Chapter 11

Unit Operations in Polymer Processing

I. INTRODUCTION

Polymer processing may be divided into two broad areas. The first is the processing of the polymer into some form such as pellets or powder. The second type describes the process of converting polymeric materials into useful articles of desired shapes. Our discussion here is restricted to the second method of polymer processing. The choice of a polymer material for a particular application is often difficult given the large number of polymer families and even larger number of individual polymers within each family. However, with a more accurate and complete specification of end-use requirements and material properties the choice becomes relatively easier. The problem is then generally reduced to the selection of a material with all the essential properties in addition to desirable properties and low unit cost. But then there is usually more than one processing technique for producing a desired item from polymeric materials or, indeed, a given polymer. For example, hollow plastic articles like bottles or toys can be fabricated from a number of materials by blow molding, thermoforming, and rotational molding. The choice of a particular processing technique is determined by part design, choice of material, production requirements, and, ultimately, cost–performance considerations.

The number of polymer processing techniques increases with each passing year as newer methods are invented and older ones modified. This chapter is limited to the most common polymer processing unit operations, but only extrusion and injection molding, the two predominant polymer processing methods, are treated in fairly great detail. Our discussion is restricted to general process descriptions only, with emphasis on the relation between process operating conditions and final product quality. Table 11.1 summarizes some polymer processing operations, their characteristics, and typical applications.

II. EXTRUSION[1]

Extrusion is a processing technique for converting thermoplastic materials in powdered or granular form into a continuous uniform melt, which is shaped into items of uniform cross-sectional area by forcing it through a die. As shown in Table 11.1, extrusion end products include pipes for water, gas, drains, and vents; tubing for garden hose, automobiles, control cable housings, soda straws; profiles for construction, automobile, and appliance industries; film for packaging; insulated wire for homes, automobiles, appliances, telephones and electric power distribution; filaments for brush bristles, rope and twine, fishing line, tennis rackets; parisons for blow molding. Extrusion is perhaps the most important plastics processing method today.

A simplified sketch of the extrusion line is shown in Figure 11.1. It consists of an extruder into which is poured the polymer as granules or pellets and where it is melted and pumped through the die of desired shape. The molten polymer then enters a sizing and cooling trough or rolls where the correct size and shape are developed. From the trough, the product enters the motor-driven, rubber-covered rolls (puller), which essentially pull the molten resin from the die through the sizer into the cutter or coiler where final product handling takes place.

A. THE EXTRUDER

Figure 11.2 is a schematic representation of the various parts of an extruder. It consists essentially of the barrel, which runs from the hopper (through which the polymer is fed into the barrel at the rear) to the die at the front end of the extruder. The screw, which is the moving part of the extruder is designed to pick up, mix, compress, and move the polymer as it changes from solid granules to a viscous melt. The screw turns in the barrel with power supplied by a motor operating through a gear reducer.

The heart of the extruder is the rotating screw (Figure 11.3). The thread of an extruder screw is called a flight, and the axial distance from the edge of one flight to the corresponding edge on the next flight is called the pitch. The pitch is a measure of the coarseness of the thread and is related to the helix

Table 11.1 *Some Unit Operations in Polymer Processing and Typical Products*

Process	Characteristics	Resin Employed	Typical Products
Extrusion	A process for making indeterminate length of thermoplastics with constant cross-section	Most thermoplastics including PE, PP, PVC, ABS, PS	Pipes and tubing used for soda straws, garden hose, drains and vents, control cable housings, gas and water pipes; profiles, e.g., auto trim, home siding, storm windows; sheets used for window glazing, refrigerator liners, signs, plates, lighting; films for bags, coverings, laminates, packaging; fibers or filaments for brush bristles, rope, fishing line; insulated wire for homes, automobiles, appliances, telephone and electric power distribution; coated paper for milk cartons, meat packaging
Injection molding	Versatile process, most suitable for high speed, low cost molding of intricate plastic parts required in high volume	Virtually all thermoplastics and some thermoset; most common are commodity plastics such as PVC, PE, PP, and PS; others include ABS, nylon, cellulosics, acrylics	Automobile parts, appliance housings, camera cases, knobs, gears, grilles, fan blades, bowls, spoons, lenses, flowers, wastebaskets and garbage cans
Blow molding	Process used for making bottles and other hollow plastic parts having relatively thin walls	Several thermoplastics with PE (particularly ND, PE) having the largest volume; others include PVC, PP, PS, ABS, acrylics, nylons, acrylonitrile, acetates, and PC	Bottles, watering cans, hollow toys, gas tanks for automobiles and trucks
Rotational molding	Economical process for the production of hollow seamless parts with heavy walls and/or complex shapes	PE, (highest volume) PP, PVC together account for almost all plastics used; others include a number of engineering thermoplastics, including ABS, acetal copolymers, nylon (6 and 11), polycarbonate	Hollow balls, squeeze toys, storage and feed tanks, automobile dashboards, door liners and gearshift covers, industrial storage tanks and shipping containers, whirlpool tubs, recreational boats, canoes and camper tops, hobby horses, heater ducts, auto armrest skins, athletic balls, portable toilets
Thermoforming	Process for forming moderately complex shapes that are not readily amenable to injection molding	Almost all thermoplastics but most commonly used include ABS, PP, PS, PVC polyesters; others include acrylics, polycarbonate, cellulosic, nitrile resins	Automobile, airline and mass transportation industries for such uses as auto headliners, fender walls, overhead panels, aircraft canopies; construction industry for exterior and interior paneling, bathtubs, shower stalls; outdoor signs; appliances, e.g., refrigerator liners, freezer panels; packaging trays for meat packing, egg cartons, fast-food disposables and carryouts, blister packages, suitcases, tote boxes, cups, and containers
Compression and transfer molding	Most widely used techniques for molding thermosets	Phenolic (largest volume), urea, melamines, epoxy, rubber, diallyl phthalate, alkyds	Pot handles, electrical connectors, radio cases, television cabinets, bottle closures, buttons, dinnerware, knobs, handles, replacement for metal parts in electrical, automotive, aircraft industries
Casting	Process for converting liquid resins into rigid objects of desired shape	Polyesters, nylons, polyurethanes, silicones, epoxies, phenolics, acrylics	Tooling and metal-forming industries' cast epoxy dies used to produce airplane and missile skins, automobile panels and truck parts; epoxies used by artists and architects for outdoor sculpture, churches, homes and commercial buildings, and encapsulation in electronic industry; cast acrylic sheets used in airplanes, helicopters, schools

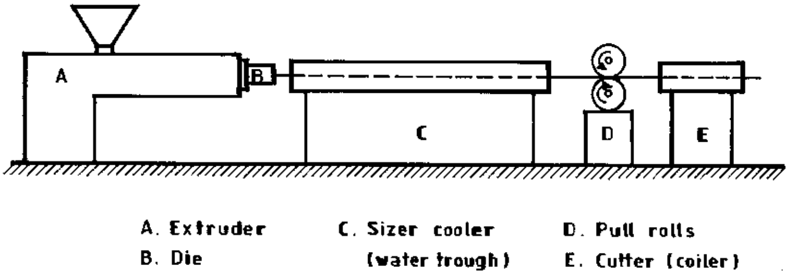

Figure 11.1 *Sketch of an extrusion line. (From Richards, P.N.,* Introduction to Extrusion, *Society of Plastics Engineers, CT, 1974. With permission.)*

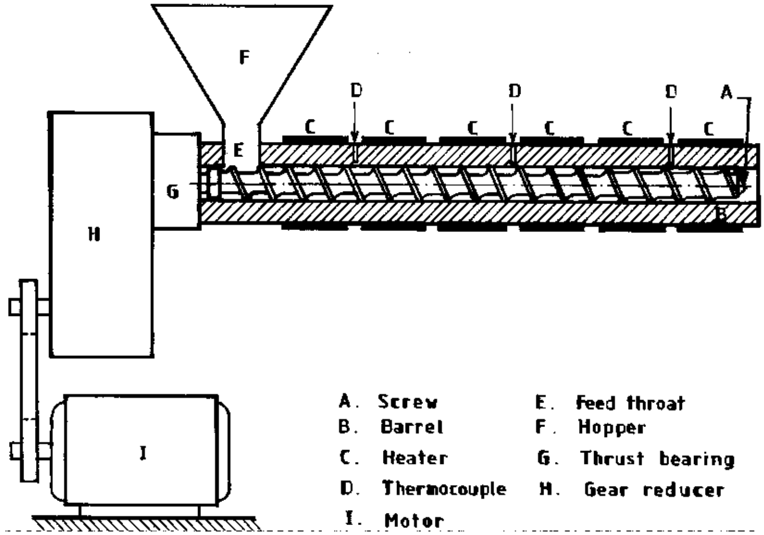

Figure 11.2 *Parts of an extruder. (From Richards, P.N.,* Introduction to Extrusion, *Society of Plastics Engineers, CT, 1974. With permission.)*

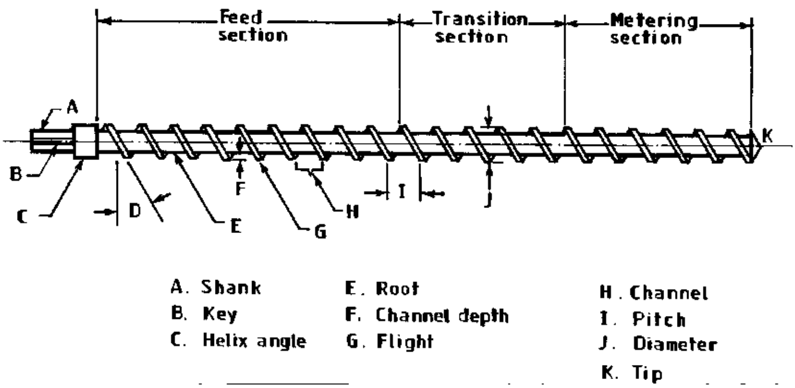

Figure 11.3 *Parts of an extruder screw. (From Richards, P.N.,* Introduction to Extrusion, *Society of Plastics Engineers, CT, 1974. With permission.)*

angle. The polymer is melted and pumped in the open section between the flights called the channel. The bottom of the channel is called the root of the screw. The distance between the root and the top of the flight is referred to as the channel depth. The hub and shank, located at the rear of the screw, fit into the driving mechanism. The hub acts as a seal preventing the polymer material from leaking into the machinery.

