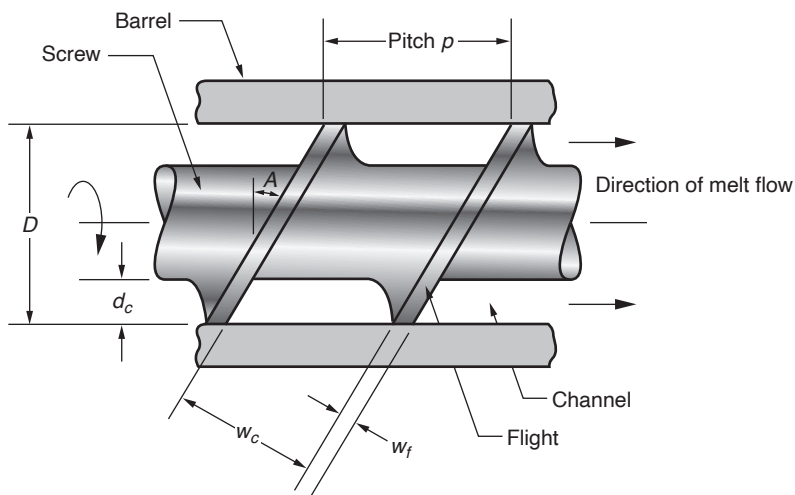

FIGURE 13.5 Details of an extruder screw inside the barrel.

whose value is usually close to the diameter D. The flight angle A is the helix angle of the screw and can be determined from the relation

$$\tan A = \frac{p}{\pi D} \qquad (13.4)$$

where p = pitch of the screw.[1]

The increase in pressure applied to the polymer melt in the three sections of the barrel is determined largely by the channel depth d_c. In Figure 13.4, d_c is relatively large in the feed section to allow large amounts of granular polymer to be admitted into the barrel. In the compression section, d_c is gradually reduced, thus applying increased pressure on the polymer as it melts. In the metering section, d_c is small and pressure reaches a maximum as flow is restrained at the die end of the barrel. The three sections of the screw are shown as being about equal in length in Figure 13.4; this is appropriate for a polymer that melts gradually, such as low-density polyethylene. For other polymers, the optimal section lengths are different. For crystalline polymers such as nylon, melting occurs rather abruptly at a specific melting point; therefore, a short compression section is appropriate. Amorphous polymers such as polyvinylchloride melt more slowly than LDPE, and the compression zone for these materials must take almost the entire length of the screw. Although the optimal screw design for each material type is different, it is common practice to use general-purpose screws. These designs represent a compromise among the different materials, and they avoid the need to make frequent screw changes, which result in costly equipment downtime.

Progress of the polymer along the barrel leads ultimately to the die zone. Before reaching the die, the melt passes through a screen pack—a series of wire meshes supported by a stiff plate (called a **breaker plate**) containing small axial holes. The screen pack assembly functions to (1) filter contaminants and hard lumps from the melt; (2) build pressure in the metering section; and (3) straighten the flow of the polymer melt and remove its "memory" of the circular motion imposed by the screw. This last function is concerned with the polymer's viscoelastic property; if the flow were left unstraightened, the polymer would play back its history of turning inside the extrusion chamber, tending to twist and distort the extrudate.

13.2.2   ANALYSIS OF EXTRUSION

In this section, mathematical models are developed to describe, in a simplified way, several aspects of polymer extrusion.

Melt Flow in the Extruder   As the screw rotates inside the barrel, the polymer melt is forced to move forward toward the die; the system operates much like an Archimedean screw. The principal transport mechanism is **drag flow**, resulting from friction between the viscous liquid and two opposing surfaces moving relative to each other: (1) the stationary barrel and (2) the channel of the turning screw. The arrangement can be likened to the fluid flow that occurs between a stationary plate and a moving plate separated by a viscous liquid, as illustrated in Figure 3.17. Given

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[1]Unfortunately, p is the natural symbol to use for two variables in this chapter. It represents the screw pitch here and in several other chapters. The same symbol p is also used for pressure later in the chapter.

that the moving plate has a velocity v, it can be reasoned that the average velocity of the fluid is $v/2$, resulting in a volume flow rate of

$$Q_d = 0.5 \, v \, d \, w \qquad (13.5)$$

where Q_d = volume drag flow rate, m³/s (in³/sec.); v = velocity of the moving plate, m/s (in/sec.); d = distance separating the two plates, m (in); and w = the width of the plates perpendicular to velocity direction, m (in). These parameters can be compared with those in the channel defined by the rotating extrusion screw and the stationary barrel surface.

$$v = \pi D N \cos A \qquad (13.6)$$

$$d = d_c \qquad (13.7)$$

$$\text{and } w = w_c = (\pi D \tan A - w_f) \cos A \qquad (13.8)$$

where D = screw flight diameter, m (in); N = screw rotational speed, rev/s; d_c = screw channel depth, m (in); w_c = screw channel width, m (in); A = flight angle; and w_f = flight land width, m (in). If the flight land width is assumed to be negligibly small, then the last of these equations reduces to

$$w_c = \pi D \tan A \cos A = \pi D \sin A \qquad (13.9)$$

Substituting Equations (13.6), (13.7), and (13.9) into Equation (13.5), and using several trigonometric identities,

$$Q_d = 0.5 \, \pi^2 \, D^2 \, N \, d_c \sin A \cos A \qquad (13.10)$$

If no forces were present to resist the forward motion of the fluid, this equation would provide a reasonable description of the melt flow rate inside the extruder. However, compressing the polymer melt through the downstream die creates a **back pressure** in the barrel that reduces the material moved by drag flow in Equation (13.10). This flow reduction, called the **back pressure flow**, depends on the screw dimensions, viscosity of the polymer melt, and pressure gradient along the barrel. These dependencies can be summarized in this equation [12]:

$$Q_b = \frac{\pi D d_c^3 \sin^2 A}{12\eta} \left(\frac{dp}{dl} \right) \qquad (13.11)$$

where Q_b = back pressure flow, m³/s (in³/sec); η = viscosity, N-s/m² (lb-sec/in²); dp/dl = the pressure gradient, MPa/m (lb/in²/in); and the other terms were previously defined. The actual pressure gradient in the barrel is a function of the shape of the screw over its length; a typical pressure profile is given in Figure 13.6. If the profile is assumed to be a straight line, indicated by the dashed line in the figure, then the pressure gradient becomes a constant p/L, and the previous equation reduces to

$$Q_b = \frac{p \pi D d_c^3 \sin^2 A}{12\eta L} \qquad (13.12)$$

where p = head pressure in the barrel, MPa (lb/in²); and L = length of the barrel, m (in). Recall that this back pressure flow is really not an actual flow by itself; it is a

FIGURE 13.6 Typical pressure gradient in an extruder; dashed line indicates a straight line approximation to facilitate computations.
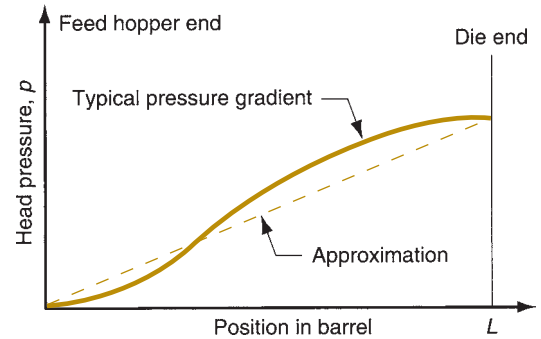
reduction in the drag flow. Thus, the magnitude of the melt flow in an extruder can be computed as the difference between the drag flow and back pressure flow:

$$Q_x = Q_d - Q_b$$
$$Q_x = 0.5 \, \pi^2 \, D^2 \, N \, d_c \sin A \cos A - \frac{p \pi D d_c^3 \sin^2 A}{12 \eta L} \tag{13.13}$$

where Q_x = the resulting flow rate of polymer melt in the extruder. Equation (13.13) assumes that there is minimal **leak flow** through the clearance between flights and barrel. Leak flow of melt will be small compared with drag and back pressure flow except in badly worn extruders.

Equation (13.13) contains many parameters, which can be divided into two types: (1) design parameters, and (2) operating parameters. The design parameters define the geometry of the screw and barrel: diameter D, length L, channel depth d_c, and helix angle A. For a given extruder operation, these factors cannot be changed during the process. The operating parameters can be changed during the process to affect output flow; they include rotational speed N, head pressure p, and melt viscosity η. Of course, melt viscosity is controllable only to the extent to which temperature and shear rate can be manipulated to affect this property. The following example shows how the parameters play out their roles.

Example 13.1 Extrusion flow rates	An extruder barrel has a diameter $D = 75$ mm. The screw rotates at $N = 1$ rev/s. Channel depth $d_c = 6.0$ mm and flight angle $A = 20°$. Head pressure at the end of the barrel $p = 7.0 \times 10^6$ Pa, length of the barrel $L = 1.9$ m, and viscosity of the polymer melt is assumed to be $\eta = 100$ Pa-s. Determine the volume flow rate of the plastic in the barrel Q_x.

Solution: Equation (13.13) can be used to compute the drag flow and opposing back pressure flow in the barrel.

$$Q_d = 0.5 \, \pi^2 (75 \times 10^{-3})^2 \, (1.0) \, (6 \times 10^{-3}) \, (\sin 20) \, (\cos 20) = 53{,}525 \, (10^{-9}) \, \text{m}^3\text{/s}$$

$$Q_b = \frac{\pi (7 \times 10^6)(75 \times 10^{-3})(6 \times 10^{-3})^3 \, (\sin 20)^2}{12(100)(1.9)} = 18.276(10^{-6}) = 18{,}276(10^{-9}) \, \text{m}^3\text{/s}$$

$$Q_x = Q_d - Q_b = (53{,}525 - 18{,}276) \, (10^{-9}) = \mathbf{35{,}249(10^{-9}) \, m^3\text{/s}}$$

Extruder and Die Characteristics If back pressure is zero, so that melt flow is unrestrained in the extruder, then the flow would equal drag flow Q_d given by Equation (13.10). Given the design and operating parameters (D, A, N, etc.), this is the maximum possible flow capacity of the extruder. Denote it as Q_{max}:

$$Q_{max} = 0.5\pi^2 D^2 N d_c \sin A \cos A \qquad (13.14)$$

On the other hand, if back pressure were so great as to cause zero flow, then back pressure flow would equal drag flow; that is,

$$Q_x = Q_d - Q_b = 0, \text{ so } Q_d = Q_b$$

Using the expressions for Q_d and Q_b in Equation (13.13), we can solve for p to determine what this maximum head pressure p_{max} would have to be to cause no flow in the extruder:

$$p_{max} = \frac{6\pi DNL\eta \cot A}{d_c^2} \qquad (13.15)$$

The two values Q_{max} and p_{max} are points along the axes of a diagram known as the *extruder characteristic* (or *screw characteristic*), as in Figure 13.7. It defines the relationship between head pressure and flow rate in an extrusion machine with given operating parameters.

With a die in the machine and the extrusion process underway, the actual values of Q_x and p will lie somewhere between the extreme values, the location determined by the characteristics of the die. Flow rate through the die depends on the size and shape of the opening and the pressure applied to force the melt through it. This can be expressed as

$$Q_x = K_s p \qquad (13.16)$$

where Q_x = flow rate, m³/s (in³/sec.); p = head pressure, Pa (lb/in²); and K_s = shape factor for the die, m⁵/Ns (in⁵/lb-sec). For a circular die opening of a given channel length, the shape factor can be computed [12] as

$$K_s = \frac{\pi D_d^4}{128\eta L_d} \qquad (13.17)$$

where D_d = die opening diameter, m (in) η = melt viscosity, N-s/m² (lb-sec/in²); and L_d = die opening length, m (in). For shapes other than round, the die shape factor is less than for a round of the same cross-sectional area, meaning that greater pressure is required to achieve the same flow rate.
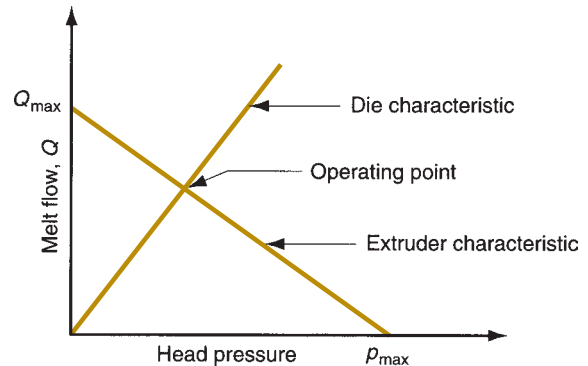

FIGURE 13.7 Extruder characteristic (also called the screw characteristic) and die characteristic. The extruder operating point is at intersection of the two lines.

The relationship between Q_x and p in Equation (13.16) is called the ***die characteristic***. In Figure 13.7, this is drawn as a straight line that intersects with the previous extruder characteristic. The intersection point identifies the values of Q_x and p that are known as the ***operating point*** for the extrusion process.

Example 13.2 Extruder and die characteristics	Consider the extruder from Example 13.1, in which $D = 75$ mm, $L = 1.9$ m, $N = 1$ rev/s, $d_c = 6$ mm, and $A = 20°$. The plastic melt has a shear viscosity $\eta = 100$ Pa-s. Determine (a) Q_{max} and p_{max}, (b) shape factor K_s for a circular die opening in which $D_d = 6.5$ mm and $L_d = 20$ mm, and (c) values of Q_x and p at the operating point.

Solution: (a) Q_{max} is given by Equation (13.14).

$$Q_{max} = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5 \pi^2 (75 \times 10^{-3})^2 (1.0)(6 \times 10^{-3})(\sin 20)(\cos 20)$$

$$= \mathbf{53{,}525(10^{-9})m^3/s}$$

p_{max} is given by Equation (13.15).

$$P_{max} = \frac{6\pi DNL\eta \cot A}{d_c^2} = \frac{6\pi (75 \times 10^{-3})(1.9)(1.0)(100)\cot 20}{(6 \times 10^{-3})^2} = \mathbf{20{,}499{,}874 \ Pa}$$

These two values define the intersection with the ordinate and abscissa for the extruder characteristic.

(b) The shape factor for a circular die opening with $D_d = 6.5$ mm and $L_d = 20$ mm can be determined from Equation (13.17).

$$K_s = \frac{\pi (6.5 \times 10^{-3})^4}{128(100)(20 \times 10^{-3})} = \mathbf{21.9(10^{-12}) \ m^5/Ns}$$

This shape factor defines the slope of the die characteristic.

(c) The operating point is defined by the values of Q_x and p at which the screw characteristic intersects with the die characteristic. The screw characteristic can be expressed as the equation of the straight line between Q_{max} and p_{max}, which is

$$\begin{aligned}Q_x &= Q_{max} - (Q_{max} / p_{max})p \\ &= 53{,}525(10^{-9}) - (53{,}525(10^{-9})/20{,}499{,}874)p \\ &= 53{,}525(10^{-9}) - 2.611(10^{-12})p \end{aligned} \quad (13.18)$$

The die characteristic is given by Equation (13.16) using the value of K_s computed in part (b).

$$Q_x = 21.9(10^{-12})p$$

Setting the two equations equal,

$$53{,}525(10^{-9}) - 2.611(10^{-12})p = 21.9(10^{-12})p$$

$$p = \mathbf{2.184(10^6) \ Pa}$$

Solving for Q_x using one of the starting equations,

$$Q_x = 53.525(10^{-6}) - 2.611(10^{-12})(2.184)(10^6) = \mathbf{47.822(10^{-6}) \ m^3/s}$$

Checking this with the other equation for verification,

$$Q_x = 21.9(10^{-12})(2.184)(10^6) = 47.82(10^{-6}) \ m^3/s$$

13.2.3 DIE CONFIGURATIONS AND EXTRUDED PRODUCTS

The shape of the die orifice determines the cross-sectional shape of the extrudate. The common die profiles and corresponding extruded shapes are: (1) solid profiles; (2) hollow profiles, such as tubes; (3) wire and cable coating; (4) sheet and film; and (5) filaments. The first three categories are covered in the present section. Methods for producing sheet and film are examined in Section 13.3; and filament production is discussed in Section 13.4. These latter shapes sometimes involve forming processes other than extrusion.

Solid Profiles   Solid profiles include regular shapes such as rounds and squares and irregular cross sections such as structural shapes, door and window moldings, automobile trim, and house siding. The side view cross section of a die for these solid shapes is illustrated in Figure 13.8. Just beyond the end of the screw and before the die, the polymer melt passes through the screen pack and breaker plate to straighten the flow lines. Then it flows into a (usually) converging die entrance, the shape designed to maintain laminar flow and avoid dead spots in the corners that would otherwise be present near the orifice. The melt then flows through the die opening itself.

When the material exits the die, it is still soft. Polymers with high melt viscosities are the best candidates for extrusion, because they hold shape better during cooling. Cooling is accomplished by air blowing, water spray, or passing the extrudate through a water trough. To compensate for die swell, the die opening is made long enough to remove some of the memory in the polymer melt. In addition, the extrudate is often drawn (stretched) to offset expansion from die swell.