The most common and versatile extruder currently in use is the single screw extruder. Extruders are normally characterized by the bore diameters D and the length of the barrel specified as the length-to-diameter ratio, L/D. Diameters range from about 1 in. for laboratory to about 8 in. for specialized production machines. Typical L/D ratios for commercial extruders range from 20/1 to 34/1. In general, the shorter machines (L/D = 20/1 range) are used for elastomer processing while the longer ones are employed for processing thermoplastics. Screws with pitch equal to diameter are referred to as square-pitched screws and have a helix angle of 17.7°. The number of turns of the flight in a square-pitched screw gives the L/D ratio.

The channel depth changes along the screw length; it is deepest at the section under the hopper and shallowest toward the tip. In a few cases where the channel depth changes gradually from one end to the other, the screw is called a constant taper screw. In most cases, however, the screw is divided into three distinct zones each with a different channel depth. These zones are referred to as the feed, transition, and metering sections based on the differing functions. The feed section, 1 to 10 diameters long, picks up the resin under the hopper and advances it into the externally heated barrel to begin melting. The compression section or the transition zone, about 5 diameters long, compacts the loosely packed polymer feed and in the process eliminates air pockets. It melts and forms the resin into a continuous stream of molten material. The frictional force generated between the resin, the barrel wall, and the rotating screw (viscous energy dissipation) is an important energy source for melting the resin. The metering or pump section ensures a uniform flow rate and generates the pressure needed to force the polymer melt through the rest of the extruder and out through the die. Screws are also sometimes described in terms of compression ratio, which is essentially the ratio of the channel depth of the first turn at the rear end of the screw to that of the channel at the last turn. Screws vary from a compression ratio of two for a low-compression screw to four for a high-compression screw.

Various modifications of the single screw design are available. Multiscrew extruders are also in current use for specialized application for which the single screw designs are inefficient. Examples of such applications include production of large-diameter PVC pipe and processing of heat-sensitive materials or resins that must leave the die at relatively low temperatures. Screw configuration for multiscrew extruders may involve intermeshing, corotating, or counterrotating screws. Screws may also be nonintermeshing, of constant depth, or conical in shape.

The barrel of the extruder is normally a long tube. It is made of a special hard steel alloy to provide resistance against wear and corrosion and has thickness sufficient to withstand high internal pressure (about 10,000 to 20,000 psi) without failure. The barrel is equipped with systems for both heat input and extraction. The heaters are arranged in zones and are usually made of cast aluminum. Both halves of the heater are clamped to the barrel to ensure intimate thermal contact. Heat is extracted either by air or a liquid coolant. The simplest design is to mount the coolant or blower under each heater. The heaters, operated manually or by automatic controllers, keep each zone of the extruders at a defined temperature. The use of microprocessors for temperature control has proved increasingly successful. The feed throat at the end of the barrel is generally jacketed for cold water circulation. This keeps the surfaces of the barrel section below the temperature that could cause premature softening of the polymer, which then sticks to and rotates with the screw. The resulting material buildup could seal off the screw channel and prevent the forward movement of the polymer — a phenomenon known as bridging.

As can be seen in Figure 11.2, the extruder is also equipped with a gearbox, thrust-bearing mechanism, and motor. The screw derives its power for rotation from an electric motor. Power requirements are in the range of 1 hp per 5 to 10 lb per hour of material passing through the extruder. The electric motor has a speed of about 1700 rpm, which is too fast for a direct connection to the screw, which has speeds in the range 20 to 200 rpm. It is therefore necessary to employ a gear reducer, which provides varying screw speeds by matching the speed of the drive motor and the rotating screw. Variable speed units can usually provide a change of screw speed from 8 to 1. This enables control of extruder output since there is a direct relation between the extruder pumping rate and the screw speed.

The extruder screw is designed to develop the pressure required to pump the molten polymer through the die. This pressure also acts on the screw. Since the thrust bearing mechanism supports the drive mechanism into which fits the shank of the screw, the thrust-bearing mechanism resists the axial thrust exerted by the molten polymer on the screw. Pressures of up to 2000 psi can be developed in many extruder operations.

Some polymers contain unreacted volatile monomer, moisture, and entrapped gases, which when emitted during the extrusion process could potentially contribute to poor product quality. Some extruders are provided with vents to remove these volatiles from the melt before it reaches the die. The vent is a hole in the barrel about screw diameter size, and located about three-fourths of the distance from the feed throat to the front of the barrel. In some cases, a vacuum is attached to the vent to facilitate gas removal.

The screw for a vented extruder, referred to as a two-stage screw, has a special design. The screw section under the vent has a deep channel. The section of screw before the vent can be considered a normal screw with feed, transition, and metering sections. The section following the vent consists of a short transition zone and a metering section. The channels of the metering section after the vent are deeper than those of the metering section before the vent. This, coupled with the relatively higher channel depth under the vent, means that the channel is partially filled at and beyond the vent section and aids gas removal.

Example 11.1: The barrel of a 6-in. extruder must be able to withstand an internal pressure of 10,000 psi without elastic deformation of 0.15%, at which the alloy will crack in tension. If the barrel material is made of hard steel, estimate the thickness of the tube.

Solution: The stresses existing in the walls of a cylindrical vessel under pressure can be reduced to (1) the tangential or hoop stress σ_h, (2) the radial stress σ_r, and (3) the longitudinal stress σ_l. For a cylinder under internal pressure, σ_h and σ_l are tensile stresses while σ_r is a compressive stress. σ_l is generally smaller (about half the magnitude) than σ_h and is not considered in connection vessel failure. For a thick-walled vessel (i.e., where $r_o/r_i = R > 1.2$):

$$\sigma_n = \frac{p_i\left(R^2+1\right)}{R^2-1}$$

where P_i = internal pressure. The maximum allowable hoop stress $\sigma_h = E\varepsilon$.

$$E \text{ for hard alloy} = 30 \times 10^6 \text{ psi}$$

$$\varepsilon = \text{strain}$$

$$\sigma_n = 0.0015 \times 30 \times 10^6$$

$$= 4.5 \times 10^4 \text{ psi}$$

$$4.5 \times 10^4 = \frac{10^4\left(R^2+1\right)}{R^2-1}$$

$$4.5\left(R^2-1\right) = R^2+1$$

$$R^2(4.5-1) = 5.5$$

$$R = 1.25$$

$$r_o = 1.25 r_i = 7.5 \text{ in.}$$

$$r_o - r_i = 1.5 \text{ in.}$$

B. EXTRUSION PROCESSES

The die shapes the polymer extrudate into the desired article. There are a large number of extrusion processes, the simplest of which is compounding. In one variation of extrusion, the die has a series of holes and as the polymer exudes from these holes it is cooled and cut into pellets. In pipe extrusion, the extrudate exiting the die is vacuum-sized and quenched in a water trough. Polymer melts, being viscoelastic, recover the stored elastic energy as they emerge from the die — a process known as die swell. In pipe extrusion, die swell must be controlled to ensure that the pipe dimensions meet standard codes. Profile extrusion is similar to pipe extrusion. However, unlike pipes whose shape is round, hollow, and uniform, the shapes of profiles depend on the end product, which usually is the raw material for downstream processing.

Fibers of various gauges and lengths are obtained in fiber extrusion. These can range from monofilament such as fishing lines to hundreds of continuous filaments extruded from the same die and drawn to hair-sized thickness. The continuous filaments may be crimped for added bulk or made into staples. Almost all electrical wire and cable insulation is currently done by covering the wires or cables with one or more layers of thermoplastic insulation. These take different forms: wire strands may be covered with several layers by successive insulation; multiple preinsulated wires may be covered to form a single cable; or several bore wires may be drawn through the die simultaneously and covered with insulation forming a ribbon cable. In coextrusion, two or more different materials or the same material with two different colors are extruded through the same die so that one material flows over and coats the other. Coextrusion is used to achieve different objectives: a solid cap may be extruded over a foamed core for overall weight reduction or to obtain insulation in addition to a serviceable outer surface; for materials with surfaces sensitive to color, a virgin cap may be extruded over reground, or several different materials may be coextruded so that each material contributes a derived property to the end product.

III. INJECTION MOLDING[2-4]

Injection molding is one of the processing techniques for converting thermoplastics, and recently, thermosetting materials, from the pellet or powder form into a variety of useful products. Forks, spoons, computer, television, and radio cabinets, to mention just a few, are some of these products. Simply, injection molding consists of heating the pellet or powder until it melts. The melt is then injected into and held in a cooled mold under pressure until the material solidifies. The mold opens and the product is ejected. The injection molding machine must, therefore, perform essentially three functions:

1. Melt the plastic so that it can flow under pressure.
2. Inject the molten material into the mold.
3. Hold the melt in the cold mold while it solidifies and then eject the solid plastic.

These functions must be performed automatically under conditions that ideally should result in a high quality and cost-effective part. Injection molding machines have two principal components to perform the cyclical steps in the injection molding process. These are the injection unit and the clamp unit (Figure 11.4). We now describe the operation of the various units of the injection molding machine that perform these functions.

A. THE INJECTION UNIT

The injection unit essentially has two functions: melt the pellet or powder and then inject the melt into the mold. It consists of the hopper, a device for feeding process material; a heated cylinder or chamber where the material is melted; and a device for injecting the molten material into the mold. In the early days when the amount of processed material was relatively small, the two functions of melting and injecting the polymer were accomplished by using a simple plunger machine (Figure 11.5). In this system, a measured volume of the plastic material is delivered into the heated cylinder from the hopper while the ram is retracted. At the beginning of the injection cycle, the plunger pushes forward and forces the material through the heated cylinder compacting it tightly behind and over the centrally located spreader or torpedo. The material is melted by heat convection and conduction. The sustained forward motion of the plunger forces the melt through the nozzle of the cylinder into the mold.

In the plunger-type machine, material flow in the cylinder is essentially laminar. Consequently there is hardly any mixing in this system and, as such, large temperature gradients exist in the melt, and color

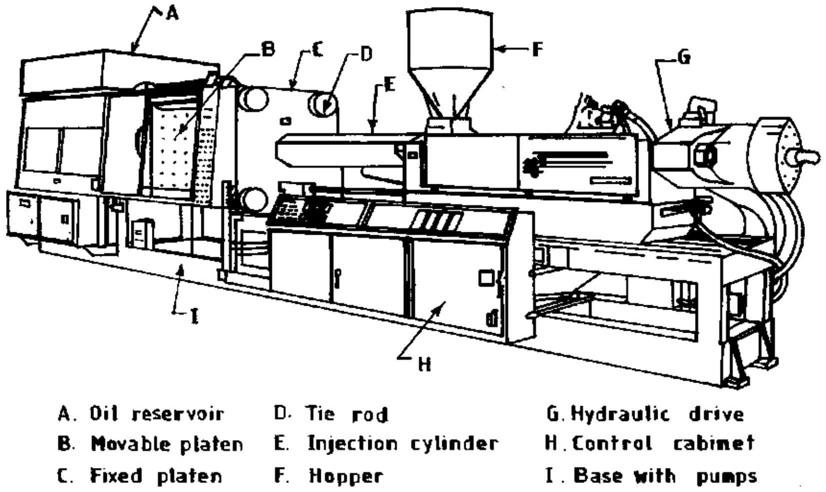

Figure 11.4 *Major parts of a typical injection-molding machine. (From Weir, C.L., Introduction to Molding, Society of Plastics Engineers, CT, 1975. With permission.)*

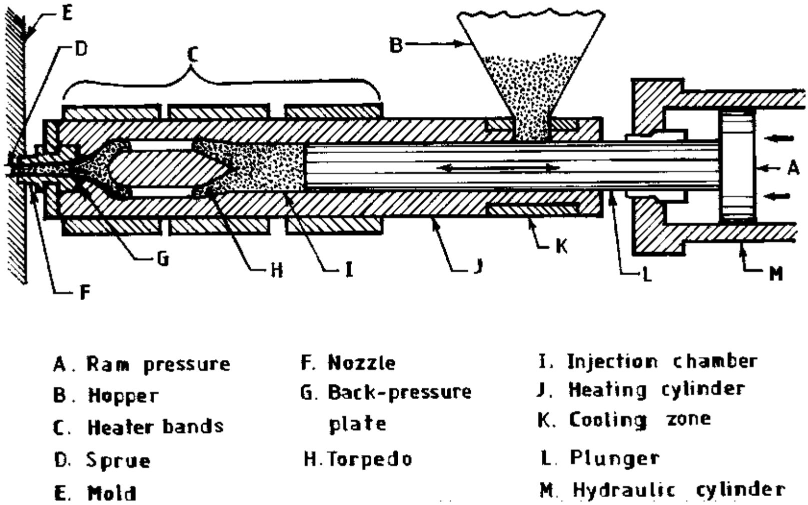

Figure 11.5 *Schematic diagram of a plunger-type injection molding machine. (From Weir, C.L., Introduction to Molding, Society of Plastics Engineers, CT, 1975. With permission.)*

blending is thus problematic. Also, as a result of the friction between the cold resin pellets in the neighborhood of the hopper and the barrel walls, a considerable loss of pressure, up to 80% of the total ram pressure, occurs. This necessitates long injection time. As indicated above, the resin is melted by heat conduction from the walls of the cylinder and the resin itself. Since plastics are poor heat conductors, high cylinder temperatures are required to achieve fast resin plasticization. This can result in the degradation of the material. To avoid such possible material deterioration, the heating of the cylinder is limited, and this also limits the plasticizing capacity of plunger-type injection machines.

Today, the plunger has been replaced almost totally by the plasticating screw. As described in Section II, the screw consists basically of three sections: the feed, the transition zone, and the metering section. Melting normally starts halfway down the length of the screw at which point the depth of the screw flights decreases initiating the compression of the melt. This marks the beginning of the transition zone, which terminates at that metering section — the point where the depth of the flights is minimum. A

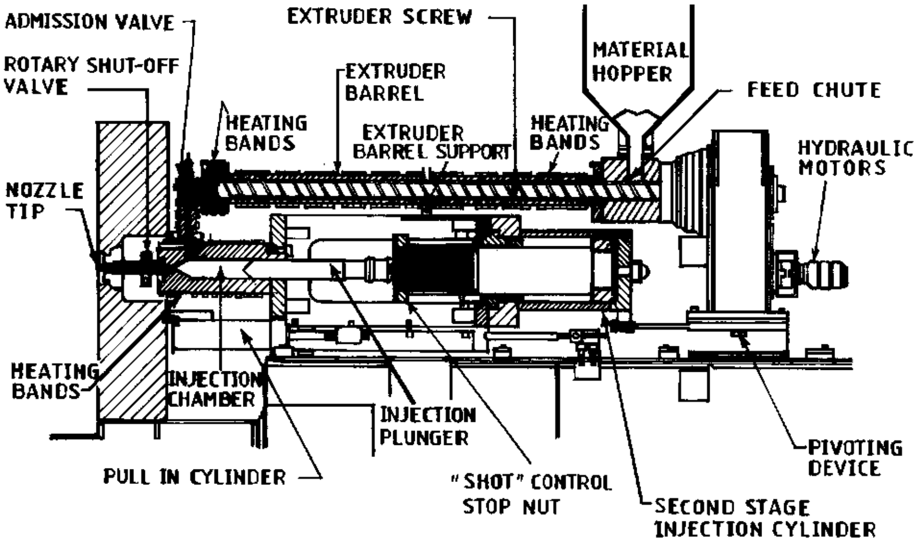

Figure 11.6 *Schematic drawing of injection end of two-stage screw-plunger machine. (From Kaufman, H.S. and Falcetta, J.J., Eds., Introduction to Polymer Science and Technology,* John Wiley & Sons, New York, 1977. *With permission.)*

number of screw configurations exist, including the mixing screw, the marblizing screw, and that with a decompression zone geometry to permit venting and ridding the melted material of volatiles.

There are essentially two methods of using the plasticating screw. The first is the screw-plunger system also called the two-stage or screw-pot system. The screw rotates in the heated barrel and consequently plasticizes the polymer material. The plasticized material is then transferred into a second heated cylinder from which it is injected into the mold by a plunger. Figure 11.6 shows the basic features of a screw-pot injection molding machine.

In the second approach developed in the mid-1950s, a reciprocating screw is employed. As the screw rotates, it picks up the material from the hopper. The material is melted primarily by the shearing action of the screw on the resin. The electrical heating bands attached to the barrel essentially provide start-up and compensate for heat losses. The rotation of the screw moves the melted material forward ahead of the screw. The pumping action of the screw generates back-pressure, which forces back the screw, the screw drive system, and the hydraulic motor when enough melted material required for a single shot has accumulated in front of the screw. As the screw moves backward, it continues to turn until it hits a limit switch, which stops the rotation and backward movement. The location of the limit switch is adjustable and determines the shot size. Meanwhile the clamp ram has moved forward with the movable platen and closed the mold. When the backward movement of the screw is stopped, the hydraulic cylinders bring the screw forward rapidly and inject the melted material through the nozzle into the mold cavity. A ball check or check ring on the end of the screw (valve) prevents the melt from leaking into the flights of the screw during injection. Consequently, most of the melt is forced into the mold (Figure 11.7). The mold is cooled and the part solidifies. At the end of the predetermined period, the mold opens as the movable platen returns to its initial position and the part is ejected. The screw starts rotating, beginning the next cycle.

The plasticating screw-type machines obviate most of the problems associated with the plunger system. The resin is heated mainly by viscous heat generation as opposed to thermal conduction from cylinder walls. In addition, in contrast to the block of material in the barrel in plunger-type machines, only a thin layer of material exists between the screw and the barrel walls and thus the resin is heated faster. Also in the screw-type machines, the melt is thoroughly mixed. Consequently, these machines produce a melt with a more uniform temperature and homogeneous color, high injection pressures, faster injection speeds and shorter cycles, and therefore higher production rates.

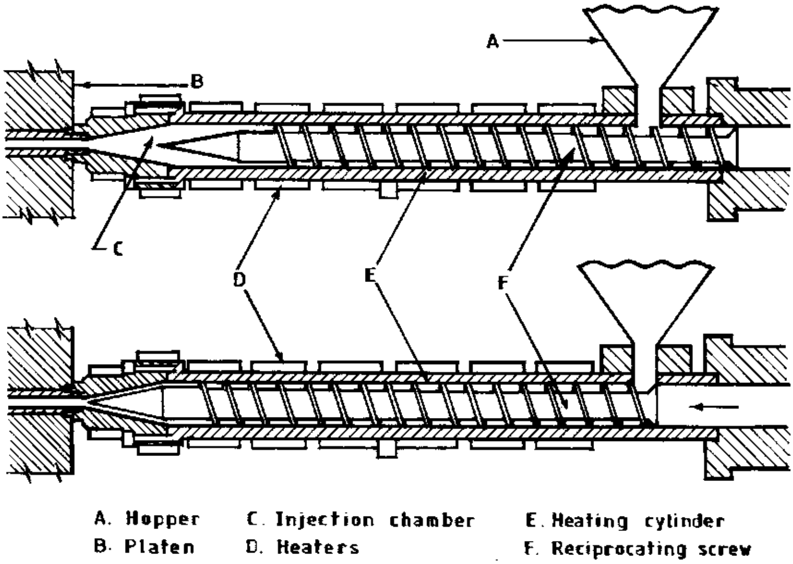

Figure 11.7 *Schematic diagrams of a screw-type injection-molding machine: (top) screw retracted, before injection; (bottom) screw forward, at end of shot. (From Weir, C.L.,* Introduction to Molding, *Society of Plastics Engineers, CT, 1975. With permission.)*

Example 11.2: Explain the following observations:

a. Screw-machine-made end products generally have better physical properties, e.g., lower shrinkage, than the same products made from plunger-type machines.
b. Polymers like PVC and HDPE are easier to handle in screw machines than plunger machines.