For shapes other than round, the die opening is designed with a cross section that is slightly different from the desired profile, so that the effect of die swell is to provide shape correction. This correction is illustrated in Figure 13.9 for a square cross section. Because different polymers exhibit varying degrees of die swell, the shape of the die profile depends on the material to be extruded. Considerable skill and judgment are required by the die designer for complex cross sections.

Hollow Profiles   Extrusion of hollow profiles, such as tubes, pipes, hoses, and other cross sections containing holes, requires a mandrel to form the hollow shape.
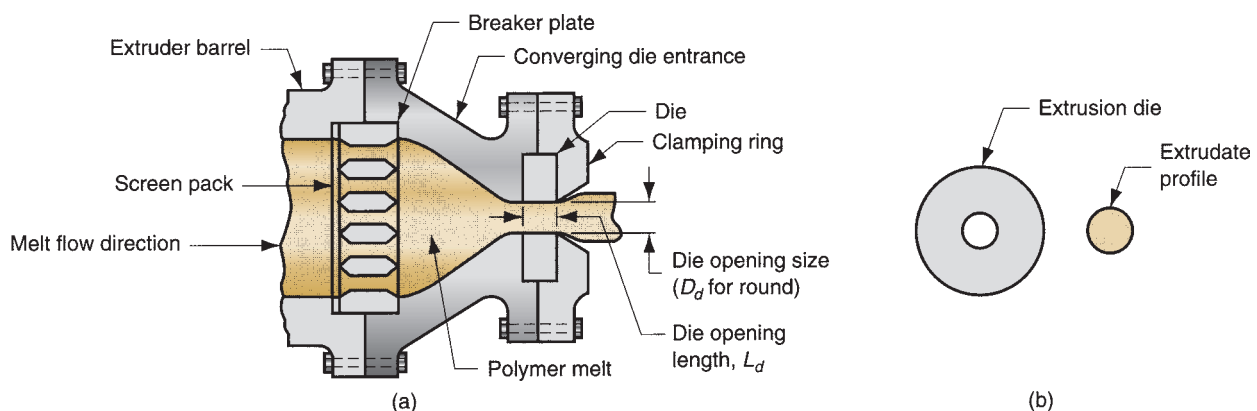

FIGURE 13.8   (a) Side view cross section of an extrusion die for solid regular shapes, such as round stock; (b) front view of die, with profile of extrudate. Die swell is evident in both views. (Some die construction details are simplified or omitted for clarity.)
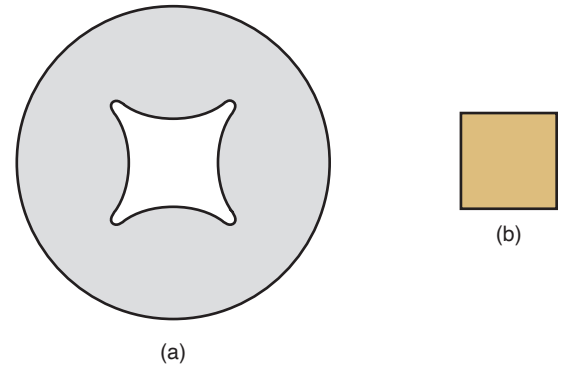
FIGURE 13.9   (a) Die cross section showing required orifice profile to obtain (b) a square extruded profile.

A typical die configuration is shown in Figure 13.10. The mandrel is held in place using a spider, seen in Section A-A of the figure. The polymer melt flows around the legs supporting the mandrel to reunite into a monolithic tube wall. The mandrel often includes an air channel through which air is blown to maintain the hollow form of the extrudate during hardening. Pipes and tubes are cooled using open water troughs or by pulling the soft extrudate through a water-filled tank with sizing sleeves that limit the OD of the tube while air pressure is maintained on the inside.

Wire and Cable Coating   The coating of wire and cable for insulation is one of the most important polymer extrusion processes. As shown in Figure 13.11 for wire coating, the polymer melt is applied to the bare wire as it is pulled at high speed through a die. A slight vacuum is drawn between the wire and the polymer to promote adhesion of the coating. The taught wire provides rigidity during cooling, which is usually aided by passing the coated wire through a water trough. The product is wound onto large spools at speeds of up to 50 m/s (10,000 ft/min).
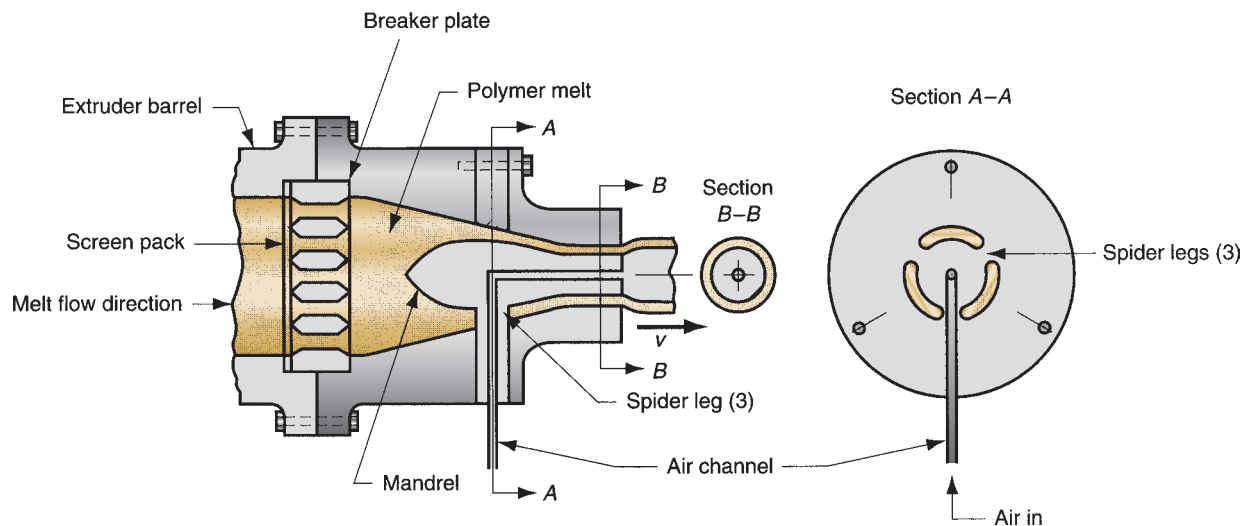

FIGURE 13.10   Side view cross section of extrusion die for shaping hollow cross sections such as tubes and pipes; Section A-A is a front view cross section showing how the mandrel is held in place; Section B-B shows the tubular cross section just prior to exiting the die; die swell causes an enlargement of the diameter. (Some die construction details are simplified.)
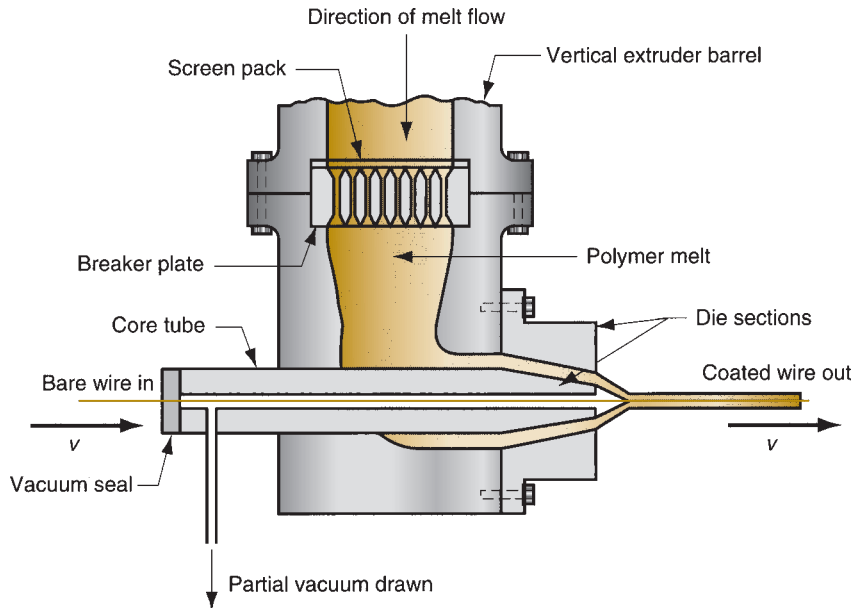
FIGURE 13.11 Side view cross section of die for coating of electrical wire by extrusion. (Some die construction details are simplified.)

13.2.4 DEFECTS IN EXTRUSION

A number of defects can afflict extruded products. One of the worst is *melt fracture*, in which the stresses acting on the melt immediately before and during its flow through the die are so high as to cause failure, manifested in the form of a highly irregular surface on the extrudate. As suggested by Figure 13.12, melt fracture can be caused by a sharp reduction at the die entrance, causing turbulent flow that breaks up the melt. This contrasts with the streamlined, laminar flow in the gradually converging die in Figure 13.8.

A more common defect in extrusion is *sharkskin*, in which the surface of the product becomes roughened upon exiting the die. As the melt flows through the die opening, friction at the interface results in a velocity profile across the cross section, Figure 13.13. Tensile stresses develop at the surface as this material is stretched to keep up with the faster moving center core. These stresses cause minor ruptures that roughen the surface. If the velocity gradient becomes extreme, prominent marks occur on the surface, giving it the appearance of a bamboo pole; hence, the name *bambooing* for this more severe defect.
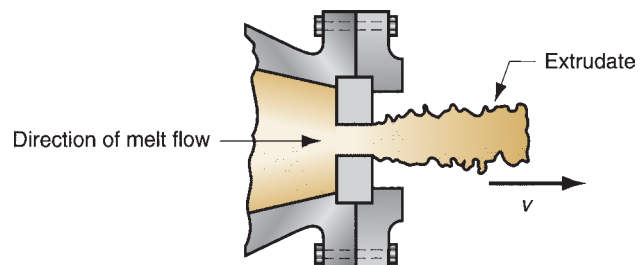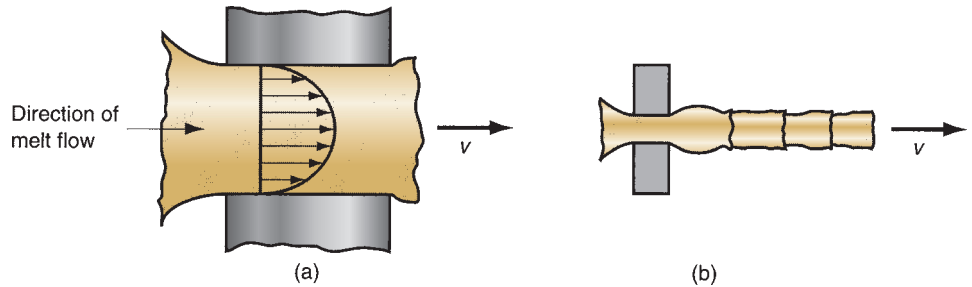
FIGURE 13.12 Melt fracture, caused by turbulent flow of the melt through a sharply reduced die entrance.

FIGURE 13.13
(a) Velocity profile of the melt as it flows through the die opening, which can lead to defects called sharkskin and (b) bambooing.

3.3 Production of Sheet and Film

Thermoplastic sheet and film are produced by a number of processes, most important of which are two methods based on extrusion. The term *sheet* refers to stock with a thickness ranging from 0.5 mm (0.020 in) to about 12.5 mm (0.5 in) and used for products such as flat window glazing and stock for thermoforming (Section 13.9). *Film* refers to thicknesses below 0.5 mm (0.020 in). Thin films are used for packaging (product wrapping material, grocery bags, and garbage bags); thicker film applications include covers and liners (pool covers and liners for irrigation ditches).

All of the processes covered in this section are continuous, high-production operations. More than half of the films produced today are polyethylene, mostly low-density PE. The principal other materials are polypropylene, polyvinylchloride, and regenerated cellulose (cellophane). These are all thermoplastic polymers.

Slit-Die Extrusion of Sheet and Film Sheet and film of various thicknesses are produced by conventional extrusion, using a narrow slit as the die opening. The slit may be up to 3 m (10 ft) wide and as narrow as around 0.4 mm (0.015 in). One possible die configuration is illustrated in Figure 13.14. The die includes a manifold that spreads the polymer melt laterally before it flows through the slit (die orifice). One of the difficulties in this extrusion method is uniformity of thickness throughout the width of the stock. This is caused by the drastic shape change experienced by
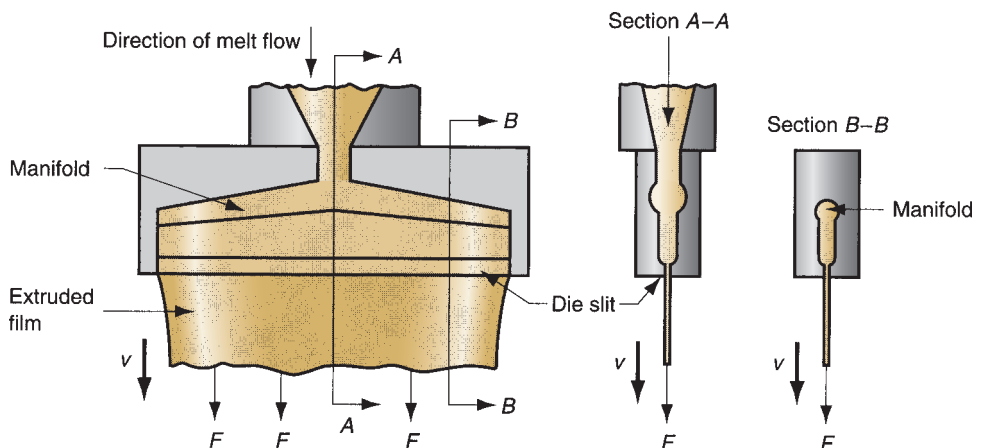

FIGURE 13.14 One of several die configurations for extruding sheet and film.
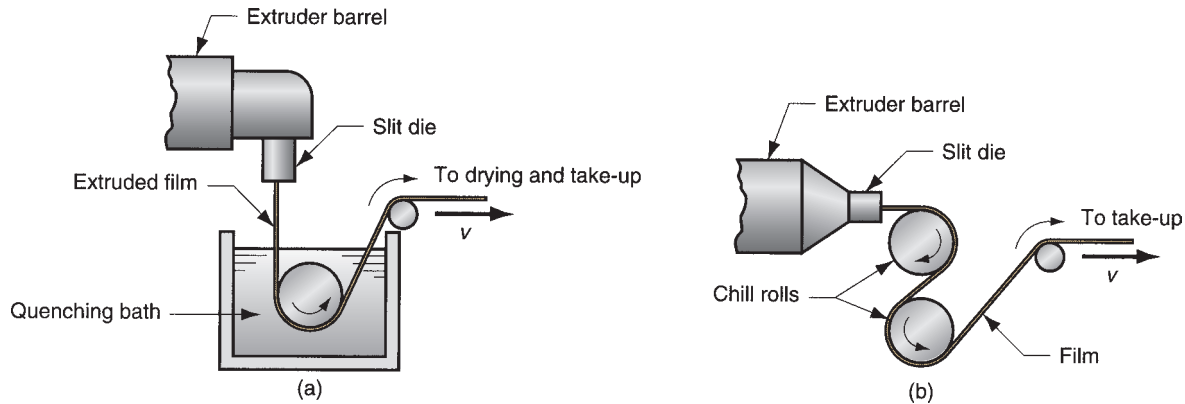
FIGURE 13.15   Use of (a) water quenching bath or (b) chill rolls to achieve fast solidification of the molten film after extrusion.

the polymer melt during its flow through the die and also to temperature and pressure variations in the die. Usually, the edges of the film must be trimmed because of thickening at the edges.

To achieve high production rates, an efficient method of cooling and collecting the film must be integrated with the extrusion process. This is usually done by immediately directing the extrudate into a quenching bath of water or onto chill rolls, as shown in Figure 13.15. The chill roll method seems to be the more important commercially. Contact with the cold rolls quickly quenches and solidifies the extrudate; in effect, the extruder serves as a feeding device for the chill rolls that actually form the film. The process is noted for very high production speeds—5 m/s (1000 ft/min). In addition, close tolerances on film thickness can be achieved. Owing to the cooling method used in this process, it is known as ***chill-roll extrusion***.

Blown-Film Extrusion Process   This is the other widely used process for making thin polyethylene film for packaging. It is a complex process, combining extrusion and blowing to produce a tube of thin film; it is best explained with reference to the diagram in Figure 13.16. The process begins with the extrusion of a tube that is immediately drawn upward while still molten and simultaneously expanded in size by air inflated into it through the die mandrel. A "frost line" marks the position along the upward moving bubble where solidification of the polymer occurs. Air pressure in the bubble must be kept constant to maintain uniform film thickness and tube diameter. The air is contained in the tube by pinch rolls that squeeze the tube back together after it has cooled. Guide rolls and collapsing rolls are also used to restrain the blown tube and direct it into the pinch rolls. The flat tube is then collected onto a windup reel.