Solution:

a. To a very large extent, high injection pressures create internal stresses in the molded part. The resulting part, consequently, has inferior physical properties and is vulnerable to rapid quality deterioration in use. Low injection pressures are therefore desirable. In plunger-type machines, there is usually excessive pressure loss. Therefore, injection pressures are necessarily high in these machines. In contrast, the same parts can be molded in reciprocating screw machines with much lower pressures. Indeed, pressures can be reduced to as much as one-half to two-thirds those of the plunger-type machines, particularly with high viscosity materials. Thus, parts produced in reciprocating screw machines have better physical properties than the same part made from a plunger-type machine.
b. Although screw machines are more complicated than plunger type machines, they are also more flexible and their operation and adjustment to varying molding conditions are simpler. Resin hang-up and the attendant decomposition and the loss of physical properties due to overheating occur very rarely in screw machines. Also, it is much easier to keep the melt temperature within limits by the regulation of screw speed and barrel heating. Thus heat-sensitive polymers like PVC are easier to handle in screw-type machines. In addition, some polymers require a greater heat input to effect plasticization. For example, the heat requirement for high-density polyethylene (HDPE) is about 310 Btu/lb. As a result of the greater shearing action and the attendant viscous heat generated in screw-type machines, polymers like HDPE are easier to handle in these machines.

B. THE PLASTICIZING SCREW

Given the relative advantages of screw type machines over plunger-type machines, it is instructive to examine the plasticizing screw more closely. The rotation of the screw generates a torque related to the power requirements according to Equation 11.1.

$$\text{Horsepower}\,(\text{hp}) = \frac{[\text{Torque}\,(\text{ft-lb})][\text{Rpm}]}{5252} \tag{11.1}$$

where rpm is revolution per minute of the screw. Recall that torque is the product of the tangential force and the distance from the center of the rotating member. It is clear from Equation 11.1 that there is an inverse relation between the speed and the torque generated by the screw. Generally, a motor of a given horsepower has a fixed speed. Consequently, a unit with a higher torque (lower speed) has a larger frame than that with a lower torque. The screw can be attached to the motor directly or through a gear train. The latter provides an alternative mechanism of changing the speed and therefore the torque generated by the screw. A range of torque values is desirable for handling various materials due to the different processing characteristics of polymers. For example, much higher torque is required to plasticize polycarbonate than polystyrene.

For a given horsepower, the slower the screw speed, the higher the torque developed. However, the yield strength, and therefore the torque a screw can sustain, varies as the cube of the root diameter of the screw. It follows that if the torque generated is too high, the yield strength of the screw material may be exceeded, causing a shearing of the screw. On the other hand, if the screw speed (shear rate) is too high, the material may be degraded. As indicated earlier, plasticization of the polymer is a result of the viscous energy developed from the work done by the rotating screw. In other words, the screw output is related to the energy developed from the shearing forces. Therefore, if different screw designs have similar efficiency, the maximum screw output is determined largely by the power rating of the screw.

Example 11.3: A plasticizing screw driven by a 50-hp motor is used to raise the temperature of the polymer feed from 25°C to the processing temperature. Assuming a mechanical efficiency of 60% and neglecting the energy required to pump the polymer and that from the heating bands, estimate the screw output if:

a. The processing temperature is 440°F and the specific heat of the polymer material is 0.8 Btu/lb °F.
b. The processing temperature is 500°F and the specific heat of the polymer material is 0.8 Btu/lb °F.
c. The processing temperature is 500°F and the specific heat of the polymer material is 0.4 Btu/lb °F.

Solution: a. Since the energy from the heating bands and the energy required to pump the polymer are to be neglected, the power supplied by the motor is converted into work by the screw. The viscous energy dissipated goes into melting the polymer.

Power = $C_p\, Q\, (T_m - T_f)$
T_m = temp of polymer melt
T_f = temp of polymer feed
C_p = specific heat of polymer material (assumed constant)
Q = Screw output (in mass/time)

If Power = hp, Q = lb/h, then since 1 Btu/h = 0.0004 hp, hp = 0.0004 $C_p\, Q\, [T_m - T_f]$.

$$Q = \frac{\text{hp}}{0.0004\, C_p\,(T_m - T_f)}\,(\text{lb/h})$$

$$= \frac{50 \times 0.6}{0.0004 \times 0.8\,(440 - 72)}$$

$$= 255\ \text{lb/h}$$

$$Q = \frac{50 \times 0.6}{0.0004 \times 0.8\,(500 - 72)}$$

$$= 219\ \text{lb/h}$$

$$Q = \frac{50 \times 0.6}{0.0004 \times 0.4\,(500 - 72)}$$

$$= 438\ \text{lb/h}$$

Example 11.4: Explain the following observations:

a. It is generally necessary to mold plastics at the lowest possible melt temperature.
b. If two screws with different diameters but with the same L/D ratio are operated under identical conditions, the polymer material has a longer residence time in the larger diameter screw machine even though the machine output is the same. However, it is preferable sometimes to operate machines with the larger diameter screws.

Solution:

a. From Problem 11.3 it is obvious that raising the material processing temperature lowers output. Also, it increases the cycle time because the mold cooling time is longer. Therefore, to maximize output and increase overall productivity, it is best to mold at the lowest possible melt temperature.
b. Productivity or machine output is the primary concern of injection molders. However, high screw speeds and hence high productivity can result in material degradation and poor product quality. Consequently, it is generally prudent to operate machines at reasonably slower speeds. But because of the inverse relation between torque and screw speed (Equation 11.1) for the same power input drive, the magnitude of the torque developed by the smaller diameter screw will be higher than that of the larger diameter screw and may be high enough to shear the screw. Therefore, even when machine output is the same, larger diameter screws may be preferable to smaller ones to prevent possible screw damage.

C. THE HEATING CYLINDER

The heating or plasticizing cylinder of the injection molding machine is the primary element of the machine. It is here that the polymer material is softened or conditioned for injection into the mold cavity where it is shaped. The temperature and pressure of the melt as it leaves the cylinder nozzle into the mold cavity are two important variables that determine product quality. Cylinders are generally rated on the basis of their plasticizing capacity which is the rate at which the given cylinder can condition a given polymer material into a state suitable for injection. As may be expected, for a given cylinder, this varies with the particular plastic material being processed because the molding (softening or melting) temperature, specific heat, thermal conductivity, and specific gravity — all of which contribute to the complex heat generation and transfer processes which occur during processing — differ for various materials. Consequently, the plasticizing capacity of a machine is rated conventionally on the basis of one material — general purpose polystyrene, which is taken as the standard. The machine capacity with respect to other materials is then related to this standard material using the relative specific gravities of the two materials.

Table 11.2 gives the specific gravities of some plastic materials, while Table 11.3 shows the appropriate cylinder heater inputs and power requirements of typical machine sizes.

Table 11.2 *Specific Gravities of Some Polymers*

Resin	Specific Gravity
ABS	1.04
Acetal	1.42
Cellulose acetate	1.27
Cellulose acetate butyrate	1.19
Cellulose propionate	1.21
Ethyl cellose	1.10
Nylon	1.14
Polycarbonate	1.20
Polyethylene	
Low density	0.92
High density	0.95
Poly(methyl methacrylate)	1.19
Polypropylene	0.90
Polystyrene	
General purpose	1.05
High impact	1.04
Polyvinyl chloride	
Plasticized	1.20
Unplasticized	

From Weir, C.L., *Introduction to Molding,* Society of Plastics Engineers, CT, 1975. With permission.

Table 11.3 *Cylinder-Heater Inputs and Power Requirements Typical Machine Sizes*

Shot Size (oz)	Plasticizing Capacity (lb/h)	Approximate Heat Input (kW)	Screw Power Input (hp)
1	17.5	2.0–2.5	3.5
3	45	2.8–4.1	5
6	80	4.4–5.2	10
9	125	8.5–9.0	15
12	220	9.0–10.5	25
24	250	10.6–12.0	40
40	400	15–20	50
60	440	20–25	60
80	700	25–30	75
100	750	30–40	90
150	850	40–50	100
200	1000	60–70	125
225	1500	68–75	150
350	1800	75–100	200

From Weir, C.L., *Introduction to Molding,* Society of Plastics Engineers, CT, 1975. With permission.

Example 11.5: An injection molding machine is rated 100 oz per shot. What is the plasticizing capacity (lb/h) of this machine if the total cycle time is 30 s? What is the average residence time of the material in the heating cylinder for an inventory weight of 50 oz? Estimate the plasticizing capacity of the heating cylinder for low density polyethylene.

Solution: The machine output or plasticizing capacity, Q, is the ratio of the shot weight W to the cycle time t_c.

$$Q = \frac{W(oz)}{t_c(s)}$$

$$\frac{W(oz)}{t_c(s)} \frac{1\ lb}{16\ oz} \frac{3600\ s}{1\ h}$$

$$= 225 \frac{W}{t_c} \frac{lb}{h}$$

$$Q = \frac{225 \times 100\ oz}{30} = 750\ lb/h$$

Residence or contact time in the heating cylinder, t_c, is given by the inventory weight, I_w, divided by the machine output Q.

$$t = \frac{I_w}{Q}$$

$$t(s) = 225\left(\frac{I_w\ oz}{Q\ lb/h}\right) = \frac{225 \times 50}{750} = 15\ s$$

$$\text{Plasticizing capacity for LDPE} = \frac{0.93}{1.05} \times 750$$

$$= 657\ lb/h$$

D. THE CLAMP UNIT

The clamp unit or press end of the injection molding machine performs three functions: opens and closes the mold at appropriate times during the molding cycle; ejects the molded part; and provides enough pressure to prevent the mold from opening due to the pressure developed in the mold cavity as it is filled with the melt by the injection unit. Injection pressures in the plasticating cylinder can range from 15,000 to 20,000 psi in a given system. As a result of possible pressure drops in the cylinder and the nozzle, the effective pressure within the mold cavity may be reduced to 25 to 50% of this value. Consequently, the force needed to resist the premature opening of the mold and obtain an acceptable part can be quite large. For example, assuming a 50% pressure drop and using the upper possible pressure in the cylinder stated above, the melt pressure in the mold cavity becomes 10,000 psi. This translates into a clamp force of 5 tons/in^2 of the projected area of the part. However, as a result of greater degree of homogenization achievable in screw-type machines, the clamp tonnage required in these machines is generally less than in plunger-type machines.