The effect of air inflation is to stretch the film in both directions as it cools from the molten state. This results in isotropic strength properties, which is an advantage over other processes in which the material is stretched primarily in one direction. Other advantages include the ease with which extrusion rate and air pressure can be changed to control stock width and gage. Comparing this process with slit-die extrusion, the blown-film method produces stronger film (so that a thinner film can be used to package a product), but thickness control and production rates are lower.
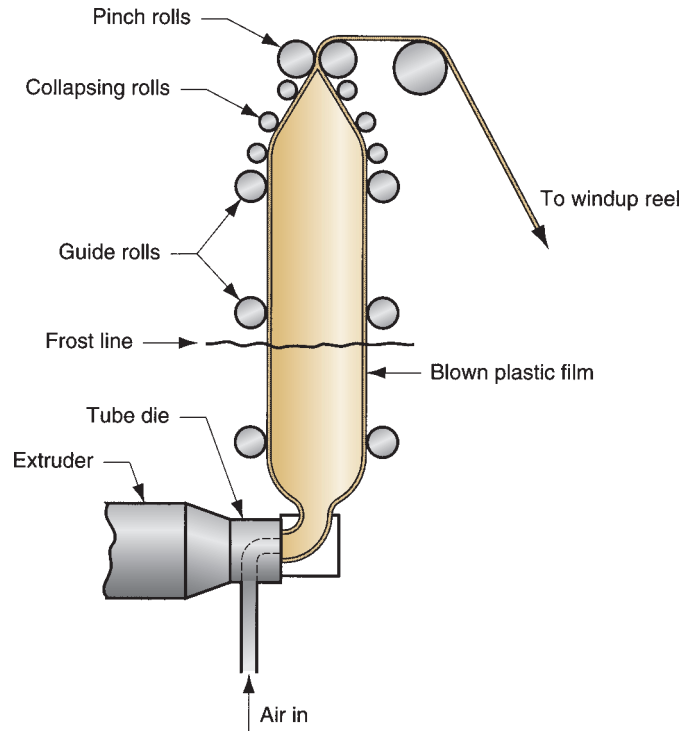
FIGURE 13.16 Blown-film process for high production of thin tubular film.

The final blown film can be left in tubular form (e.g., for garbage bags), or it can be subsequently cut at the edges to provide two parallel thin films.

Calendering   Calendering is a process for producing sheet and film stock out of rubber (Section 14.5.3) or rubbery thermoplastics such as plasticized PVC. In the process, the initial feedstock is passed through a series of rolls to work the material and reduce its thickness to the desired gage. A typical setup is illustrated in Figure 13.17. The equipment is expensive, but production rate is high; speeds approaching 2.5 m/s (500 ft/min) are possible. Close control is required over roll temperatures, pressures, and rotational speed. The process is noted for its good surface finish and high gage accuracy in the film. Plastic products made by the calendering process include PVC floor covering, shower curtains, vinyl table cloths, pool liners, and inflatable boats and toys.
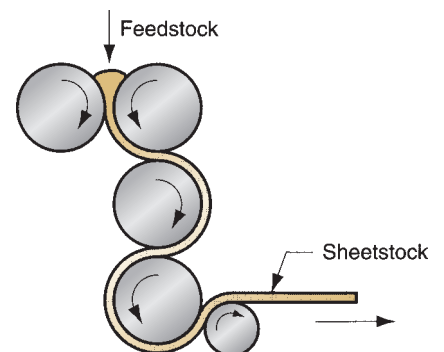

FIGURE 13.17   A typical roll configuration in calendering.

3.4 Fiber and Filament Production (Spinning)

The most important application of polymer fibers and filaments is in textiles. Their use as reinforcing materials in plastics (composites) is a growing application, but still small compared with textiles. A *fiber* can be defined as a long, thin strand of material whose length is at least 100 times its cross-sectional dimension. A *filament* is a fiber of continuous length.

Fibers can be natural or synthetic. Synthetic fibers constitute about 75% of the total fiber market today, polyester being the most important, followed by nylon, acrylics, and rayon. Natural fibers are about 25% of the total produced, with cotton by far the most important staple (wool production is significantly less than cotton).

The term *spinning* is a holdover from the methods used to draw and twist natural fibers into yarn or thread. In the production of synthetic fibers, the term refers to the process of extruding a polymer melt or solution through a *spinneret* (a die with multiple small holes) to make filaments that are then drawn and wound onto a *bobbin*. There are three principal variations in the spinning of synthetic fibers, depending on the polymer being processed: (1) melt spinning, (2) dry spinning, and (3) wet spinning.

Melt spinning is used when the starting polymer can best be processed by heating to the molten state and pumping through the spinneret, much in the manner of conventional extrusion. A typical spinneret is 6 mm (0.25 in) thick and contains approximately 50 holes of diameter 0.25 mm (0.010 in); the holes are countersunk, so that the resulting bore has an *L/D* ratio of only 5/1 or less. The filaments that emanate from the die are drawn and simultaneously air cooled before being collected together and spooled onto the bobbin, as shown in Figure 13.18. Significant
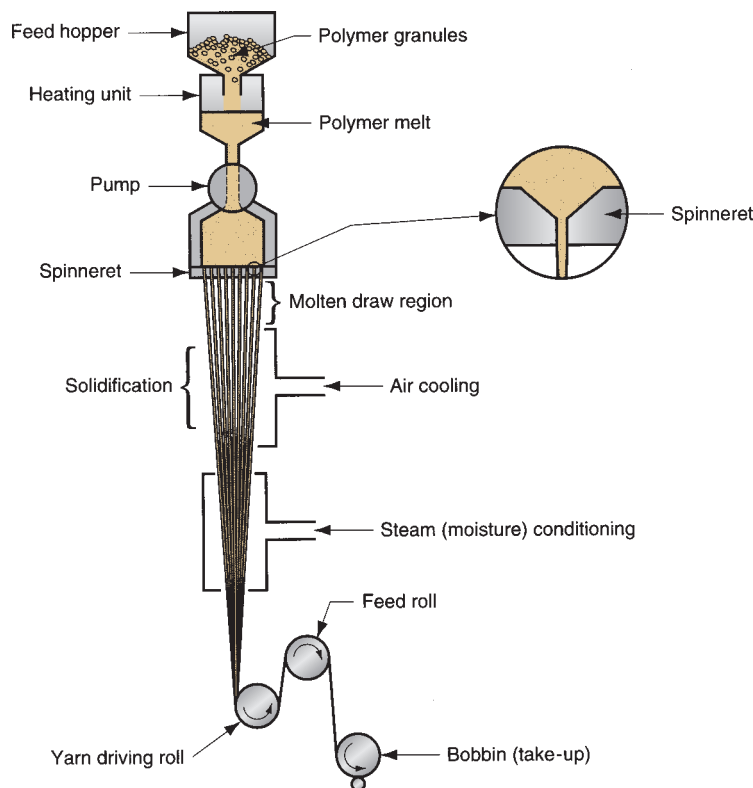

FIGURE 13.18   Melt spinning of continuous filaments.

extension and thinning of the filaments occur while the polymer is still molten, so that the final diameter wound onto the bobbin may be only 1/10 of the extruded size. Melt spinning is used for polyesters and nylons; because these are the most important synthetic fibers, melt spinning is the most important of the three processes for synthetic fibers.

In *dry spinning*, the starting polymer is in solution and the solvent can be separated by evaporation. The extrudate is pulled through a heated chamber that removes the solvent; otherwise the sequence is similar to the previous. Fibers of cellulose acetate and acrylic are produced by this process. In *wet spinning*, the polymer is also in solution—only the solvent is nonvolatile. To separate the polymer, the extrudate must be passed through a liquid chemical that coagulates or precipitates the polymer into coherent strands that are then collected onto bobbins. This method is used to produce rayon (regenerated cellulose fibers).

Filaments produced by any of the three processes are usually subjected to further cold drawing to align the crystal structure along the direction of the filament axis. Extensions of 2 to 8 are typical [13]. This has the effect of significantly increasing the tensile strength of the fibers. Drawing is accomplished by pulling the thread between two spools, where the winding spool is driven at a faster speed than the unwinding spool.

3.5 Coating Processes

Plastic (or rubber) coating involves application of a layer of the given polymer onto a substrate material. Three categories are distinguished [6]: (1) wire and cable coating; (2) planar coating, which involves the coating of a flat film; and (3) contour coating—the coating of a three-dimensional object. Wire and cable coating has already been covered (Section 13.2.3); it is basically an extrusion process. The other two categories are surveyed in the following paragraphs. In addition, there is the technology of applying paints, varnishes, lacquers, and other similar coatings (Section 27.6).

Planar coating is used to coat fabrics, paper, cardboard, and metal foil; these items are major products for some plastics. The important polymers include polyethylene and polypropylene, with lesser applications for nylon, PVC, and polyester. In most cases, the coating is only 0.01 to 0.05 mm (0.0005–0.002 in) thick. The two major planar coating techniques are illustrated in Figure 13.19. In the *roll method*,
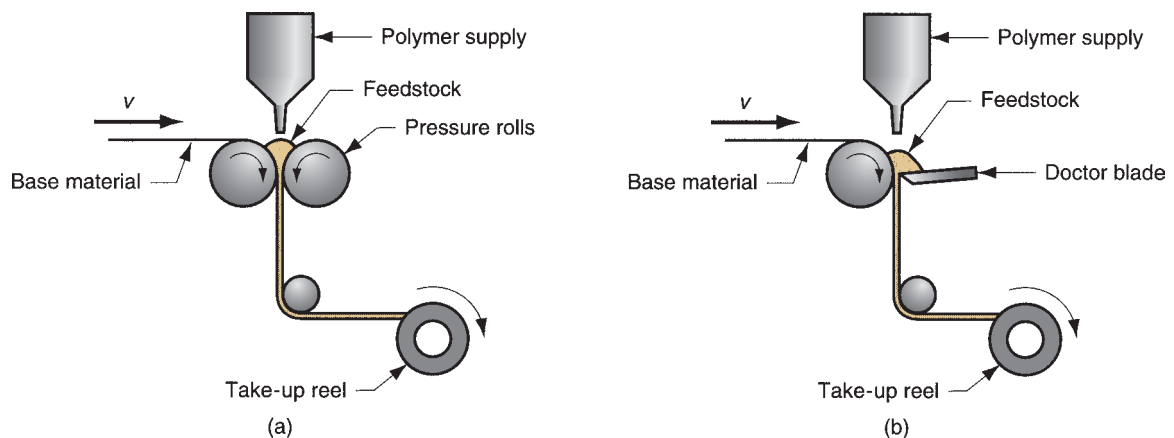

FIGURE 13.19   Planar coating processes: (a) roll method, and (b) doctor-blade method.

the polymer coating material is squeezed against the substrate by means of opposing rolls. In the **doctor blade method**, a sharp knife edge controls the amount of polymer melt that is coated onto the substrate. In both cases, the coating material is supplied either by a slit-die extrusion process or by calendering.

Contour coating of three-dimensional objects can be accomplished by dipping or spraying. **Dipping** involves submersion of the object into a suitable bath of polymer melt or solution, followed by cooling or drying. **Spraying** (such as spray-painting) is an alternative method for applying a polymer coating to a solid object.

3.6 Injection Molding

Injection molding is a process in which a polymer is heated to a highly plastic state and forced to flow under high pressure into a mold cavity, where it solidifies. The molded part, called a **molding**, is then removed from the cavity. The process produces discrete components that are almost always net shape. The production cycle time is typically in the range of 10 to 30 sec, although cycles of 1 min or longer are not uncommon for large parts. Also, the mold may contain more than one cavity, so that multiple moldings are produced each cycle. A collection of plastic injection moldings is displayed in Figure 13.20.

Complex and intricate shapes are possible with injection molding. The challenge in these cases is to fabricate a mold whose cavity is the same geometry as the part and that also allows for part removal. Part size can range from about 50 g (2 oz) up to about 25 kg (more than 50 lb), the upper limit represented by components such as refrigerator doors and automobile bumpers. The mold determines the part shape and size and is the special tooling in injection molding. For large, complex parts, the mold can cost hundreds of thousands of dollars. For small parts, the mold can be built to contain multiple cavities, also making the mold expensive. Thus, injection molding is economical only for large production quantities.

FIGURE 13.20
A collection of plastic injection-molded parts. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

FIGURE 13.21 A large (3000-ton capacity) injection molding machine. (Courtesy of Cincinnati Milacron.)
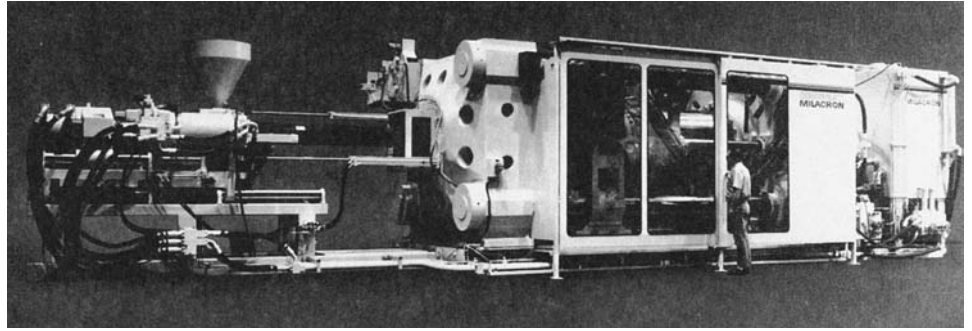
Injection molding is the most widely used molding process for thermoplastics. Some thermosets and elastomers are injection molded, with modifications in equipment and operating parameters to allow for cross-linking of these materials. These and other variations of injection molding are discussed in Section 13.6.5.

13.6.1 PROCESS AND EQUIPMENT

Equipment for injection molding evolved from metal die casting (Historical Note 13.1). A large injection molding machine is shown in Figure 13.21. As illustrated in the schematic in Figure 13.22, an injection molding machine consists of two principal components: (1) the plastic injection unit and (2) the mold clamping unit. The *injection unit* is much like an extruder. It consists of a barrel that is fed from one end by a hopper containing a supply of plastic pellets. Inside the barrel is a screw whose operation surpasses that of an extruder screw in the following respect: in addition to turning for mixing and heating the polymer, it also acts as a ram that rapidly moves forward to inject molten plastic into the mold. A nonreturn valve mounted near the tip of the screw prevents the melt from flowing backward along the screw threads. Later in the molding cycle the ram retracts to its former position. Because of its dual
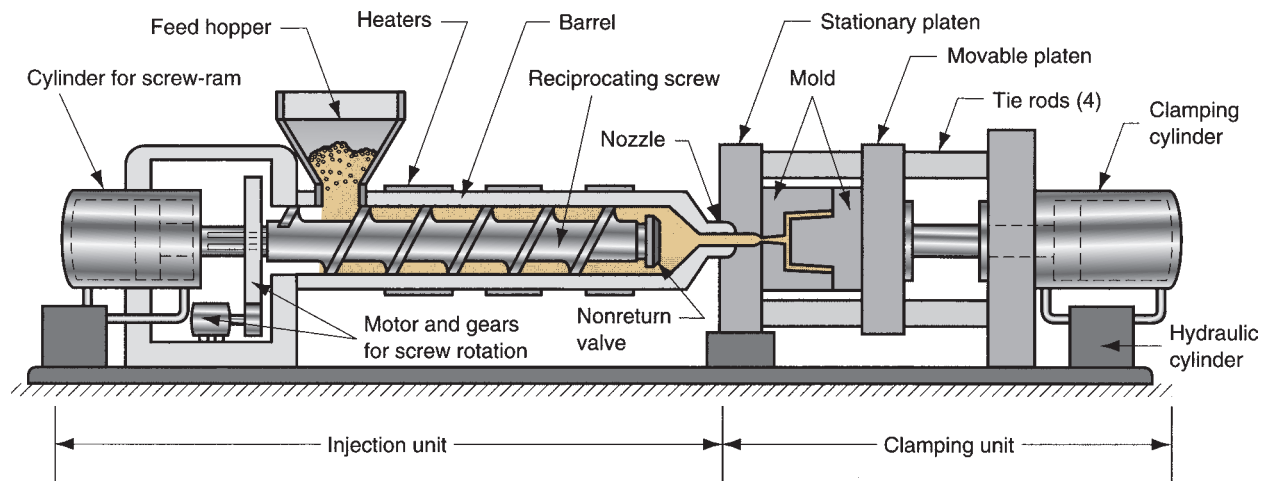

FIGURE 13.22 Diagram of an injection molding machine, reciprocating screw type (some mechanical details are simplified).

action, it is called a ***reciprocating screw***, a name that also identifies the machine type. Older injection molding machines used a simple ram (without screw flights), but the superiority of the reciprocating screw design has led to its widespread adoption in today's molding plants. To summarize, the functions of the injection unit are to melt and homogenize the polymer, and then inject it into the mold cavity.

The ***clamping unit*** is concerned with the operation of the mold. Its functions are to (1) hold the two halves of the mold in proper alignment with each other; (2) keep the mold closed during injection by applying a clamping force sufficient to resist the injection force; and (3) open and close the mold at the appropriate times in the molding cycle. The clamping unit consists of two platens, a fixed platen and a movable platen, and a mechanism for translating the latter. The mechanism is basically a power press that is operated by hydraulic piston or mechanical toggle devices of various types. Clamping forces of several thousand tons are available on large machines.

The cycle for injection molding of a thermoplastic polymer proceeds in the following sequence, illustrated in Figure 13.23. The action begins with the mold open and the machine ready to start a new molding: (1) The mold is closed and clamped. (2) A ***shot*** of polymer melt, which has been brought to the right temperature and viscosity by heating and the mechanical working of the screw, is injected under high pressure into the mold cavity. The plastic cools and begins to solidify when it encounters the cold surface of the mold. Ram pressure is maintained to pack additional melt into the cavity to compensate for contraction during cooling. (3) The screw is rotated and retracted with the nonreturn valve open to permit fresh polymer to flow into the forward portion of the barrel. Meanwhile, the polymer in the mold has completely solidified. (4) The mold is opened, and the part is ejected and removed.
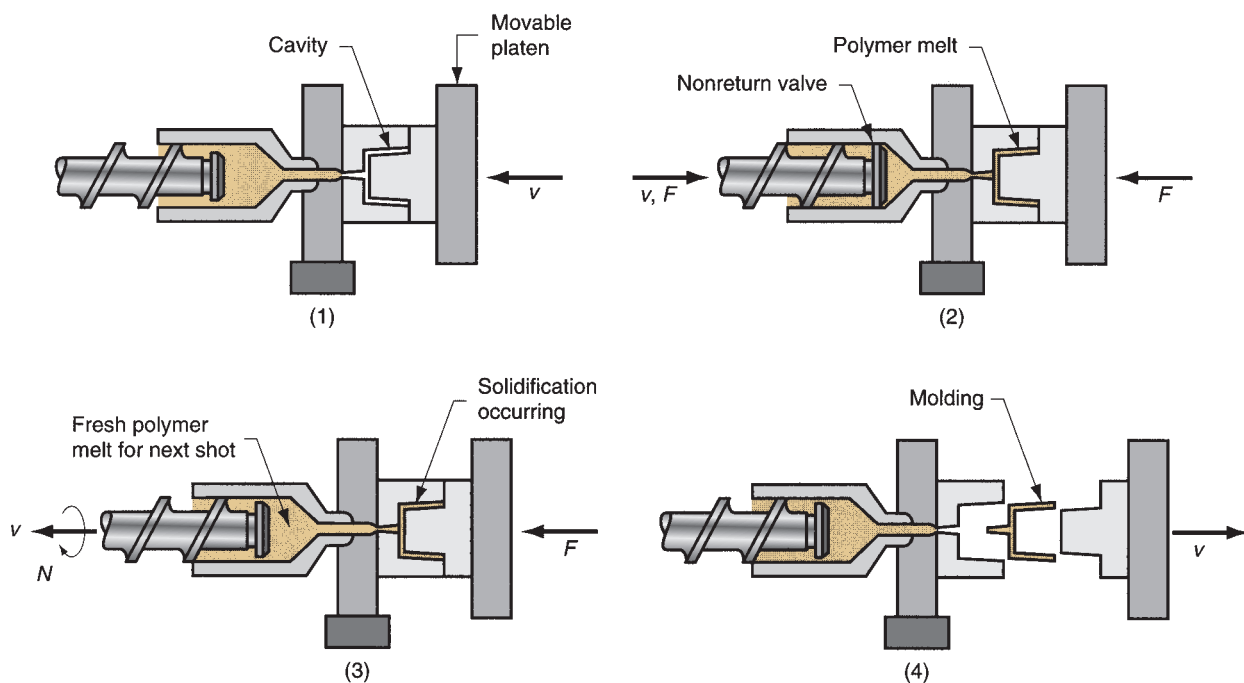

FIGURE 13.23   Typical molding cycle: (1) mold is closed, (2) melt is injected into cavity, (3) screw is retracted, and (4) mold opens, and part is ejected.
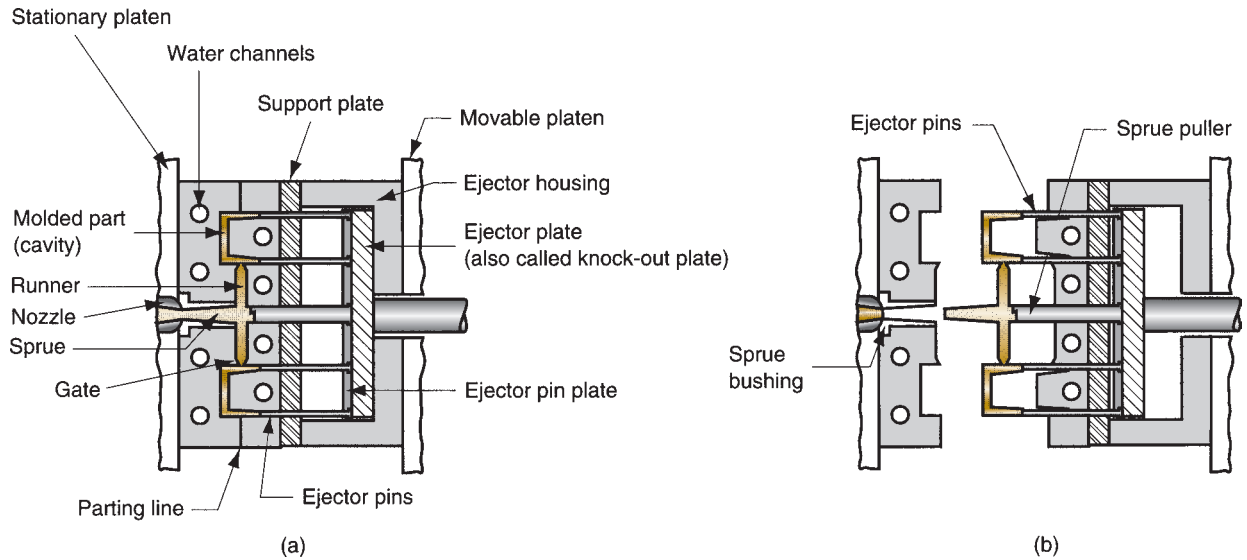
FIGURE 13.24 Details of a two-plate mold for thermoplastic injection molding: (a) closed and (b) open. Mold has two cavities to produce two cup-shaped parts (cross section shown) with each injection shot.

13.6.2 THE MOLD

The mold is the special tool in injection molding; it is custom-designed and fabricated for the given part to be produced. When the production run for that part is finished, the mold is replaced with a new mold for the next part. This section examines several types of mold for injection molding.

Two-Plate Mold The conventional *two-plate mold*, illustrated in Figure 13.24, consists of two halves fastened to the two platens of the molding machine's clamping unit. When the clamping unit is opened, the two mold halves open, as shown in (b). The most obvious feature of the mold is the *cavity*, which is usually formed by removing metal from the mating surfaces of the two halves. Molds can contain a single cavity or multiple cavities to produce more than one part in a single shot. The figure shows a mold with two cavities. The *parting surfaces* (or *parting line* in a cross-sectional view of the mold) are where the mold opens to remove the part(s).

In addition to the cavity, other features of the mold serve indispensable functions during the molding cycle. A mold must have a distribution channel through which the polymer melt flows from the nozzle of the injection barrel into the mold cavity. The distribution channel consists of (1) a *sprue*, which leads from the nozzle into the mold; (2) *runners*, which lead from the sprue to the cavity (or cavities); and (3) *gates* that constrict the flow of plastic into the cavity. The constriction increases the shear rate, thereby reducing the viscosity of the polymer melt. There are one or more gates for each cavity in the mold.

An *ejection system* is needed to eject the molded part from the cavity at the end of the molding cycle. *Ejector pins* built into the moving half of the mold usually accomplish this function. The cavity is divided between the two mold halves in such a way that the natural shrinkage of the molding causes the part to stick to the moving half. When the mold opens, the ejector pins push the part out of the mold cavity.

A *cooling system* is required for the mold. This consists of an external pump connected to passageways in the mold, through which water is circulated to remove heat from the hot plastic. Air must be evacuated from the mold cavity as the polymer rushes in. Much of the air passes through the small ejector pin clearances in the mold. In addition, narrow *air vents* are often machined into the parting surface; only about 0.03 mm (0.001 in) deep and 12 to 25 mm (0.5–1.0 in) wide, these channels permit air to escape to the outside but are too small for the viscous polymer melt to flow through.

To summarize, a mold consists of (1) one or more cavities that determine part geometry, (2) distribution channels through which the polymer melt flows to the cavities, (3) an ejection system for part removal, (4) a cooling system, and (5) vents to permit evacuation of air from the cavities.

Other Mold Types   The two-plate mold is the most common mold in injection molding. An alternative is a *three-plate mold*, shown in Figure 13.25, for the same part geometry as before. There are advantages to this mold design. First, the flow of molten plastic is through a gate located at the base of the cup-shaped part, rather than at the side. This allows more even distribution of melt into the sides of the cup. In the side gate design in the two-plate mold of Figure 13.24, the plastic must flow around the core and join on the opposite side, possibly creating a weakness at the weld line. Second, the three-plate mold allows more automatic operation of the molding machine. As the mold opens, it divides into three plates with two openings between them. This action separates the runner from the parts, which drop by gravity into containers beneath the mold.

The sprue and runner in a conventional two- or three-plate mold represent waste material. In many instances they can be ground and reused; however, in some cases the product must be made of "virgin" plastic (plastic that has not been previously molded). The *hot-runner mold* eliminates the solidification of the sprue and runner by locating heaters around the corresponding runner channels. Although the plastic in the mold cavity solidifies, the material in the sprue and runner channels remains molten, ready to be injected into the cavity in the next cycle.
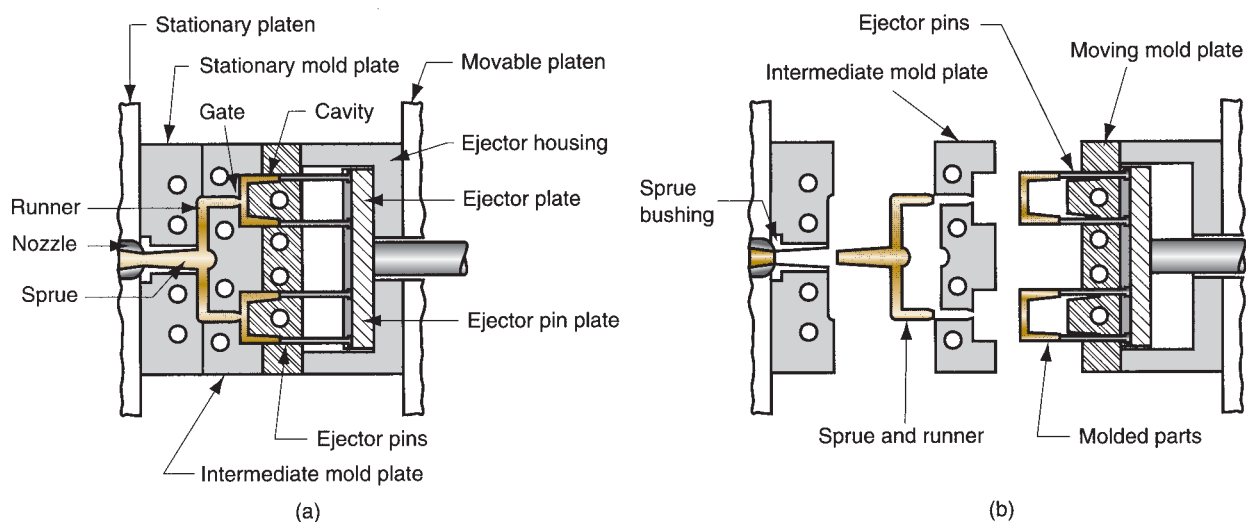

FIGURE 13.25   Three-plate mold: (a) closed, and (b) open.

13.6.3 INJECTION MOLDING MACHINES

Injection molding machines differ in both injection unit and clamping unit. This section discusses the important types of machines available today. The name of the injection molding machine is generally based on the type of injection unit used.

Injection Units   Two types of injection units are widely used today. The *reciprocating-screw machine* (Section 13.6.1, Figures 13.21 and 13.22) is the most common. This design uses the same barrel for melting and injection of plastic. The alternative unit involves the use of separate barrels for plasticizing and injecting the polymer, as shown in Figure 13.26(a). This type is called a *screw-preplasticizer machine* or *two-stage machine*. Plastic pellets are fed from a hopper into the first stage, which uses a screw to drive the polymer forward and melt it. This barrel feeds a second barrel which uses a plunger to inject the melt into the mold. Older machines used one plunger-driven barrel to melt and inject the plastic. These machines are referred to as *plunger-type injection molding machines*, Figure 13.26(b).

Clamping Units   Clamping designs are of three types [11]: toggle, hydraulic, and hydromechanical. *Toggle clamps* include various designs, one of which is illustrated in Figure 13.27(a). An actuator moves the crosshead forward, extending the toggle links to push the moving platen toward a closed position. At the beginning of the movement, mechanical advantage is low and speed is high; but near the end of the stroke, the reverse is true. Thus, toggle clamps provide both high speed and high force at different points in the cycle when they are desirable. They are actuated either by hydraulic cylinders or ball screws driven by electric motors. Toggle-clamp units seem most suited to relatively low tonnage machines. *Hydraulic clamps*, shown in Figure 13.27(b), are used on higher-tonnage injection molding machines, typically in the range 1300 to 8900 kN (150 to 1000 tons). These units are also more flexible than toggle clamps in terms of setting the tonnage at given positions during the stroke. *Hydromechanical clamps* are designed for large tonnages, usually above 8900 kN (1000 tons). They operate by (1) using hydraulic cylinders to rapidly move the mold toward closing position, (2) locking the position by mechanical means, and (3) using high-pressure hydraulic cylinders to finally close the mold and build tonnage.
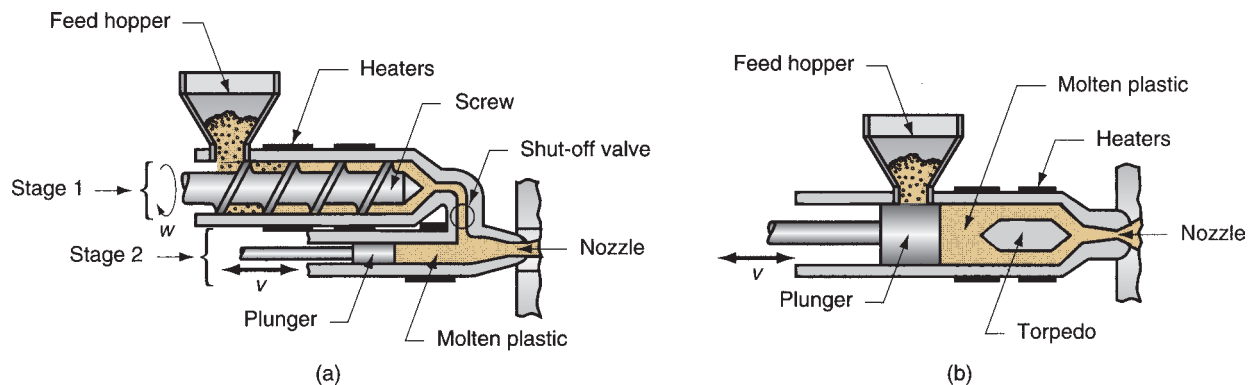

FIGURE 13.26   Two alternative injection systems to the reciprocating screw shown in Figure 13.22: (a) screw preplasticizer, and (b) plunger type.
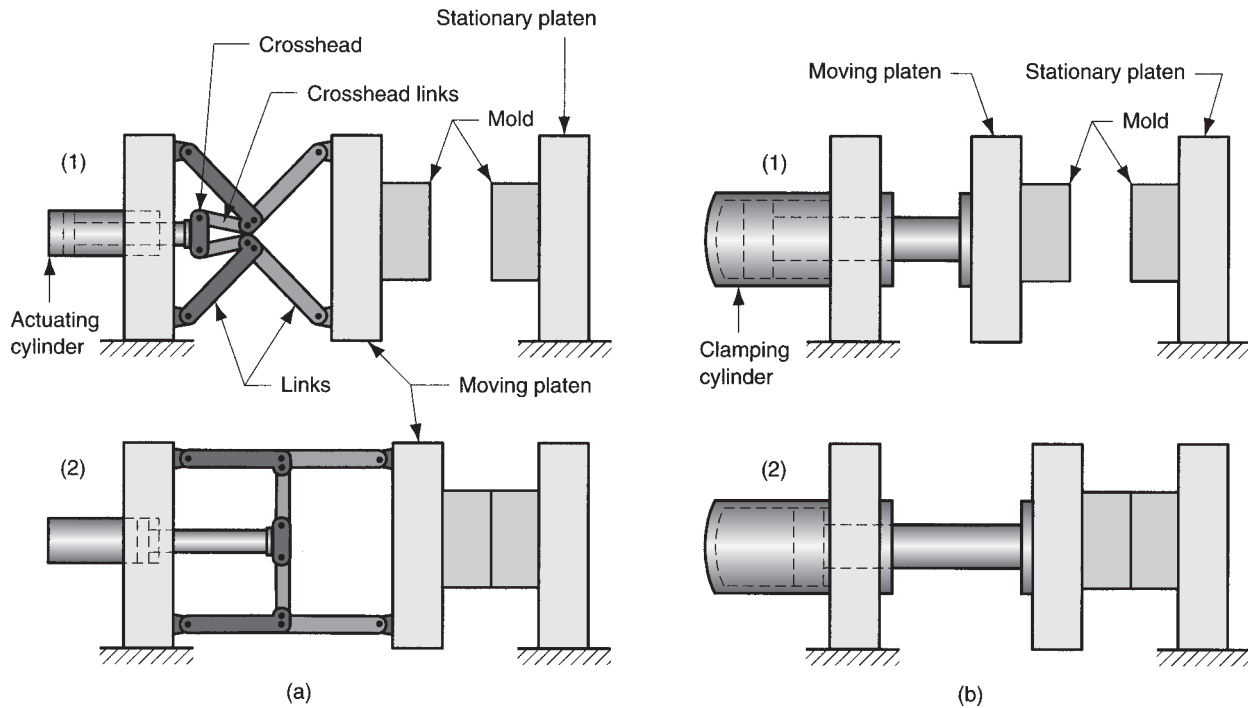
FIGURE 13.27   Two clamping designs: (a) one possible toggle clamp design: (1) open and (2) closed; and (b) hydraulic clamping: (1) open, and (2) closed. Tie rods used to guide moving platens not shown.