The halves of the mold are attached to the platens, one of which is stationary and one of which moves as the clamp mechanism is opened or closed. Molds are generally designed so that the ejection side of the mold (mold core) is on the movable platen and the injection side of the mold (mold cavity) is on the stationary platen, which must provide an entry for the nozzle of the plasticizing chambers. When the mold opens, the movable platen must be moved sufficiently for the part to be ejected. Shrinkage usually accompanies part solidification and this results in the part sticking to the core as the mold opens. Consequently, the movable platen is provided with an ejector or knockout system to eject the part. The ejector usually consists of a hydraulically actuated ejector plate mounted off the back face of the movable platen. The ejector system causes the knockout plate to change its location relative to the rest of the mold. The ejector pins attached to this plate push against the molded part and eject it from the mold. The force required to eject the part is usually less than 1% of the nominal clamp force; its magnitude depends on the part geometry, material, and packing pressure.

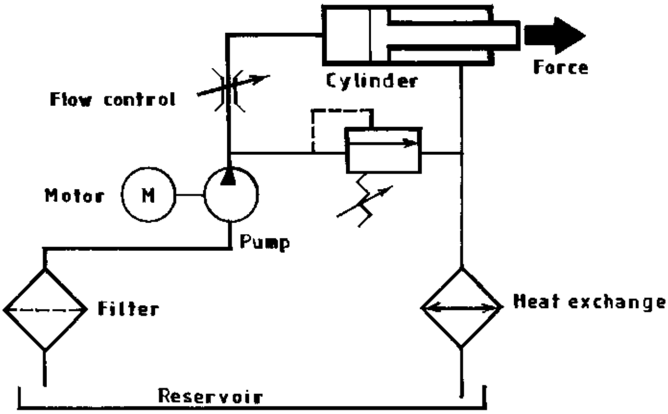

Figure 11.8 *Elements of hydraulic system.*

There are essentially two categories of clamp systems for moving and locking the movable platen. These are the mechanical (toggle) and hydraulic systems. The toggle system, which is used mainly in small tonnage (about 500 tons) equipment, is relatively inexpensive but requires good maintenance because wear reduces the clamping force. Hydraulic systems, used primarily in medium and large equipment (1500 to 2000 tons), are relatively slow acting but have the advantage of providing virtually limitless pressure selection, which can be followed continuously with a pressure gauge. Machine flexibility permits the necessary adjustment to match mold thickness and settings.

E. AUXILIARY SYSTEMS

The operation of the injection and clamp units and other components of the injection molding machine (opening and closing of the mold and melting and injection of the polymer material) requires power, which is supplied by an electric motor. The orderly delivery of this power depends on auxiliary systems: the hydraulic and control systems. The hydraulic system, the muscle for most machines, transmits and controls the power from the electric motor to the various parts of the machine. Machine functions are regulated by a careful control of the flow, direction, and pressure of the hydraulic fluid. The elements of the hydraulic system for most injection molding machines are essentially the same: fluid reservoir, pumps, valves, cylinders, hydraulic motors, and lines (Figure 11.8).

The pump driven by the electric motor draws oil from the reservoir and delivers it to the system through the suction filter. The restriction of oil flow by the control valve and/or the resistance to movement of the cylinder compress the oil and lead to pressure buildup. A pressure buildup of appropriate magnitude drives the hydraulic cylinder, and if this pressure reaches that set for the relief valve, the valve opens and excess fluid is bypassed to the reservoir. The opening of the relief valve decompresses the oil, converting the excess pressure energy into heat, which raises the oil temperature. The oil is cooled by passing it through a heat exchanger.

The injection molding operation involves a sequence of carefully ordered events, e.g., precise heat control and appropriate timing of injection pressures and cycles. The control system is the nerve center responsible for the orderly execution of the various machine functions. Over the years, the control system has developed from a collection of relays that perform logic, plug-in timers for timing functions, and plug-in temperature controllers for cylinder temperature regulation to solid-state circuitry for the control of these functions to the current microcomputer control, which has greatly enhanced process control.

F. THE INJECTION MOLD

The injection mold is a series of steel plates, which when assembled produces the cavity that defines the shape of the molded part. Conventional molds consist of the mold frame, components, runners, cooling channels, and ejector system. The mold frame is a collection of steel plates that contain mold components and runners, cooling and ejection systems. Components are parts inserted into either bored holes or cutout pockets in the mold frame. The polymer melt enters into the mold cavity or cavities through the runners, which are passages cut into the mold frame. The hot polymer material in the mold

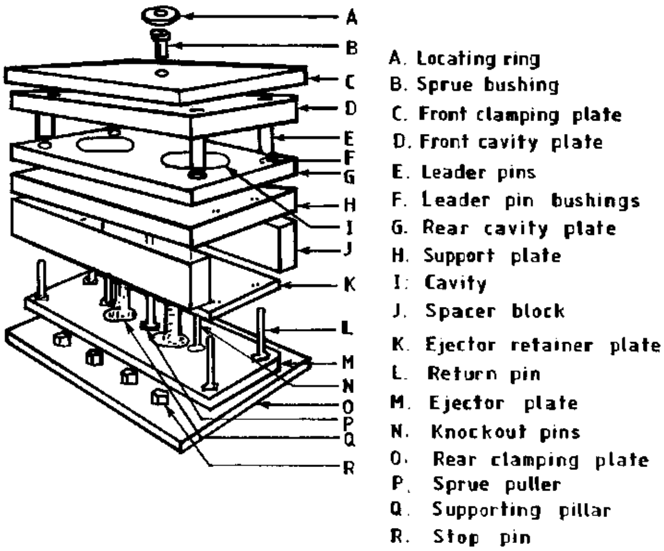

Figure 11.9 *Exploded view of a six-plate mold base. (From Weir, C.L., Introduction to Molding, Society of Plastics Engineers, CT, 1975. With permission.)*

is cooled by a coolant, usually water, which circulates through the cooling channels drilled at strategic locations into the mold frame and components for proper mold temperature control. When the material has cooled (hardened) sufficiently, the mold opens and the hardened part is removed from the mold by the ejector system.

Since the quality of the molded part depends to a large extent on the mold, it is essential to expand on the functions of the various parts of the mold. Details of mold components are shown in Figure 11.9. The register or retainer ring, which is fitted into the stationary platen, aligns the mold with the cylinder nozzle. Sometimes, the retainer ring, as the name suggests, also acts as the retainer of the sprue bushing within the mold. The sprue is the pathway through which the molten polymer material is introduced into the mold cavity area or the runner system from the cylinder nozzle. The sprue is generally made as small as practical since large diameter sprues have been known to require longer cooling time and consequently prolong cycle time beyond what is usually necessary for part thickness. In some newer mold designs, the sprue is completely eliminated.

The front clamp plate, which houses the retaining ring and sprue bushings, is used to support the stationary half of the mold, including the front cavity plate. The cavity (cavities) of the part to be molded is contained in the cavity plate in either of two ways. In one case the cavity is drilled directly into the steel plate, and in the other the cavity plate provides sockets for the insertion of cavities that have been constructed separately. The rear cavity plate, mounted on the rear support plate, contains the core section of the molded part or second half of the mold cavity. The leader (guide) pins and guide pin bushings are housed in the front cavity and rear cavity plates, respectively. The passage of the guide pins through the bushings ensures that the plates are properly aligned during closing of the mold. The knockout and reset pins are mounted on a series of plates that compose the ejector plate. At appropriate times during the molding cycle, these pins pass through holes in the cavity and cavity retainer plates and make contact with either the molded part to effect its ejection or the stationary cavity plate to initiate the movement of the pin plate back in readiness for the next injection shot. The movable half of the mold is anchored to the movable platen by the rear clamp plate.

As the mold cavity is filled with polymer melt, the pressure increase within the cavity can produce stresses of up to 10,000 to 180,000 psi in the mold cavity material. The resulting deformation is substantial but can be accommodated provided the elastic limit of the material is not exceeded. However, where the dimensional tolerance of the molded part is critical, it is imperative that the mold material modulus is sufficiently stiff to ensure part dimensional accuracy. Maintenance of proper temperature of the mold cavity and core is also necessary in this respect as well as for the production of a molded part with good physical and mechanical properties. Dimensional accuracy of the part also demands that the dimensions of the mold be slightly larger than those of the molded part so as to compensate for the shrinkage that normally accompanies the solidification of a polymer melt. Finally, a good surface appearance of the molded part such as luster and smoothness requires a polished mold cavity.

Runners are the channels through which the polymer melt is fed into the mold cavities from the cylinder nozzle. In a multicavity mold, it is necessary to fill all the mold cavities simultaneously and uniformly. Control of the size of the runners provides a means of controlling the flow resistance and balancing the flow into the mold cavities. In most multicavity molds, the runners form part of the mold frame. Consequently, the ejected part is accompanied by the runner system, which must be removed and, in the case of thermoplastics, reground for reuse. The use of the hot runner mold whereby the runner channels are heated to keep the polymer in the molten state, eliminates this need for plastic runner separation and avoids possible generation of scrap material. With proper machine operation, a hot runner mold requires a smaller amount of melt per shot than an equivalent cold runner mold, leading to reduced injection time and faster cycles.

Runners feed the mold cavities through the gates. The gate of an injection mold is one of its most vital components. The size, type, and location of the gate affect production rate and the quality of the molded part. As the polymer melt flows into the mold cavity, pressure in the cavity builds up and, if not controlled, can develop an undesirable magnitude. Control of pressure in the cavity requires that the gate freeze as soon as sufficient material has been fed into the mold cavity and only to the point where available pressure is sufficient to cause resumption and maintenance of adequate melt flow. If the gate freezes prematurely, the mold will not be completely filled and/or adequately packed to compensate for shrinkage. This produces a warped and unacceptable part. If, on the other hand, the mold cavity is filled and the gate takes too long to freeze, the resultant back pressure causes the still-hot polymer melt to flow back out of the mold into the nozzle and cylinder when the ram or screw is withdrawn.

Finally, to conclude this section, we briefly address mold cooling and the associated shrinkage and possible warpage of the molded part. As we discussed earlier, to complete the injection cycle the polymer melt injected into the mold cavity must be cooled to such a stage that the solidified part can be ejected. Ideally the temperature distribution of the mold surface should be uniform so as to ensure uniform temperature reduction, even shrinkage, and reduced warpage tendency of the molded part. This demands that the size and distribution of the cooling lines be such that cooling rate is highest near the gating and sprue where the melt temperature is highest and lowest in areas farthest from these points.