13.6.4   SHRINKAGE AND DEFECTS IN INJECTION MOLDING

Polymers have high thermal expansion coefficients, and significant shrinkage can occur during cooling of the plastic in the mold. Contraction of crystalline plastics tends to be greater than for amorphous polymers. Shrinkage is usually expressed as the reduction in linear size that occurs during cooling to room temperature from the molding temperature for the given polymer. Appropriate units are therefore mm/mm (in/in) of the dimension under consideration. Typical values for selected polymers are given in Table 13.1.

Fillers in the plastic tend to reduce shrinkage. In commercial molding practice, shrinkage values for the specific molding compound should be obtained from the producer before making the mold. To compensate for shrinkage, the dimensions of

TABLE • 13.1 Typical values of shrinkage for moldings of selected thermoplastics.

Plastic	Shrinkage, mm/mm (in/in)	Plastic	Shrinkage, mm/mm (in/in)
ABS	0.006	Polyethylene	0.025
Nylon-6,6	0.020	Polystyrene	0.004
Polycarbonate	0.007	PVC	0.005

Compiled from [14].

the mold cavity must be made larger than the specified part dimensions. The following formula can be used [14]:

$$D_c = D_p + D_pS + D_pS^2 \tag{13.19}$$

where D_c = dimension of cavity, mm (in); D_p = molded part dimension, mm (in), and S = shrinkage values obtained from Table 13.1. The third term on the right-hand side corrects for shrinkage that occurs in the shrinkage.

Example 13.3 Shrinkage in injection molding	The nominal length of a part made of polyethylene is to be 80 mm. Determine the corresponding dimension of the mold cavity that will compensate for shrinkage.
	Solution: From Table 13.1, the shrinkage for polyethylene is $S = 0.025$. Using Equation (13.19), the mold cavity diameter should be
	$$D_c = 80.0 + 80.0(0.025) + 80.0(0.025)^2$$
	$$= 80.0 + 2.0 + 0.05 = \textbf{82.05 mm}$$

Because of differences in shrinkage among plastics, mold dimensions must be determined for the particular polymer to be molded. The same mold will produce different part sizes for different polymer types.

Values in Table 13.1 represent a gross simplification of the shrinkage issue. In reality, shrinkage is affected by a number of factors, any of which can alter the amount of contraction experienced by a given polymer. The most important factors are injection pressure, compaction time, molding temperature, and part thickness. As injection pressure is increased, forcing more material into the mold cavity, shrinkage is reduced. Increasing compaction time has a similar effect, assuming the polymer in the gate does not solidify and seal off the cavity; maintaining pressure forces more material into the cavity while shrinkage is taking place. Net shrinkage is thereby reduced.

Molding temperature refers to the temperature of the polymer in the cylinder immediately before injection. One might expect that a higher polymer temperature would increase shrinkage, on the reasoning that the difference between molding and room temperatures is greater. However, shrinkage is actually lower at higher molding temperatures. The explanation is that higher temperatures significantly lower the viscosity of the polymer melt, allowing more material to be packed into the mold; the effect is the same as higher injection pressures. Thus, the effect on viscosity more than compensates for the larger temperature difference.

Finally, thicker parts show greater shrinkage. A molding solidifies from the outside; the polymer in contact with the mold surface forms a skin that grows toward the center of the part. At some point during solidification, the gate solidifies, isolating the material in the cavity from the runner system and compaction pressure. When this happens, the molten polymer inside the skin accounts for most of the remaining shrinkage that occurs in the part. A thicker part section experiences greater shrinkage because it contains more molten material.

In addition to the shrinkage issue, other things can also go wrong. Here are some of the common defects in injection molded parts:

➢ **Short shots**. As in casting, a short shot is a molding that has solidified before completely filling the cavity. The defect can be corrected by increasing temperature and/or pressure. The defect may also result from use of a machine with insufficient shot capacity, in which case a larger machine is needed.

➢ **Flashing**. Flashing occurs when the polymer melt is squeezed into the parting surface between mold plates; it can also occur around ejection pins. The defect is usually caused by (1) vents and clearances in the mold that are too large; (2) injection pressure too high compared with clamping force; (3) melt temperature too high; or (4) excessive shot size.

➢ **Sink marks and voids**. These are defects usually related to thick molded sections. A **sink mark** occurs when the outer surface on the molding solidifies, but contraction of the internal material causes the skin to be depressed below its intended profile. A **void** is caused by the same basic phenomenon; however, the surface material retains its form and the shrinkage manifests itself as an internal void because of high tensile stresses on the still-molten polymer. These defects can be addressed by increasing the packing pressure after injection. A better solution is to design the part to have uniform section thicknesses and thinner sections.

➢ **Weld lines**. Weld lines occur when polymer melt flows around a core or other convex detail in the mold cavity and meets from opposite directions; the boundary thus formed is called a weld line, and it may have mechanical properties that are inferior to those in the rest of the part. Higher melt temperatures, higher injection pressures, alternative gating locations on the part, and better venting are ways of dealing with this defect.

13.6.5 OTHER INJECTION MOLDING PROCESSES

The vast majority of injection molding applications involve thermoplastics. Several variants of the process are described in this section.

Thermoplastic Foam Injection Molding Plastic foams have a variety of applications, and these materials and their processing are discussed in Section 13.11. One of the processes, sometimes called **structural foam molding**, is appropriate to discuss here because it is injection molding. It involves the molding of thermoplastic parts that possess a dense outer skin surrounding a lightweight foam center. Such parts have high stiffness-to-weight ratios suitable for structural applications.

A structural foam part can be produced either by introducing a gas into the molten plastic in the injection unit or by mixing a gas-producing ingredient with the starting pellets. During injection, an insufficient amount of melt is forced into the mold cavity, where it expands (foams) to fill the mold. The foam cells in contact with the cold mold surface collapse to form a dense skin, while the material in the core retains its cellular structure. Items made of structural foam include electronic cases, business machine housings, furniture components, and washing machine tanks. Advantages cited for structural foam molding include lower injection pressures and clamping forces, and thus the capability to produce large components, as suggested

by the preceding list. A disadvantage of the process is that the resulting part surfaces tend to be rough, with occasional voids. If good surface finish is needed for the application, then additional processing is required, such as sanding, painting, and adhesion of a veneer.

Multi-Injection Molding Processes   Unusual effects can be achieved by multiple injection of different polymers to mold a part. The polymers are injected either simultaneously or sequentially, and there may be more than one mold cavity involved. Several processes fall under this heading, all characterized by two or more injection units—thus, the equipment for these processes is expensive.

Sandwich molding involves injection of two separate polymers—one is the outer skin of the part and the other is the inner core, which is typically a polymer foam. A specially designed nozzle controls the flow sequence of the two polymers into the mold. The sequence is designed so that the core polymer is completely surrounded by the skin material inside the mold cavity. The final structure is similar to that of a structural foam molding. However, the molding possesses a smooth surface, thus overcoming one of the major shortcomings of the previous process. In addition, it consists of two distinct plastics, each with its own characteristics suited to the application.

Another multi-injection molding process involves sequential injection of two polymers into a two-position mold. With the mold in the first position, the first polymer is injected into the cavity. Then the mold opens to the second position, and the second melt is injected into the enlarged cavity. The resulting part consists of two integrally connected plastics. *Bi-injection molding* is used to combine plastics of two different colors (e.g., automobile tail light covers) or to achieve different properties in different sections of the same part.

Injection Molding of Thermosets   Injection molding is used for thermosetting (TS) plastics, with certain modifications in equipment and operating procedure to allow for cross-linking. The machines for thermoset injection molding are similar to those used for thermoplastics. They use a reciprocating-screw injection unit, but the barrel length is shorter to avoid premature curing and solidification of the TS polymer. For the same reason, temperatures in the barrel are kept at relatively low levels, usually 50°C to 125°C (120°F–260°F), depending on the polymer. The plastic, usually in the form of pellets or granules, is fed into the barrel through a hopper. Plasticizing occurs by the action of the rotating screw as the material is moved forward toward the nozzle. When sufficient melt has accumulated ahead of the screw, it is injected into a mold that is heated to 150°C to 230°C (300°F–450°F), where cross-linking occurs to harden the plastic. The mold is then opened, and the part is ejected and removed. Molding cycle times typically range from 20 sec to 2 min, depending on polymer type and part size.

Curing is the most time-consuming step in the cycle. In many cases, the part can be removed from the mold before curing is completed, so that final hardening occurs because of retained heat within a minute or two after removal. An alternative approach is to use a multiple-mold machine, in which two or more molds are attached to an indexing head served by a single injection unit.

The principal thermosets for injection molding are phenolics, unsaturated polyesters, melamines, epoxies, and urea-formaldehyde. Elastomers are also injected molded (Section 14.5.3). More than 50% of the phenolic moldings currently produced in the United States are made by this process [11], representing

a shift away from compression and transfer molding, the traditional processes used for thermosets (Section 13.7). Most of the TS molding materials contain large proportions of fillers (up to 70% by weight), including glass fibers, clay, wood fibers, and carbon black. In effect, these are composite materials that are being injected molded.

Reaction Injection Molding   Reaction injection molding (RIM) involves the mixing of two highly reactive liquid ingredients and immediately injecting the mixture into a mold cavity, where chemical reactions leading to solidification occur. The two ingredients form the components used in catalyst-activated or mixing-activated thermoset systems (Section 8.3.1). Urethanes, epoxies, and urea-formaldehyde are examples of these systems. RIM was developed with polyurethane to produce large automotive components such as bumpers, spoilers, and fenders. These kinds of parts still constitute the major application of the process. RIM-molded polyurethane parts typically possess a foam internal structure surrounded by a dense outer skin.

   As shown in Figure 13.28, liquid ingredients are pumped in precisely measured amounts from separate holding tanks into a mixing head. The ingredients are rapidly mixed and then injected into the mold cavity at relatively low pressure where polymerization and curing occur. A typical cycle time is around 2 min. For relatively large cavities the molds for RIM are much less costly than corresponding molds for conventional injection molding. This is because of the low clamping forces required in RIM and the opportunity to use lightweight components in the molds. Other advantages of RIM include (1) low energy is required in the process; (2) equipment costs are less than injection molding; (3) a variety of chemical systems are available that enable specific properties to be obtained in the molded product; and (4) the production equipment is reliable, and the chemical systems and machine relationships are well understood [17].
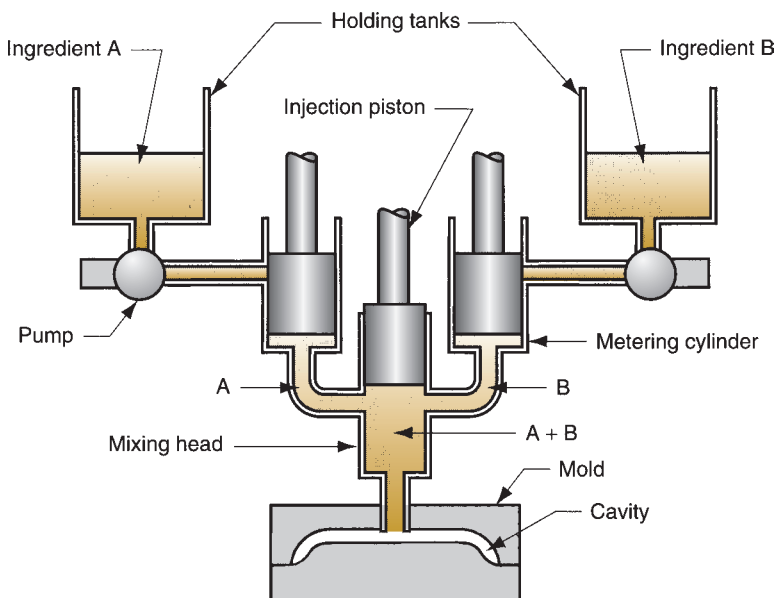

FIGURE 13.28   Reaction injection molding (RIM) system, shown immediately after ingredients A and B have been pumped into the mixing head prior to injection into the mold cavity (some details of processing equipment omitted).

3.7 Compression and Transfer Molding

Discussed in this section are two molding techniques widely used for thermosetting polymers and elastomers. For thermoplastics, these techniques cannot match the efficiency of injection molding, except for very special applications.

13.7.1 COMPRESSION MOLDING

Compression molding is an old and widely used molding process for thermosetting plastics. Its applications also include rubber tires and various polymer matrix composite parts. The process, illustrated in Figure 13.29 for a TS plastic, consists of (1) loading a precise amount of molding compound, called the ***charge***, into the bottom half of a heated mold; (2) bringing the mold halves together to compress the charge, forcing it to flow and conform to the shape of the cavity; (3) heating the charge by means of the hot mold to polymerize and cure the material into a solidified part; and (4) opening the mold halves and removing the part from the cavity.

The initial charge of molding compound can be any of several forms, including powders or pellets, liquid, or preform. The amount of polymer must be precisely controlled to obtain repeatable consistency in the molded product. It has become common practice to preheat the charge before placing it into the mold; this softens the polymer and shortens the production cycle time. Preheating methods include infrared heaters, convection heating in an oven, and use of a heated rotating screw in a barrel. The latter technique (borrowed from injection molding) is also used to meter the amount of the charge.

Compression molding presses are oriented vertically and contain two platens to which the mold halves are fastened. The presses involve either of two types of actuation: (1) upstroke of the bottom platen or (2) downstroke of the top platen, the former being the more common machine configuration. They are generally powered
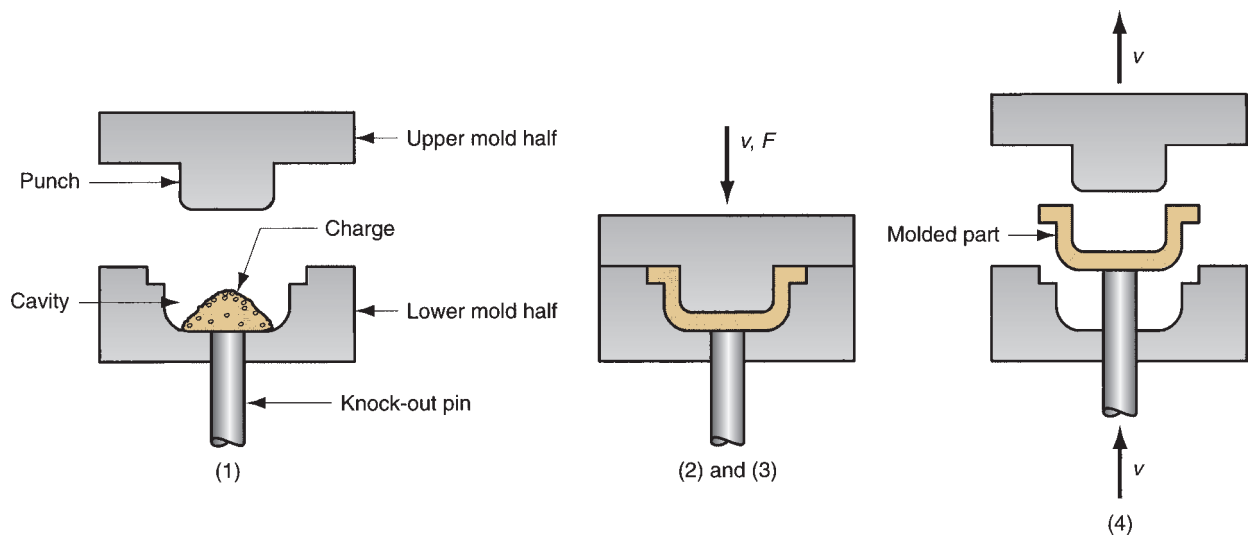

FIGURE 13.29 Compression molding for thermosetting plastics: (1) charge is loaded; (2) and (3) charge is compressed and cured; and (4) part is ejected and removed (some details omitted).

by a hydraulic cylinder that can be designed to provide clamping capacities up to several hundred tons.