You will recall from our discussion in Chapter 5 that polymers undergo a reduction in specific volume (shrinkage) as they undergo a phase transformation from the molten to the solid state. The severity of this dimensional change varies with the nature of the polymer: crystalline polymers are more seriously affected than amorphous polymers. Therefore, a certain amount of mold shrinkage is inevitable in polymer molding operations. For most applications, this can be accommodated by proper mold design. However, for sophisticated parts and those parts that require close tolerance, mold shrinkage assumes an added importance. This must be addressed not only through mold design but by a more careful control of operating conditions.

Polymer molecules generally assume a random orientation in the melt. As the melt is forced through the gate during mold filling, polymer molecules tend to lose this random orientation and align themselves along the direction of flow. The polymer material that comes into contact with the much colder mold surface chills rapidly and becomes frozen in place. Meanwhile, the melt not yet in contact with the mold surface continues to move. The frictional forces (shearing stresses) between the moving and stationary polymer material, which are generally high, stretch the polymer molecules in the direction of flow. This orientation of the polymer molecules results in orientation strains or built-in stresses in the molded part. The relaxation of these stresses in the ejected part leads to a further or postmold shrinkage of the molded part. Uneven shrinkage causes the part to warp, particularly in large, thick, and flat molded articles and may lead to part rejection.

Example 11.6: Explain the following observations:

a. Nonferrous metals are used in injection molds for cavity and core components but must be properly supported on steel forms.
b. The dimensions of the mold cavity are generally made larger than those of the molded part to allow for the shrinkage that occurs when the molten polymer cools. Typical shrinkage allowances for some plastics are shown in Table E11.6.

Table E11.6 *Shrinkage Allowances for Some Polymers*

Polymer	Shrinkage Allowance (in./in.)
Poly(methyl methacrylate)	0.006
Nylon	0.023
Polyethylene	0.023
Polystyrene	0.006

Solution:

a. The surface finish of the mold cavity contributes to the surface appearance (luster and smoothness) of an injection-molded part. Consequently, mold cavities must be properly polished. Nonferrous metals are generally softer and easier to polish than hardened steel. To ensure the dimensional accuracy of the finished part, the surface temperature of injection mold cavities and cores must be maintained at appropriate temperatures during operation. Nonferrous metals with their high thermal conductivities ensure uniform temperature distribution. However, nonferrous metals are not sufficiently stiff and therefore are susceptible to permanent deformation that may affect not only the surface appearance but also the dimensional accuracy of the molded part. Consequently, it is often necessary to support nonferrous metals on the much stiffer hardened steel.

b. On cooling from the viscous state (melt), crystalline polymers shrink more than amorphous polymers because the process of crystallization involves a considerable contraction of volume. Poly(methyl methacrylate) and polystyrene are amorphous, while nylon and polyethylene are crystalline.

Example 11.7: Explain and comment on the following observation: prevention of excessive shrinkage of a molded part requires molding at low injection temperatures, running a cold mold, or operating at high melt pressures, whereas reduction of part warpage calls for maximum injection pressure.

Solution: Polymeric materials exhibit a marked decrease in specific volume (shrink) as they are cooled from the melt. Crystalline materials shrink more than amorphous materials as a result of the more ordered molecular arrangement. The amount of shrinkage is determined by the rate of quenching or temperature drop from the injection temperature to the mold temperature. Lowering the injection temperature reduces this temperature drop and consequently reduces shrinkage. High mold temperature allows the polymer melt to cool more slowly, promotes Brownian movement, and thus facilitates a more ordered molecular arrangement. On the other hand, running a cold mold essentially freezes in the amorphous arrangement of the melt. This in effect translates into a higher specific volume or a reduction in part shrinkage.

As the hot material comes into contact with the cold mold surface, it solidifies and shrinks. Operating at high injection pressures results in a compression of the material and therefore permits more material to flow into the mold cavity and compensate for the shrinkage. The increased mold packing that is associated with high injection pressures means that more material can be packed into a given volume, therefore reducing shrinkage.

Warpage is due largely to the internal stress developed in the molded part during the molding operation. Molding at high injection temperatures tends to diminish the elastic memory of the polymer melt and thus reduce the tendency to create stresses that might cause warpage. As indicated above, the faster the cooling rate of the polymer melt, the more disorder the molecular arrangement of the resulting solidified material and consequently the greater the built-in stresses in the molded part. Operating high mold temperatures allows the molecular rearrangement that is required for stress relief and thus a reduction of the internal stresses that cause part warpage. Low injection pressures lead to the generation of much lower orientation strain.

It is obvious from this discussion that procedures for reducing part shrinkage work in direct opposition to those required for preventing its warpage. Therefore, the injection molding of a trouble-free part requires a careful balancing of these operating conditions.

IV. BLOW MOLDING[4,5,8]

Blow molding is a process used extensively for the production of bottles and other hollow plastic items with thin walls. Blow-molded objects may range in size from less than 1 oz to a few hundred gallons.

A. PROCESS DESCRIPTION

The blow molding process consists of a sequence of steps leading to the production of a hollow tube or parison from a molten thermoplastic resin. This is then entrapped between the two halves of a mold of the desired shape. Air, usually at about 100 psi, is blown into the soft parison, expanding it against the contours of the cold mold cavity. The part is cooled and removed from the mold, and where necessary the excess plastic material or flash accompanying the molded part is trimmed and reclaimed for reuse.

The blow molding process therefore involves essentially two properly synchronized operations: parison formation from the plastic material and blowing the parison into the shape of the desired part. There are two techniques for plasticizing the resin for parison formation. These are extrusion blow molding (which is the most common method and which is characterized by scrap production) and injection blow molding. The latter process is versatile and scrap free and is beginning to be more understood and accepted by processors.

B. EXTRUSION BLOW MOLDING

In extrusion blow molding, an extruder, as described in Section II, is used to plasticize the resin and form the parison. The process may be continuous or intermittent. In the continuous process, a continuous parison is formed at a rate synchronized with the rates of part blowing, cooling, and removal. Two general mold clamp mechanisms are used for part formation from the extruded parison. In the first arrangement or shuttle system, the blowing station is situated on one or both sides of the extruder. As soon as an appropriate length of parison is extruded, the clamp mechanism moves from the blowing station to a position under the die head, captures and cuts the parison, and then returns to the blowing station for part blowing, cooling, and removal. This ensures that there is no interference with parison formation. In the second or rotary system, a number of clamping stations are mounted on a vertical or horizontal wheel. As the wheel rotates at a predetermined rate, blowing stations successively pass the parison head(s) where it is entrapped for subsequent part formation. In this case, parison entrapment and blowing, part cooling, and removal occur simultaneously in a number of adjacent blowing stations.

In the intermittent extrusion process, molding, cooling, and part removal take place under the extrusion head. An extruder system, which may be of the reciprocating screw, ram accumulator, or accumulator head type, extrudes the parison in a downward direction where it is captured at the proper time between the two halves of the mold. The part is then formed and ejected and a new cycle begins (Figure 11.10). As the name suggests, in the intermittent extrusion blow molding process, parison formation is not continuous. For example, with the reciprocating screw machine, after the parison is extruded, melt is accumulated in front of the screw causing a retraction of the screw. After the molded part has cooled and the mold opens and ejects the part, the screw is immediately pushed forward by hydraulic pressure, forcing the melt into the die to initiate the formation of the next parison.

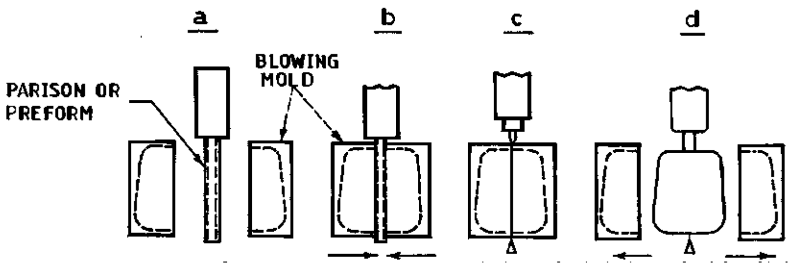

Figure 11.10 *Schematic of the blowing stage. (a) The molten, hollow tube — the parison or preform — is placed between the halves of the mold; (b) the mold closes around the parison; (c) the parison, still molten, is pinched off and inflated by an air blast that forces its wall against the inside contours of the cooled mold; (d) when the piece has cooled enough to have become solid, the mold is opened and the finished piece is ejected. (From Kaufman, H.S. and Falcetta, J.J., Eds., Introduction to Polymer Science and Technologies, John Wiley & Sons, New York, 1977. With permission.)*

C. INJECTION BLOW MOLDING

The injection blow molding process is a noncontinuous cyclic process consisting essentially of two phases. In the first phase, a preform is molded by injecting melted plastic into a steel mold cavity where it is kept hot and conditioned. In the second or subsequent phase, the preform is metered into the blow mold where the blowing operation takes place to form the final part. The major advantages of injection blow molding are the quality of the molded part and productivity. There is no flash production. Therefore, the molded part neither has a pinch-off scar from flash nor requires additional trimming or other finishing steps for waste retrieval. Also, the molded parts show hardly any variation in weight, wall thickness, and volume from the accurately molded preform. However, only blow-molded parts with limited size and shape and without handles are feasible with the injection blow molding process.

V. ROTATIONAL MOLDING[4,5]

A. PROCESS DESCRIPTION

Rotational molding is a process used for producing hollow, seamless products having heavy and/or complex shapes. In rotational molding a premeasured amount of powder or liquid polymer is placed in the bottom half of the mold, and the two halves of the mold are locked together mechanically. The mold is then rotated continuously about its vertical and horizontal axes to distribute the material uniformly over the inner surface of the mold (Figure 11.11). The rotating mold then passes through a heated oven. As the mold is heated, the powdered polymer particles fuse forming a porous skin that subsequently melts and forms a homogeneous layer of uniform thickness. In the case of a liquid polymer, it flows over and coats the mold surface and then gels at the appropriate temperature. While still rotating axially, the mold passes into a cooling chamber where it is cooled by forced air and/or water spray. The mold is then moved to the work station and opened, and the finished solid part whose outside surfaces and contour faithfully duplicate those of the inner mold surface is removed. The mold is recharged for the next cycle.