Molds for compression molding are generally simpler than their injection mold counterparts. There is no sprue and runner system in a compression mold, and the process itself is generally limited to simpler part geometries because of the lower flow capabilities of the starting thermosetting materials. However, provision must be made for heating the mold, usually accomplished by electric resistance heating, steam, or hot oil circulation. Compression molds can be classified as ***hand molds***, used for trial runs; ***semiautomatic***, in which the press follows a programmed cycle but the operator manually loads and unloads the press; and ***automatic***, which operate under a fully automatic press cycle (including automatic loading and unloading).

Materials for compression molding include phenolics, melamine, urea-formaldehyde, epoxies, urethanes, and elastomers. Typical moldings include electric plugs and sockets, pot handles, and dinnerware plates. Advantages of compression molding in these applications include (1) molds that are simpler and less expensive, (2) less scrap, and (3) low residual stresses in the molded parts. A typical disadvantage is longer cycle times and therefore lower production rates than injection molding.

13.7.2 TRANSFER MOLDING

In this process, a thermosetting charge is loaded into a chamber immediately ahead of the mold cavity, where it is heated; pressure is then applied to force the softened polymer to flow into the heated mold where curing occurs. There are two variants of the process, illustrated in Figure 13.30: (a) ***pot transfer molding***, in which the charge is injected from a "pot" through a vertical sprue channel into the cavity; and (b) ***plunger transfer molding***, in which the charge is injected by means of a plunger from a heated well through lateral channels into the mold cavity. In both cases, scrap is produced each cycle in the form of the leftover material in the base of the well and lateral channels, called the ***cull***. In addition, the sprue in pot transfer is scrap material. Because the polymers are thermosetting, the scrap cannot be recovered.

Transfer molding is closely related to compression molding, because it is used on the same polymer types (thermosets and elastomers). One can also see similarities to injection molding, in the way the charge is preheated in a separate chamber and then injected into the mold. Transfer molding is capable of molding part shapes that are more intricate than compression molding but not as intricate as injection molding. Transfer molding also lends itself to molding with inserts, in which a metal or ceramic insert is placed into the cavity before injection, and the heated plastic bonds to the insert during molding.

3.8 Blow Molding and Rotational Molding

Both of these processes are used to make hollow, seamless parts out of thermoplastic polymers. Rotational molding can also be used for thermosets. Parts range in size from small plastic bottles of only 5 mL (0.15 oz) to large storage drums of 38,000-L (10,000-gal) capacity. Although the two processes compete in certain cases, generally they have found their own niches. Blow molding is more suited to the mass production of small disposable containers, whereas rotational molding favors large, hollow shapes.
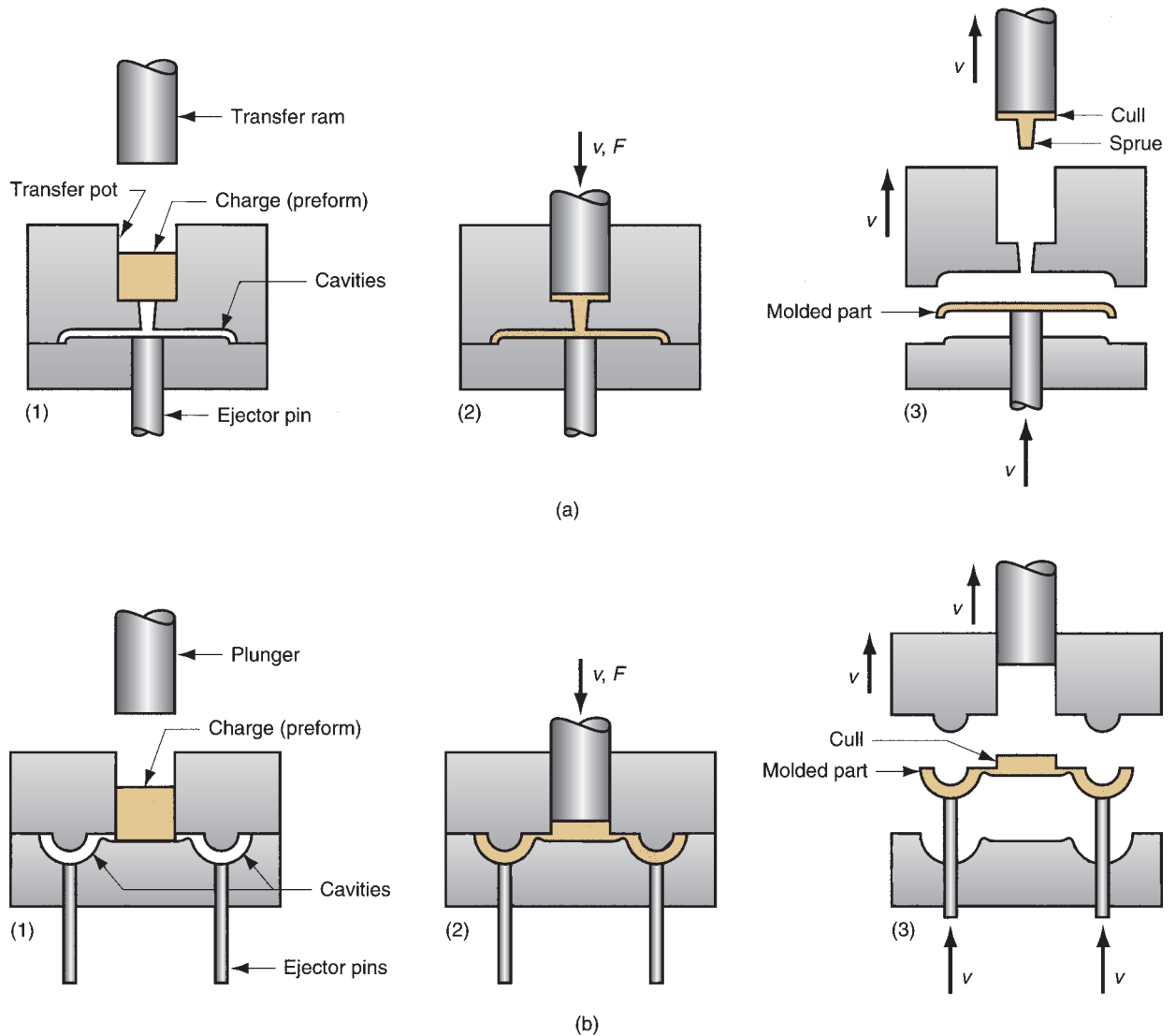
FIGURE 13.30   (a) Pot transfer molding, and (b) plunger transfer molding. Cycle in both processes is: (1) charge is loaded into pot, (2) softened polymer is pressed into mold cavity and cured, and (3) part is ejected.

13.8.1   BLOW MOLDING

Blow molding is a molding process in which air pressure is used to inflate soft plastic inside a mold cavity. It is an important industrial process for making one-piece hollow plastic parts with thin walls, such as bottles and similar containers. Because many of these items are used for consumer beverages for mass markets, production is typically organized for very high quantities. The technology is borrowed from the glass industry (Section 12.2.1) with which plastics compete in the disposable and recyclable bottle market.

Blow molding is accomplished in two steps: (1) fabrication of a starting tube of molten plastic, called a *parison* (same as in glass-blowing); and (2) inflation of the
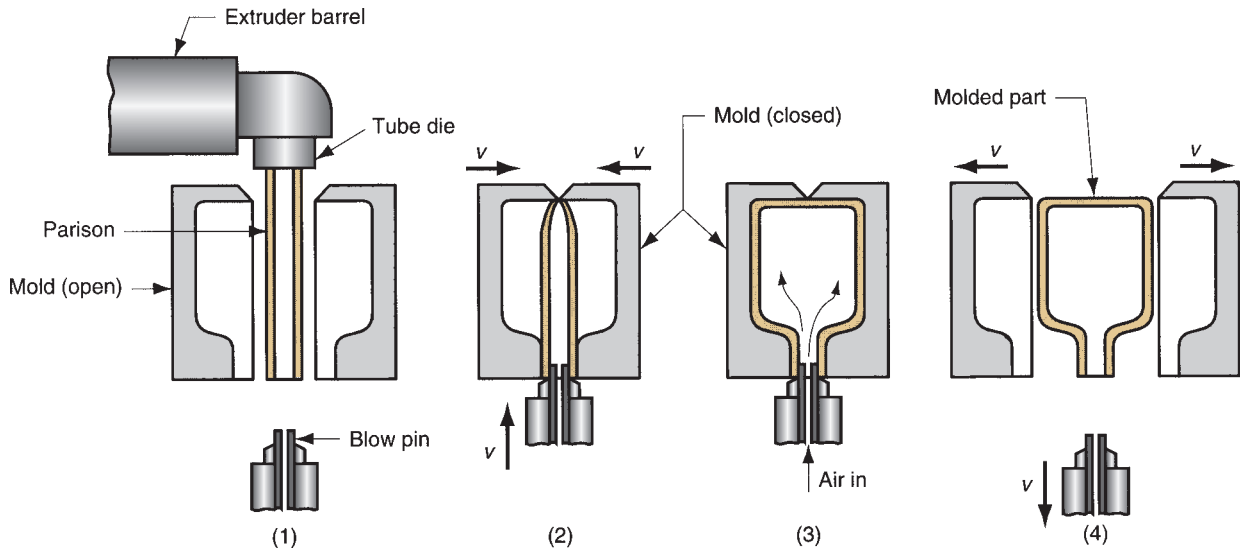
FIGURE 13.31 Extrusion blow molding: (1) extrusion of parison; (2) parison is pinched at the top and sealed at the bottom around a metal blow pin as the two halves of the mold come together; (3) the tube is inflated so that it takes the shape of the mold cavity; and (4) mold is opened to remove the solidified part.

tube to the desired final shape. Forming the parison is accomplished by either extrusion or injection molding.

Extrusion Blow Molding This form of blow molding consists of the cycle illustrated in Figure 13.31. In most cases, the process is organized as a very high production operation for making plastic bottles. The sequence is automated and often integrated with downstream operations such as bottle filling and labeling.

It is usually a requirement that the blown container be rigid, and rigidity depends on wall thickness among other factors. The wall thickness of the blown container can be related to the starting extruded parison [12], assuming a cylindrical shape for the final product. The effect of die swell on the parison is shown in Figure 13.32. The mean diameter of the tube as it exits the die is determined by the mean die diameter
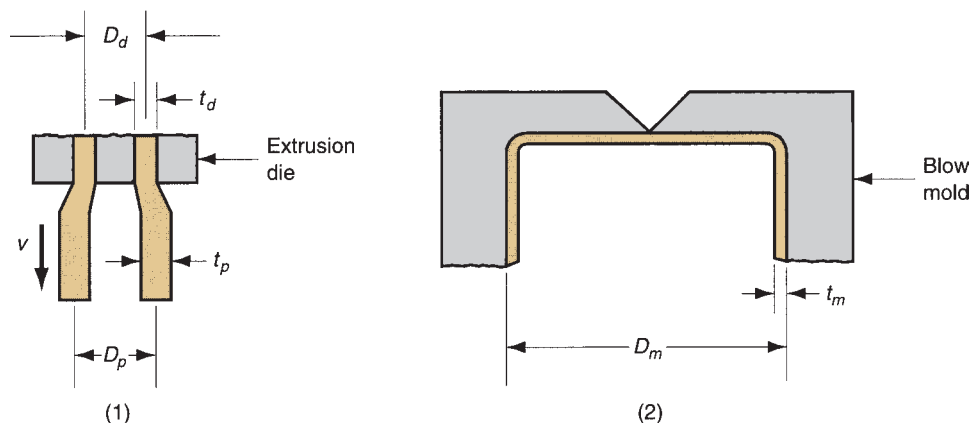

FIGURE 13.32
(1) Dimensions of extrusion die, showing parison after die swell; and (2) final blow-molded container in extrusion blow molding.

D_d. Die swell causes expansion to a mean parison diameter D_p. At the same time, wall thickness swells from t_d to t_p. The swell ratio of the parison diameter and wall thickness is given by

$$r_s = \frac{D_p}{D_d} = \frac{t_p}{t_d} \qquad (13.20)$$

When the parison is inflated to the blow mold diameter D_m, there is a corresponding reduction in wall thickness to t_m. Assuming constant volume of cross section,

$$\pi D_p t_p = \pi D_m t_m \qquad (13.21)$$

Solving for t_m,

$$t_m = \frac{D_p t_p}{D_m}$$

Substituting Equation (13.20) into this equation,

$$t_m = \frac{r_s^2 t_d D_d}{D_m} \qquad (13.22)$$

The amount of die swell in the initial extrusion process can be measured by direct observation; and the dimensions of the die are known. Thus, the wall thickness on the blow-molded container can be determined.

Injection Blow Molding   In this process, the starting parison is injection molded rather than extruded. A simplified sequence is outlined in Figure 13.33. Compared to its extrusion-based competitor, injection blow molding usually has the following advantages: (1) higher production rate, (2) greater accuracy in the final dimensions, (3) lower scrap rates, and (4) less wasteful of material. On the other hand, larger containers can be produced with extrusion blow molding because the mold in injection molding is so expensive for large parisons. Also, extrusion blow molding is technically more feasible and economical for double-layer bottles used for storing certain
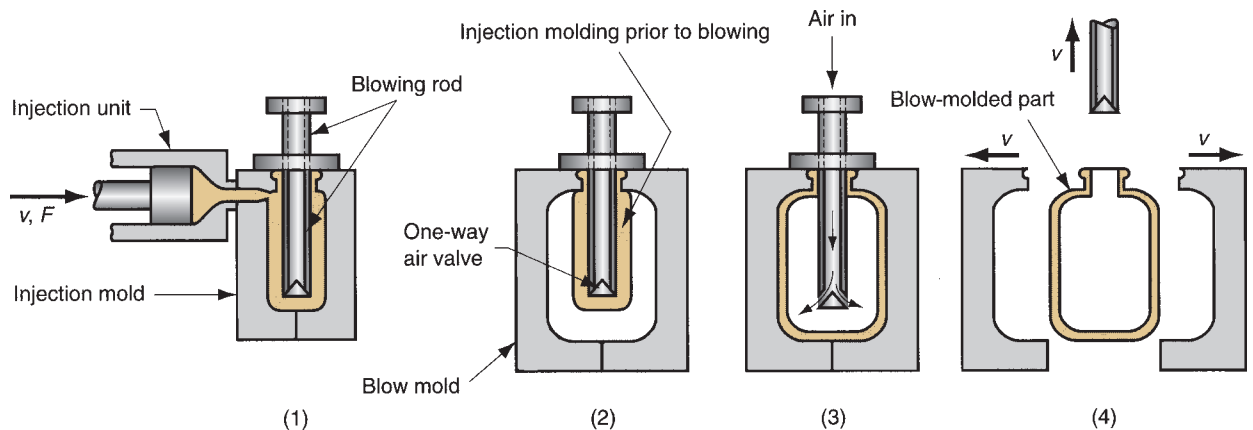

FIGURE 13.33   Injection blow molding: (1) parison is injected molded around a blowing rod; (2) injection mold is opened, and parison is transferred to a blow mold; (3) soft polymer is inflated to conform to the blow mold; and (4) blow mold is opened, and blown product is removed.

FIGURE 13.34 An injection blow molded bottle on the left and a parison for a similar part on the right. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

medicines, personal care products, and various chemical compounds.[2] Figure 13.34 shows an injection blow molded bottle and a parison for a similar part.

In a variation of injection blow molding, called ***stretch blow molding*** (Figure 13.35), the blowing rod extends downward into the injection molded parison during step 2, thus stretching the soft plastic and creating a more favorable stressing of the polymer than conventional injection blow molding or extrusion blow molding. The resulting structure is more rigid, with higher transparency and better impact resistance. The most widely used material for stretch blow molding is polyethylene terephthalate (PET), a polyester that has very low permeability and is strengthened by the stretch-blow-molding process. The combination of properties makes it ideal as a container for carbonated beverages (e.g., 2-L soda bottles).

Materials and Products   Blow molding is limited to thermoplastics. Polyethylene is the polymer most commonly used for blow molding—in particular, high density and high molecular weight polyethylene (HDPE and HMWPE). In comparing their properties with those of low density PE given the requirement for stiffness in the final product, it is more economical to use these more expensive materials because the container walls can be made thinner. Other blow moldings are made of polypropylene (PP), polyvinylchloride (PVC), and polyethylene terephthalate.