B. PROCESS VARIABLES

Different types of heating systems, including hot air, molten salts, or circulation of oil through a jacketed mold have been used. The essential requirement of any heating system is to ensure that the mold is heated uniformly and at a properly controlled rate so that the desired part thickness is obtained without causing resin degradation. Given the potential hazards and maintenance problems associated with the use of molten salts, the use of hot oil has gained wide commercial acceptance because of the relatively cleaner, cheaper, and safer operation involved.

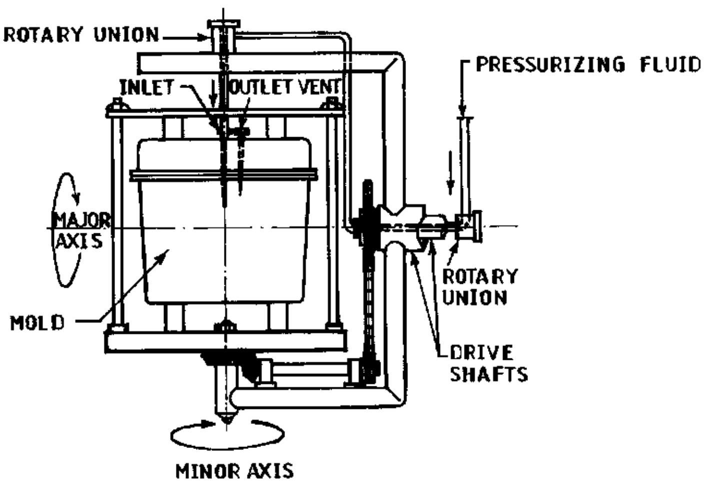

Figure 11.11 *Schematic diagram of rotation molding showing major and minor axes of rotation.*

While the heating cycle has virtually no effect on the properties of the finished part, the cooling rate determines part shrinkage, final density, brittleness, and other physical properties. Mold cooling is accomplished by the use of forced air and/or application of water spray.

Rotational molding machines vary from the simple one-arm rotocast system with capability for producing parts of up to 20 gal size to the industrially predominant three-arm machines that are capable of producing up to 5000 gal capacity tanks. In the latter case, each arm is always in one of the three stations: load-unload, oven, or cooling. More recently, shuttle-type machines with molds mounted on large self-driven shuttle carts have been developed. The carts move on tracks from the oven to the cooling chamber. These machines can make products of much larger capacities. Rotational molding machines with microprocessor controls and other solid-state devices for regulating operating variables such cycle time, oven temperature, rotational speed ratio (ratio of the speed of major to minor axis), and fan and water on–off times are now available.

The rotational molding operation involves neither high pressure nor shear rates. In addition, precise metering of materials is not crucial. Therefore, rotational molding machinery is relatively cheap and has a more extended lifetime. Other advantages of rotational molding include favorable cost–performance (productivity) ratio, absence of additional finishing operations even of complex parts, minimal scrap generation, and capability for simultaneous production of multiple parts and colors.

Example 11.8: Explain the variation in the physical properties of rotational molded parts from polypropylene and polystyrene shown in Table E11.8 with changes in the cooling cycle

Table E11.8 *Physical Properties of Rotational Molded Parts*

	Polypropylene Cooling Time		Polystyrene Cooling Time	
Property	**10 min**	**2 min**	**10 min**	**2 min**
Specific gravity	0.96	0.90	1.20	1.19
Shrinkage	0.040	0.015	0.003	0.004
Elongation at break (%)	300	100	1.5	1.3

Solution: A reduction in cooling time means faster cooling rates of the rotational molded parts. This is accompanied by marked changes in the physical properties of the part from polypropylene (crystalline polymer). On the other hand, the cooling rate has little effect on the part from polystyrene (amorphous polymer). A longer cooling time permits a greater ordered molecular arrangement in the crystalline polymer. The resultant enhanced crystallinity leads to higher specific gravity and shrinkage and reduced brittleness. Cooling rates do not seriously affect molecular arrangement in the amorphous polymer.

VI. THERMOFORMING[4,5]

Thermoforming is a process for forming moderately complex shaped parts that cannot be injection molded because the part is either very large and too expensive or has very thin walls. It consists essentially of two stages: elevation of the temperature of a thermoplastic sheet material until it is soft and pliable and forming the material into the desired shape using one of several techniques.

A. PROCESS DESCRIPTION

Thermoforming techniques may be grouped into three broad categories: vacuum, mechanical, and air blowing processes.

1. Vacuum Forming

The vacuum forming process is shown schematically in Figure 11.12. The plastic sheet is clamped in place mechanically and heated. A vacuum is then placed beneath the hot elastic sheet, and this makes atmospheric pressure push the sheet down onto the contours of the cold mold. The plastic material cools down, and after an appropriate time the cooled part is removed.

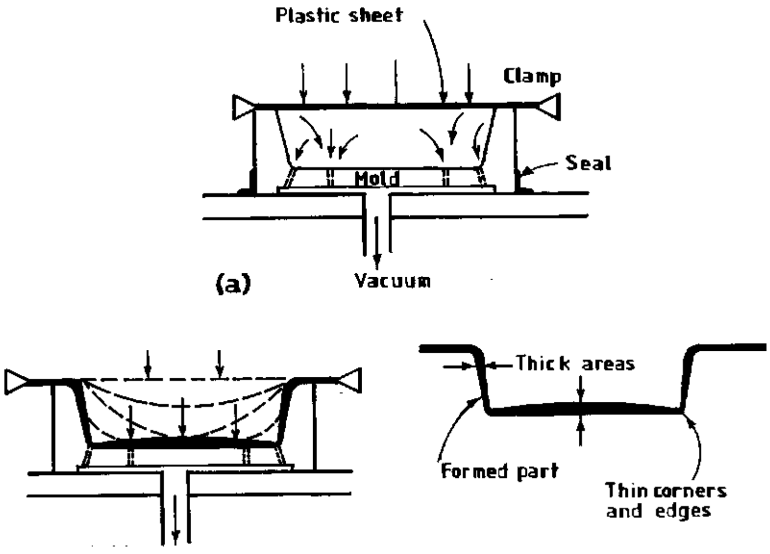

Figure 11.12 *Steps in vacuum forming process.*

2. Mechanical Forming

In this case, a hot sheet is stretched over a mold or matched molds without the use of air or pressure. For example, in matched mold forming, the heated sheet is clamped over a female mold or draped over the mold force (male mold) (Figure 11.13). The two molds are then closed. The resulting part has excellent dimensional accuracy and good reproduction of the mold detail, including any lettering and grained surfaces.

3. Air Blowing Process

Here compressed air is used to form the sheet. In one variation, a plastic sheet is heated and sealed across the female cavity (Figure 11.14). Air at controlled pressure is introduced into the mold cavity. This blows the sheet upward into an evenly stretched bubble. A plug which fits roughly into the mold cavity descends on the sheet. When the plug reaches its lowest possible position, a vacuum or, in some cases, air under pressure is used to complete part formation.

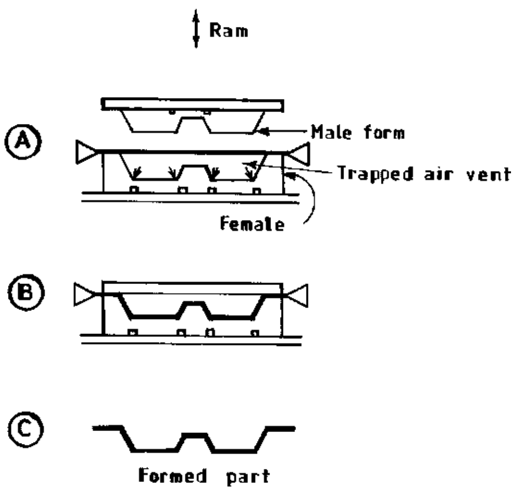

Figure 11.13 *Steps in mechanical forming process.*

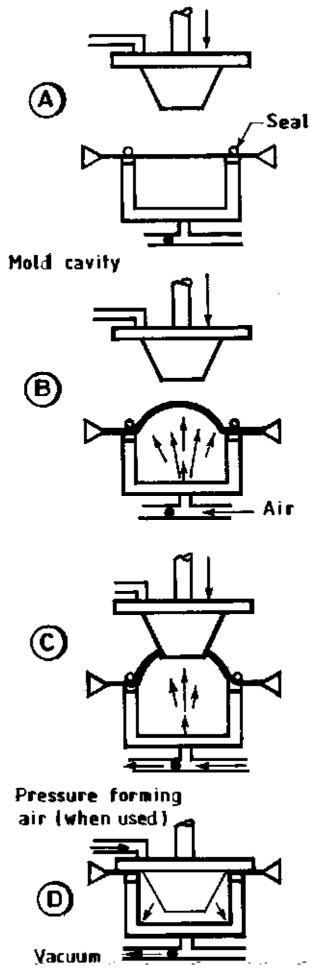

Figure 11.14 *Steps in air-blowing thermoforming process.*

From the foregoing discussion, it is evident that the basic steps in the thermoforming process involve a sequence of operations: loading the sheet or web through the system in increments and heating, forming, and cooling. Other secondary functions that may be integrated into the process include trimming and other finishing operations. Thermoforming machinery is categorized on the basis of the arrangement for performing these operations. In single station machines, the loading, heating, forming, cooling, and unloading operations are performed in succession. Consequently, even though these machines are versatile, they are characterized by comparatively long cycle times. With in-line machines, which are quite popular in the packaging industry, the different operations are performed simultaneously in a multistation in-line system. In this case, therefore, the cycle time is determined by the longest operation in the entire process. The third category of thermoforming machines is the rotary type, which is supported on a horizontal circular frame that has three work (and possibly other secondary stations for the loading–unloading, heating, and forming (possibly secondary) operations. By rotating the cut sheets sequentially from station to station, the rotary machine configuration is well suited for high production rates.