Disposable containers for packaging liquid consumer goods constitute the major share of products made by blow molding; but they are not the only products. Other

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[2]The author is indebted to Tom Walko, plant manager at one of Graham Packaging Company's blow molding plants for providing the comparisons between extrusion and injection blow molding.
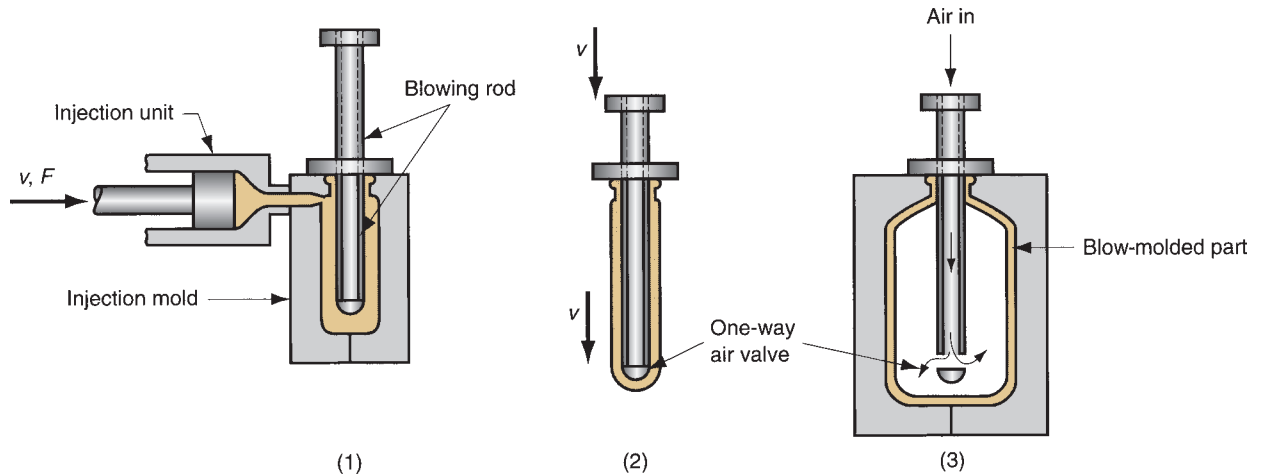
FIGURE 13.35   Stretch blow molding: (1) injection molding of parison, (2) stretching, and (3) blowing.

items include large shipping drums (55-gal) for liquids and powders, large storage tanks (2000-gal), automotive gasoline tanks, toys, and hulls for sail boards and small boats. In the latter case, two boat hulls are made in a single blow molding and subsequently cut into two open hulls.

13.8.2 ROTATIONAL MOLDING

Rotational molding uses gravity inside a rotating mold to achieve a hollow form. Also called **rotomolding**, it is an alternative to blow molding for making large, hollow shapes. It is used principally for thermoplastic polymers, but applications for thermosets and elastomers are becoming more common. Rotomolding tends to favor more complex external geometries, larger parts, and lower production quantities than blow molding. The process consists of the following steps: (1) A predetermined amount of polymer powder is loaded into the cavity of a split mold. (2) The mold is then heated and simultaneously rotated on two perpendicular axes, so that the powder impinges on all internal surfaces of the mold, gradually forming a fused layer of uniform thickness. (3) While still rotating, the mold is cooled so that the plastic skin solidifies. (4) The mold is opened, and the part is unloaded. Rotational speeds used in the process are relatively slow. It is gravity, not centrifugal force, that causes uniform coating of the mold surfaces.

Molds in rotational molding are simple and inexpensive compared to injection molding or blow molding, but the production cycle is much longer, lasting perhaps 10 min or more. To balance these advantages and disadvantages in production, rotational molding is often performed on a multicavity indexing machine, such as the three-station machine shown in Figure 13.36. The machine is designed so that three molds are indexed in sequence through three workstations. Thus, all three molds are working simultaneously. The first workstation is an unload–load station in which the finished part is unloaded from the mold, and the powder for the next part is loaded into the cavity. The second station consists of a heating chamber where hot-air convection heats the mold while it is simultaneously rotated. Temperatures inside the chamber are around 375°C (700°F), depending on the polymer and the
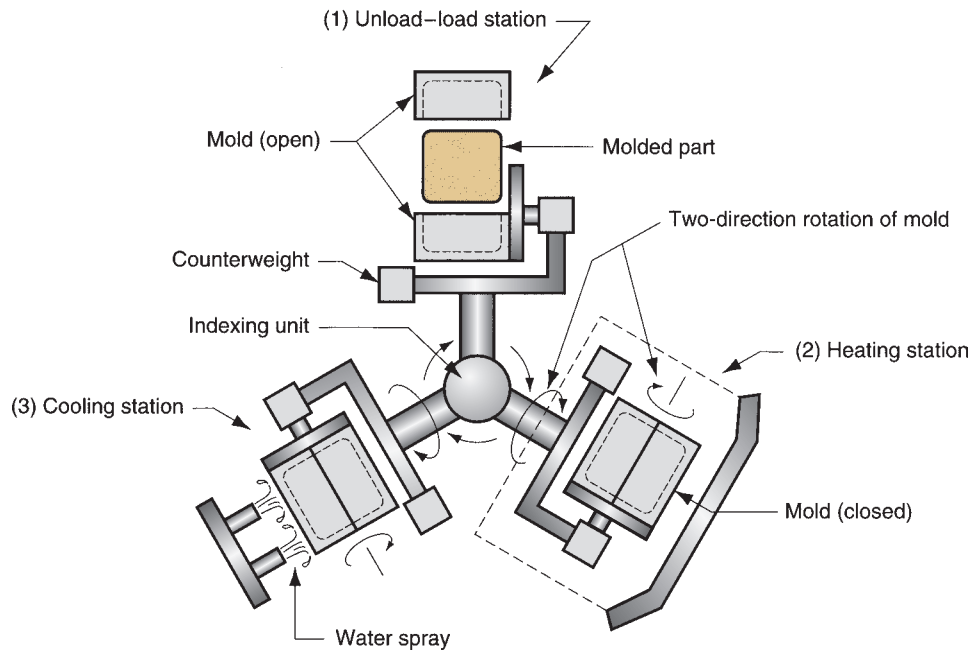
(1) Unload–load station

Mold (open)

Molded part

Two-direction rotation of mold

Counterweight

Indexing unit

(2) Heating station

(3) Cooling station

Mold (closed)

Water spray

FIGURE 13.36
Rotational molding
cycle performed on a
three-station indexing
machine: (1) unload–
load station; (2) heat
and rotate mold; (3) cool
the mold.

item being molded. The third station cools the mold, using forced cold air or water spray, to cool and solidify the plastic molding inside.

A fascinating variety of articles are made by rotational molding. The list includes hollow toys such as hobby horses and playing balls; boat and canoe hulls, sandboxes, small swimming pools; buoys and other flotation devices; truck body parts, automotive dashboards, fuel tanks; luggage pieces, furniture, garbage cans; fashion mannequins; large industrial barrels, containers, and storage tanks; portable outhouses, and septic tanks. The most popular molding material is polyethylene, especially HDPE. Other plastics include polypropylene, ABS, and high-impact polystyrene.

3.9   Thermoforming

Thermoforming is a process in which a flat thermoplastic sheet is heated and deformed into the desired shape. The process is widely used to package consumer products and fabricate large items such as bathtubs, contoured skylights, and internal door liners for refrigerators.

Thermoforming consists of two main steps: heating and forming. Heating is usually accomplished by radiant electric heaters, located on one or both sides of the starting plastic sheet at a distance of roughly 125 mm (5 in). Duration of the heating cycle needed to sufficiently soften the sheet depends on the polymer—its thickness and color. Methods by which forming is accomplished can be classified into three basic categories: (1) vacuum thermoforming, (2) pressure thermoforming, and (3) mechanical thermoforming. In the discussion of these methods, the forming of sheet stock is described, but most thermoforming operations in the packaging industry are performed on thin films.

Vacuum Thermoforming   This was the first thermoforming process (simply called *vacuum forming* when it was developed in the 1950s). Negative pressure
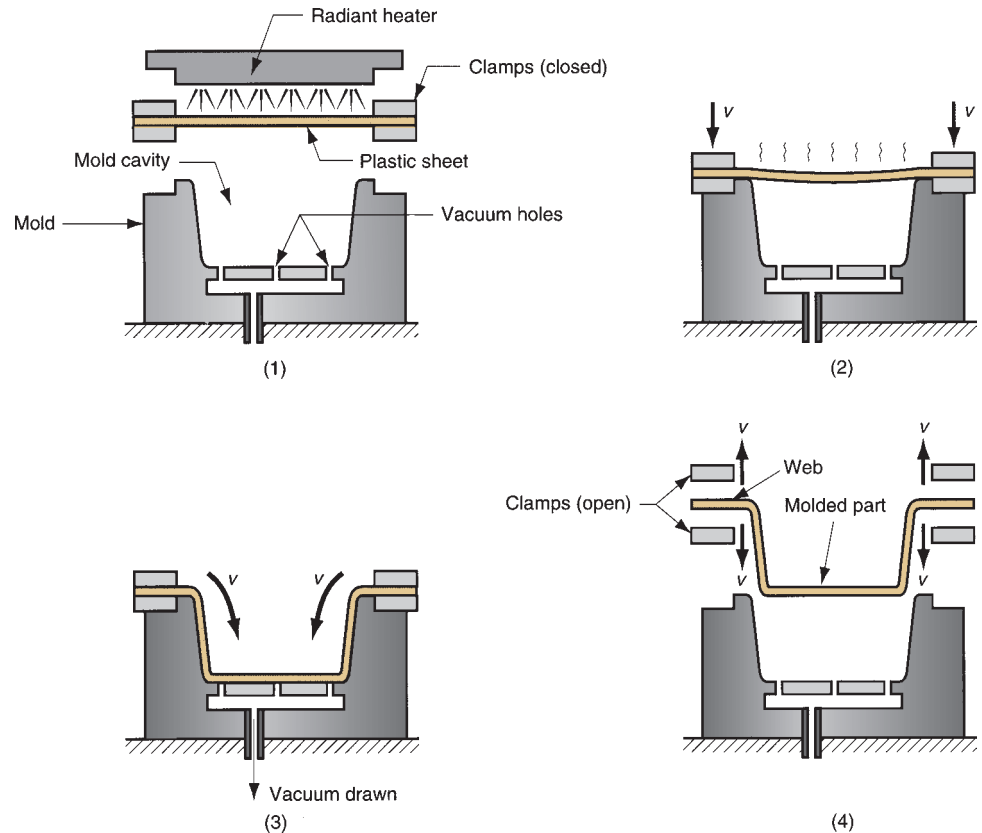
FIGURE 13.37 Vacuum thermoforming: (1) a flat plastic sheet is softened by heating; (2) the softened sheet is placed over a concave mold cavity; (3) a vacuum draws the sheet into the cavity; and (4) the plastic hardens on contact with the cold mold surface, and the part is removed and subsequently trimmed from the web.

is used to draw a preheated sheet into a mold cavity. The process is explained in Figure 13.37 in its most basic form. The holes for drawing the vacuum in the mold are on the order of 0.8 mm (0.031 in) in diameter, so their effect on the plastic surface is minor.

Pressure Thermoforming   An alternative to vacuum forming involves positive pressure to force the heated plastic into the mold cavity. This is called *pressure thermoforming* or *blow forming*; its advantage over vacuum forming is that higher pressures can be developed because the latter is limited to a theoretical maximum of 1 atm. Blow-forming pressures of 3 to 4 atm are common. The process sequence is similar to the previous, the difference being that the sheet is pressurized from above into the mold cavity. Vent holes are provided in the mold to exhaust the trapped air. The forming portion of the sequence (steps 2 and 3) is illustrated in Figure 13.38.

At this point it is useful to distinguish between negative and positive molds. The molds shown in Figures 13.35 and 13.36 are *negative molds* because they have concave cavities. A *positive mold* has a convex shape. Both types are used in thermoforming. In the case of the positive mold, the heated sheet is draped over the convex form and negative or positive pressure is used to force the plastic against the mold surface. A positive mold is shown in Figure 13.39 for vacuum thermoforming.

The difference between positive and negative molds may seem unimportant, because the part shapes are the same in the diagrams. However, if the part is drawn
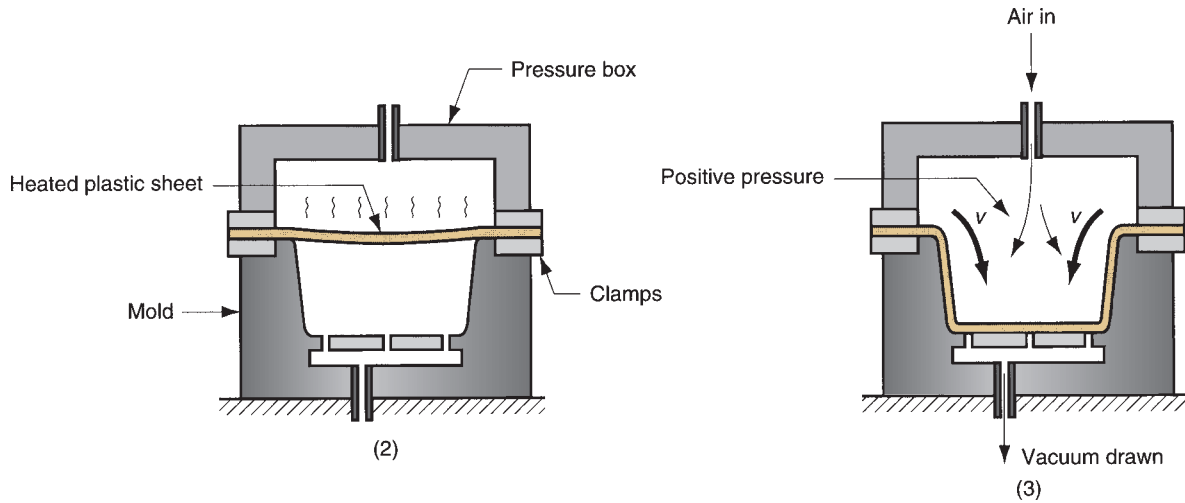
FIGURE 13.38 Pressure thermoforming. The sequence is similar to the previous figure, the difference being: (2) sheet is placed over a mold cavity; and (3) positive pressure forces the sheet into the cavity.

into the negative mold, then its exterior surface will have the exact surface contour of the mold cavity. The inside surface will be an approximation of the contour and will possess a finish corresponding to that of the starting sheet. By contrast, if the sheet is draped over a positive mold, then its interior surface will be identical to that of the convex mold; and its outside surface will follow approximately. Depending on the requirements of the product, this distinction might be important.

Another difference is in the thinning of the plastic sheet, one of the problems in thermoforming. Unless the contour of the mold is very shallow, there will be significant thinning of the sheet as it is stretched to conform to the mold contour. Positive and negative molds produce a different pattern of thinning in a given part. Consider the tub-shaped part in the figures. When the positive mold is used, as the sheet is draped over the convex form, the portion making contact with the top surface (corresponding to the base of the tub) solidifies quickly and experiences virtually no stretching. This results in a thick base but significant thinning in the walls of the tub. By contrast, a negative mold results in a more even distribution of stretching and thinning in the sheet before contact is made with the cold surface.

FIGURE 13.39 Use of a positive mold in vacuum thermoforming: (1) the heated plastic sheet is positioned above the convex mold and (2) the clamp is lowered into position, draping the sheet over the mold as a vacuum forces the sheet against the mold surface.
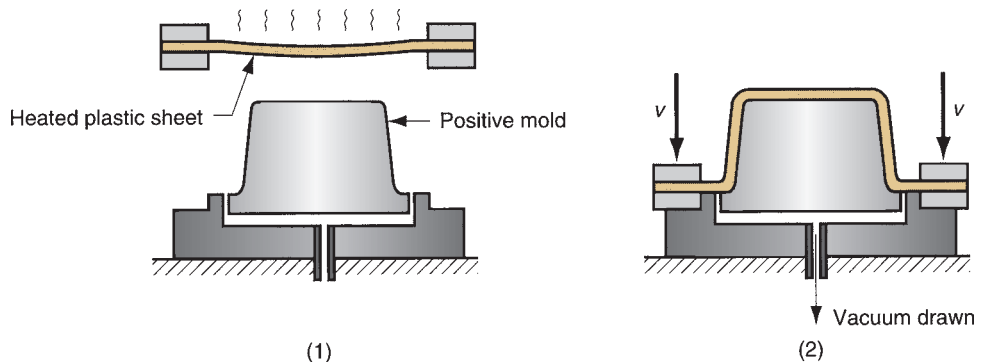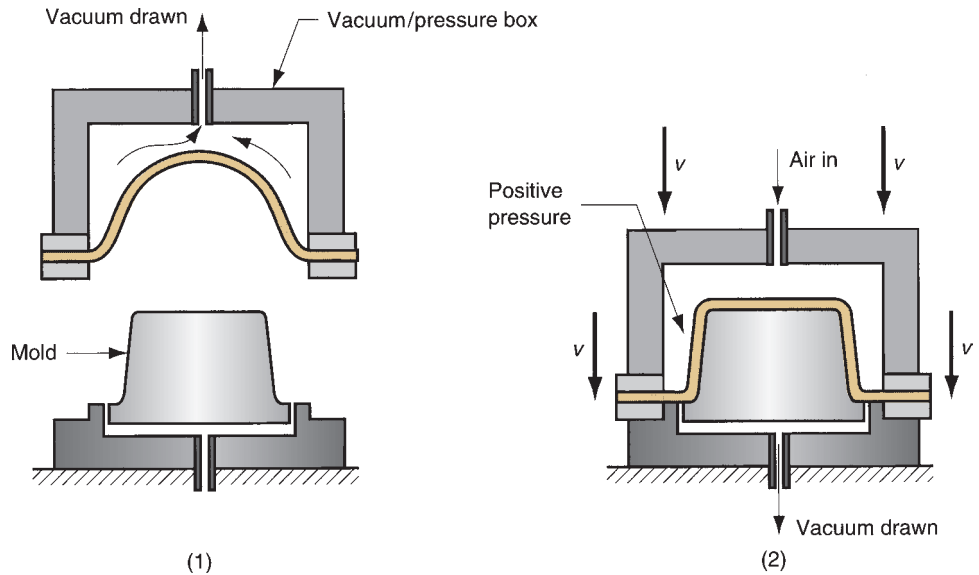
FIGURE 13.40
Prestretching the sheet in (1) prior to draping and vacuuming it over a positive mold in (2).

A way to improve the thinning distribution with a positive mold is to prestretch the sheet before draping it over the convex form. As shown in Figure 13.40, the heated plastic sheet is stretched uniformly by vacuum pressure into a spherical shape before drawing it over the mold.

The first step depicted in frame (1) of Figure 13.40 can be used alone as a method to produce globe-shaped parts such as skylight windows and transparent domes. In the process, closely controlled air pressure is applied to inflate the soft sheet. The pressure is maintained until the blown shape has solidified.

Mechanical Thermoforming   The third method, called mechanical thermoforming, uses matching positive and negative molds that are brought together against the heated plastic sheet, forcing it to assume their shape. In pure mechanical forming, air pressure is not used at all. The process is illustrated in Figure 13.41. Its advantages

FIGURE 13.41
Mechanical thermoforming: (1) heated sheet placed above a negative mold, and (2) mold is closed to shape the sheet.
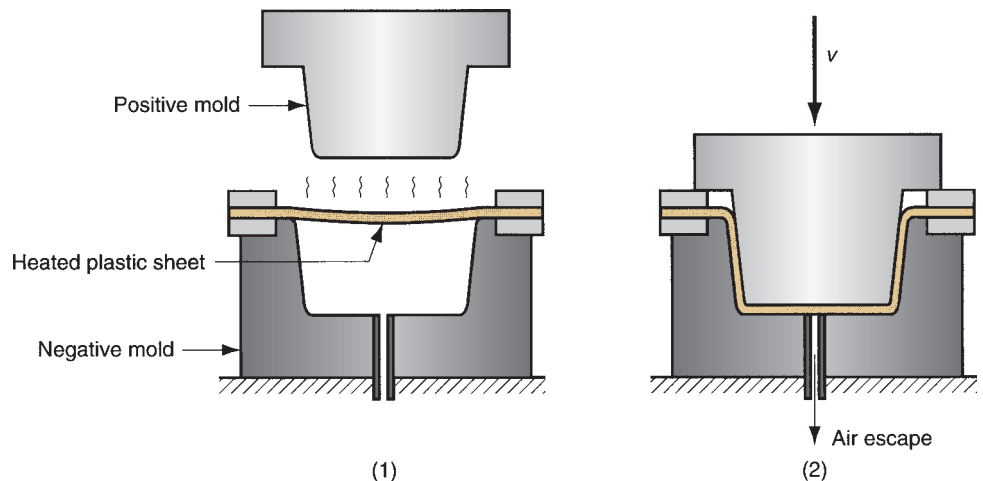
are better dimensional control and the opportunity for surface detailing on both sides of the part. The disadvantage is that two mold halves are required; therefore, the molds for the other two methods are less costly.

Applications   Thermoforming is a secondary shaping process, the primary process being that which produces the sheet or film (Section 13.3). Only thermoplastics can be thermoformed, because sheets of thermosetting or elastomeric polymers have already been cross-linked during forming and cannot be softened by reheating. Common thermoforming plastics are polystyrene, cellulose acetate and cellulose acetate butyrate, ABS, PVC, acrylic (polymethylmethacrylate), polyethylene, and polypropylene.

Mass production thermoforming operations are performed in the packaging industry. The starting sheet or film is rapidly fed through a heating chamber and then mechanically formed into the desired shape. The operations are often designed to produce multiple parts with each stroke of the press using molds with multiple cavities. In some cases, the extrusion machine that produces the sheet or film is located directly upstream from the thermoforming process, thereby eliminating the need to reheat the plastic. For best efficiency, the filling process to put the consumable food item into the container is placed immediately downstream from thermoforming.

Thin film packaging items that are mass produced by thermoforming include blister packs and skin packs. They offer an attractive way to display certain commodity products such as cosmetics, toiletries, small tools, and fasteners (nails, screws, etc.). Thermoforming applications include large parts that can be produced from thicker sheet stock. Examples include covers for business machines, boat hulls, shower stalls, diffusers for lights, advertising displays and signs, bathtubs, and certain toys. Contoured skylights and internal door liners for refrigerators are made, respectively, out of acrylic (because of its transparency) and ABS (because of its ease in forming and resistance to oils and fats found in refrigerators).

3.10 Casting

In polymer shaping, casting involves pouring of a liquid resin into a mold, using gravity to fill the cavity, and allowing the polymer to harden. Both thermoplastics and thermosets are cast. Examples of the former include acrylics, polystyrene, polyamides (nylons), and vinyls (PVC). Conversion of the liquid resin into a hardened thermoplastic can be accomplished in several ways, which include (1) heating the thermoplastic resin to a highly fluid state so that it readily pours and fills the mold cavity, and then permitting it to cool and solidify in the mold; (2) using a low-molecular-weight prepolymer (or monomer) and polymerizing it in the mold to form a high-molecular-weight thermoplastic; and (3) pouring a plastisol (a liquid suspension of fine particles of a thermoplastic resin such as PVC in a plasticizer) into a heated mold so that it gels and solidifies.

Thermosetting polymers shaped by casting include polyurethane, unsaturated polyesters, phenolics, and epoxies. The process involves pouring the liquid ingredients that form the thermoset into a mold so that polymerization and cross-linking occur. Heat and/or catalysts may be required depending on the resin system. The reactions must be sufficiently slow to allow mold pouring to be completed. Fast-reacting thermosetting systems, such as certain polyurethane systems, require alternative shaping processes like reaction injection molding (Section 13.6.5).

Advantages of casting over alternative processes such as injection molding include (1) the mold is simpler and less costly, (2) the cast item is relatively free of residual stresses and viscoelastic memory, and (3) the process is suited to low production quantities. Focusing on advantage (2), acrylic sheets (Plexiglas, Lucite) are generally cast between two pieces of highly polished plate glass. The casting process permits a high degree of flatness and desirable optical qualities to be achieved in the clear plastic sheets. Such flatness and clarity cannot be obtained by flat sheet extrusion. A disadvantage in some applications is significant shrinkage of the cast part during solidification. For example, acrylic sheets undergo a volumetric contraction of about 20% when cast. This is much more than in injection molding in which high pressures are used to pack the mold cavity to reduce shrinkage.

Slush casting is an alternative to conventional casting, borrowed from metal casting technology. In **slush casting**, a liquid plastisol is poured into the cavity of a heated split mold, so that a skin forms at the surface of the mold. After a duration that depends on the desired thickness of the skin, the excess liquid is poured out of the mold; the mold is then opened for part removal. The process is also referred to as **shell casting** [6].

An important application of casting in electronics is **encapsulation**, in which items such as transformers, coils, connectors, and other electrical components are encased in plastic by casting.

3.11 Polymer Foam Processing and Forming

A polymer foam is a polymer-and-gas mixture, which gives the material a porous or cellular structure. Other terms used for polymer foams include **cellular polymer**, **blown polymer**, and **expanded polymer**. The most common polymer foams are polystyrene (Styrofoam) and polyurethane. Other polymers used to make foams include natural rubber ("foamed rubber") and polyvinylchloride (PVC).

The characteristic properties of a foamed polymer include (1) low density, (2) high strength per unit weight, (3) good thermal insulation, and (4) good energy absorbing qualities. The elasticity of the base polymer determines the corresponding property of the foam. Polymer foams can be classified [6] as (1) **elastomeric**, in which the matrix polymer is a rubber, capable of large elastic deformation; (2) **flexible**, in which the matrix is a highly plasticized polymer such as soft PVC; and (3) **rigid**, in which the polymer is a stiff thermoplastic such as polystyrene or a thermosetting plastic such as a phenolic. Depending on chemical formulation and degree of cross-linking, polyurethanes can range over all three categories.

The characteristic properties of polymer foams, and the ability to control their elastic behavior through selection of the base polymer, make these materials highly suitable for certain types of applications, including hot beverage cups, heat insulating structural materials and cores for structural panels, packaging materials, cushion materials for furniture and bedding, padding for automobile dashboards, and products requiring buoyancy.

Common gases used in polymer foams are air, nitrogen, and carbon dioxide. The proportion of gas can range up to 90% or more. The gas is introduced into the polymer by several methods, called foaming processes. These include (1) mixing a liquid resin with air by **mechanical agitation**, then hardening the polymer by means of heat or chemical reaction; (2) mixing a **physical blowing agent** with the polymer—a gas such as nitrogen (N_2) or pentane (C_5H_{12}), which can be dissolved in the polymer
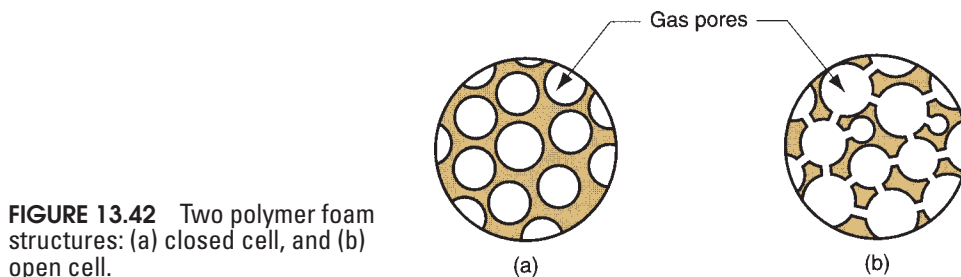
Gas pores

FIGURE 13.42 Two polymer foam structures: (a) closed cell, and (b) open cell.

(a)   (b)

melt under pressure, so that the gas comes out of solution and expands when the pressure is subsequently reduced; and (3) mixing the polymer with chemical compounds, called *chemical blowing agents*, that decompose at elevated temperatures to liberate gases such as CO_2 or N_2 within the melt.

The way the gas is distributed throughout the polymer matrix distinguishes two basic foam structures, illustrated in Figure 13.42: (a) *closed cell*, in which the gas pores are roughly spherical and completely separated from each other by the polymer matrix; and (b) *open cell*, in which the pores are interconnected to some extent, allowing passage of a fluid through the foam. A closed cell structure makes a satisfactory life jacket; an open cell structure would become waterlogged. Other attributes that characterize the structure include the relative proportions of polymer and gas (already mentioned) and the cell density (number of cells per unit volume) which is inversely related to the size of the individual air cells in the foam.

There are many shaping processes for polymer foam products. Because the two most important foams are polystyrene and polyurethane, this discussion is limited to shaping processes for these two materials. Polystyrene is a thermoplastic and polyurethane can be either a thermoset or an elastomer, so the processes covered here for these two materials are representative of those used for other polymer foams.

Polystyrene foams are shaped by extrusion and molding. In *extrusion*, a physical or chemical blowing agent is fed into the polymer melt near the die end of the extruder barrel; thus, the extrudate consists of the expanded polymer. Large sheets and boards are made in this way and are subsequently cut to size for heat insulation panels and sections.

Several molding processes are available for polystyrene foam. *Structural foam molding* and *sandwich molding* are discussed in Section 13.6.5. A more widely used process is *expandable foam molding*, in which the molding material usually consists of prefoamed polystyrene beads. The prefoamed beads are produced from pellets of solid polystyrene that have been impregnated with a physical blowing agent. Prefoaming is performed in a large tank by applying steam heat to partially expand the pellets, simultaneously agitating them to prevent fusion. Then, in the molding process, the prefoamed beads are fed into a mold cavity, where they are further expanded and fused together to form the molded product. Hot beverage cups of polystyrene foam are produced in this way. In some processes, the prefoaming step is omitted, and the impregnated beads are fed directly into the mold cavity where they are heated, expanded, and fused. In other operations, the expandable foam is first formed into a flat sheet by the *blown-film extrusion process* (Section 13.3) and then shaped by *thermoforming* (Section 13.9) into packaging containers such as egg cartons.

Polyurethane foam products are made in a one-step process in which the two liquid ingredients (polyol and isocyanate) are mixed and immediately fed into a

mold or other form, so that the polymer is synthesized and the part geometry is created at the same time. Shaping processes for polyurethane foam can be divided into two basic types [11]: spraying and pouring. ***Spraying*** involves use of a spray gun into which the two ingredients are continuously fed, mixed, and then sprayed onto a target surface. The reactions leading to polymerization and foaming occur after application on the surface. This method is used to apply rigid insulating foams onto construction panels, railway cars, and similar large items. ***Pouring*** involves dispensing the ingredients from a mixing head into an open or closed mold in which the reactions occur. An open mold can be a container with the required contour (e.g., for an automobile seat cushion) or a long channel that is slowly moved past the pouring spout to make long, continuous sections of foam. The closed mold is a completely enclosed cavity into which a certain amount of the mixture is dispensed. Expansion of the reactants completely fills the cavity to shape the part. For fast-reacting polyurethanes, the mixture must be rapidly injected into the mold cavity using ***reaction injection molding*** (Section 13.6.5). The degree of cross-linking, controlled by the starting ingredients, determines the relative stiffness of the resulting foam.

3.12 Product Design Considerations

Plastics are an important design material, but the designer must be aware of their limitations. This section lists design guidelines for plastic components, beginning with those that apply in general, and then ones applicable to extrusion and molding (injection molding, compression molding, and transfer molding).

Several general guidelines apply, irrespective of the shaping process. They are mostly limitations of plastic materials that must be considered by the designer.

➢ ***Strength and stiffness***. Plastics are not as strong or stiff as metals. They should not be used in applications in which high stresses will be encountered. Creep resistance is also a limitation. Strength properties vary significantly among plastics, and strength-to-weight ratios for some plastics are competitive with metals in certain applications.

➢ ***Impact resistance***. The capacity of plastics to absorb impact is generally good; plastics compare favorably with most metals.

➢ ***Service temperatures*** of plastics are limited relative to engineering metals and ceramics.

➢ ***Thermal expansion*** is greater for plastics than for metals, so dimensional changes resulting from temperature variations are much more significant than for metals.

➢ Many types of plastics are subject to degradation from sunlight and certain other forms of radiation. Also, some plastics degrade in oxygen and ozone atmospheres. Finally, plastics are soluble in many common solvents. On the positive side, plastics are resistant to conventional corrosion mechanisms that afflict many metals. The weaknesses of specific plastics must be taken into account by the designer.

Extrusion is one of the most widely used plastic shaping processes. Several design recommendations are presented here for conventional extrusion (compiled mostly from [3]).

➤ *Wall thickness*. Uniform wall thickness is desirable in an extruded cross section. Variations in wall thickness result in nonuniform plastic flow and uneven cooling that tend to warp the extrudate.

➤ *Hollow sections*. Hollow sections complicate die design and plastic flow. It is desirable to use extruded cross sections that are not hollow yet satisfy functional requirements.

➤ *Corners*. Sharp corners, inside and outside, should be avoided in the cross section, because they result in uneven flow during processing and stress concentrations in the final product.

The following guidelines apply to injection molding (the most popular molding process), compression molding, and transfer molding (compiled from Bralla [3], McCrum [10], and other sources).

➤ *Economic production quantities*. Each molded part requires a unique mold, and the mold for any of these processes can be costly, particularly for injection molding. Minimum production quantities for injection molding are usually around 10,000 pieces; for compression molding, minimum quantities are around 1000 parts, because of the simpler mold designs involved. Transfer molding lies between the other two.

➤ *Part complexity*. Although more complex part geometries mean more costly molds, it may nevertheless be economical to design a complex molding if the alternative involves many individual components assembled together. An advantage of plastic molding is that it allows multiple functional features to be combined into one part.

➤ *Wall thickness*. Thick cross sections are generally undesirable; they are wasteful of material, more likely to cause warping caused by shrinkage, and take longer to harden. *Reinforcing ribs* can be used in molded plastic parts to achieve increased stiffness without excessive wall thickness. The ribs should be made thinner than the walls they reinforce, to minimize sink marks on the outside wall.

➤ *Corner radii and fillets*. Sharp corners, both external and internal, are undesirable in molded parts; they interrupt smooth flow of the melt, tend to create surface defects, and cause stress concentrations in the finished part.

➤ *Holes*. Holes are quite feasible in plastic moldings, but they complicate mold design and part removal. They also cause interruptions in melt flow.

➤ *Draft*. A molded part should be designed with a draft on its sides to facilitate removal from the mold. This is especially important on the inside wall of a cup-shaped part because the molded plastic contracts against the positive mold shape. The recommended draft for thermosets is around 1/2° to 1°; for thermoplastics it usually ranges between 1/8° and 1/2°. Suppliers of plastic molding compounds provide recommended draft values for their products.

➤ *Tolerances*. Tolerances specify the allowable manufacturing variations for a part. Although shrinkage is predictable under closely controlled conditions, generous tolerances are desirable for injection moldings because of variations in process parameters that affect shrinkage and diversity of part geometries encountered. Table 13.2 lists typical tolerances for molded part dimensions of selected plastics.