Molds for the thermoforming process may be made of wood, metal, or epoxy and are relatively cheap. They are provided with vents to allow trapped air to escape and release possible pressure buildup. Temperature control, as we shall see in the following discussion, determines part quality. It is, therefore, crucial that mold temperature is controlled properly. The mold is consequently provided with channels for the passage of the cooling liquid.

B. PROCESS VARIABLES

Thermoplastic materials, in general, can be stretched when hot. However, the degree of success in forming a part from a hot, stretched sheet material depends on the particular resin, its molecular weight, and processing conditions like forming temperature and speed. We recall that the thermal response of thermoplastic polymers depends first on whether the material is amorphous or crystalline and to some extent on their molecular weights. When heated, crystalline polymers undergo a rather abrupt phase transformation from the solid to the fluid state, while amorphous polymers undergo a more gradual transformation. For a given resin, the degree of fluidity depends on molecular weight and the processing temperature. The higher the molecular weight, the higher the melt strength and consequently the greater the capacity of the material to be deep-drawn, which is a necessary condition for the proper formation of intricate parts. On the other hand, materials that are too fluid at the forming temperature are susceptible to tearing, leading to the production of bad quality parts. Given the influence of forming temperature on part quality, it is necessary to ensure that sheets have a uniform temperature distribution. This also calls for a uniform sheet thickness. A variation in sheet thickness causes a nonuniform sheet temperature distribution resulting in uneven pulling and possible tearing of the sheet. It is also essential to recognize that variation of shrinkage with sheet orientation can generate forming problems. If there is excessive differential shrinkage due to sheet orientation, the pull from the clamping frames during forming becomes unbalanced and the sheet could be pulled out.

VII. COMPRESSION AND TRANSFER MOLDING[4,5]

The two most widely used methods for molding thermoset are compression and transfer molding. Thermosets, you will recall, undergo a permanent set, i.e., become essentially insoluble and infusible under the action of heat. Consequently, techniques for fabricating thermosets must take due cognizance of and make allowance for the fact that sprues, runners, and gates are not reusable and therefore constitute rejects.

A. COMPRESSION MOLDING

In compression molding, a preweighed amount of material is loaded into the lower half of a heated mold or cavity. The force plug (plunger) is lowered into the cavity, and pressure, which can range from 20 to 1000 tons, is applied to the powder (Figure 11.15). Under heat and pressure, the powder melts and flows into all parts of the mold cavity, the resin cross-links thus becoming irreversibly hardened. After an appropriate time, the mold is opened and the part is ejected while still hot (usually under gravity) and allowed to cool outside the mold.

The machinery for compression molding is relatively simple, consisting essentially of two platens, which when brought together, apply heat and pressure to the mold material to form a part of desired shape. The

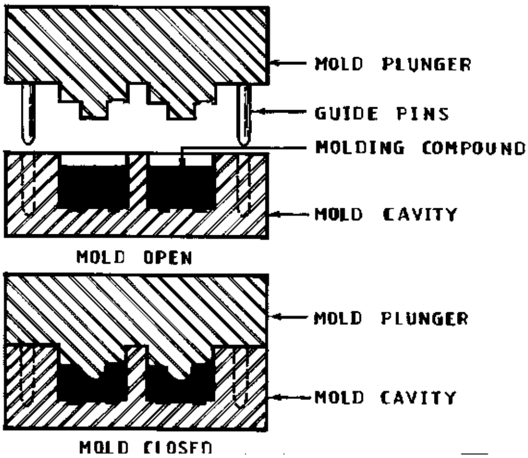

Figure 11.15 *Schematic of a compression molding operation showing material before and after forming.*

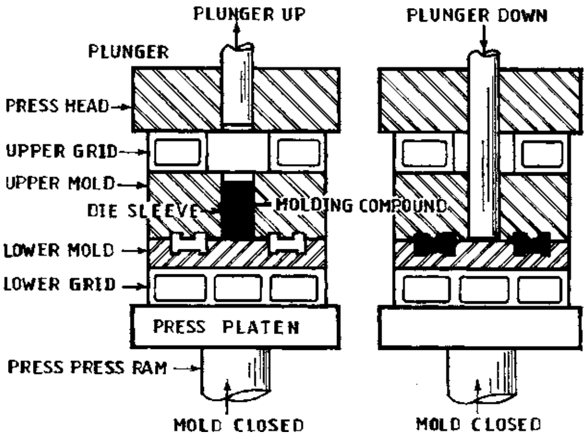

Figure 11.16 *Schematic of a transfer molding operation.*

platens move vertically, with the cavity usually mounted at the bottom so molding material can be loaded into it. Material may also be a preform, in which case it has been preheated. Material flow, cure time, and the ultimate properties of the molded part depend on the mold temperature, which therefore must be adequately controlled. A number of heating systems are employed for heating the molds. Steam heating provides uniform mold temperature but is limited to temperatures below 200°C. Electrical heating is both clean and easy and enjoys wide usage. Circulated hot oil also provides uniform heat. Most thermosets emit volatile gases or moisture during cure, and escape avenues must be provided for such volatiles to facilitate processing and obtain good quality parts. This is usually accomplished by opening the mold slightly. With modern compression molding machines various degrees of automation for feeding the material and ejecting the molded part are possible. This is achieved by the use of microprocessor controllers.

One of the major advantages of compression molding is that it is relatively inexpensive because of its simplicity. Also, since there are no sprues, runners, and gates, material waste is reduced considerably. The consistency of part size is good and the absence of gate and flow marks reduces finishing costs.

B. TRANSFER MOLDING[4,5]

In transfer molding, (Figure 11.16) a measured charge of preheated thermoset material is placed in a separate or auxiliary heated chamber called the pot. A plunger is then used to force the molten material out of the pot through the runner system into the closed mold cavity where curing occurs. As the material enters the mold, the air from the mold cavity escapes through vents located strategically on the mold. At the end of the cure cycle, the entire shot, including the gates, runners, sprues, and excess material remaining in the pot (referred to as cull) is ejected simultaneously with the molded part. If held for too long in the pot or cylinder, the thermosetting material could cure prematurely into a solid mass. Consequently, only sufficient material for a single shot is loaded at one time. In addition, preheating the material is necessary in transfer molding. When cold, the material flows relatively slowly. In this case, the first material to enter the cavity could cure prematurely resulting in overall improper material mix. This can result in poor product quality in terms of the surface finish and mechanical properties.

Transfer molding has comparatively shorter cycle and loading times than compression molding. Thick sections that cure evenly can be molded; however, mold costs are generally higher, and greater volumes of scrap are generated because of the presence of gates, runners, and sprues.

Examples 11.9: Explain why compression molding of thermoplastics is limited to small quantity production while screw injection molding is thermoset is also currently used on a limited scale.

Solution: In compression molding of thermoset, once the resin is cured the molded part can be ejected while still hot and allowed to cool outside the mold. On the other hand, compression molding of thermoplastics involves heating followed by cooling to solidify the molded part. Therefore, in compression molding of thermoplastics the relatively longer heat-and-chill cycle times involved are uneconomical for large volume production.

In screw injection molding of thermoplastics, the viscous heat generated assists in melting the resin material; during processing the resin is always held in the cylinder during and between shots. However, with thermoset, to avoid resin precure, not only must the barrel and material temperatures be carefully controlled, the resin cannot be held at high temperature for any length of time before molding.

VIII. CASTING[5]

In the casting process, a liquid material is poured into a mold and allowed to solidify by physical (e.g., cooling) or chemical (e.g., polymerization) means resulting in a rigid object that generally reproduces the mold cavity detail with great fidelity. A large number of resins are available and a variety of molds and casting methods are used in casting processes. Therefore, the choice of liquid material, mold type, and casting technique is determined by the particular application.

A. PROCESS DESCRIPTION

In casting processes, the resin material is added with an appropriate amount of hardener, catalyst, or accelerator, mixed manually or mechanically, and then poured into a mold, which is normally coated with a mold-release agent. Air is removed if necessary and the resin is allowed to solidify. The casting process is relatively slow and employs comparatively cheap equipment. Molds for casting processes are fabricated from a wide variety of materials, including wood, plaster and clay, glass, metal, rubber and latex (for flexible molds), and plastics. To facilitate the removal of the cast part from the mold, mold-releasing agents such as high melting waxes, silicone oils, greases, and some film-forming agents are used to coat the mold. Among other considerations, the choice of mold-release agents is based upon the absence of interaction between the resin system and the release agent.

The setting of the resin material is generally exothermic and is usually accompanied by a reduction in volume. For example, in the casting of acrylic, the amount of heat evolved is about 13.8 kcal/mol, while the volume reduction can be as large as 21%. The quantity of heat liberated depends on the size, but is independent of the shape of the casting. However, the rate of heat dissipation depends both on the size and shape of the casting.

Therefore, different methods have to be employed in casting thick or thin sections. Thin sections can be cast at room temperature with minimal possibility of cracking of the casting since heat can be dissipated rapidly. On the other hand, with thick sections, particularly those whose shapes limit the rate of heat removal, large temperature gradients exist between the interior and exterior sections of the casting. This generates internal stresses and enhances the possibility of cracking of the cast part. In this case, therefore, where the quantity of heat liberated cannot be changed, the rate of heat dissipation is controlled by carefully selecting the hardener and a mold material with appropriate thermal properties and by using a possible stepwise increase in casting temperature. To reduce shrinkage and the attendant built-in stresses in the cast part, flexibilizers, diluents, flexibilized resins or hardeners, or fillers are used.

B. CASTING PROCESSES

1. Casting of Acrylics

Acrylic castings are prepared with polymers derived from methacrylic ester monomers. They usually consist of poly(methyl methacrylate) or its copolymers as the major component modified with small amounts of other monomers. Acrylic castings are made by heating the monomers or partially polymerized syrups containing 0.02 to 0.1% radical initiator (e.g., peroxide or azo-bis-isobutyronitrile) in a mold. Syrups are prepared by dissolving finely divided polymer in the monomer. As indicated earlier, the polymerization reaction involved in the acrylic casting process is exothermic and is usually accompanied by about 15 to 21% volume shrinkage. Because of the exothermic nature of this reaction, measures are usually taken to deal with the problems of heat removal and residual stresses in the casting.

The outstanding optical properties of acrylic casting make acrylic sheets invaluable in applications where excellent transparency and resistance to UV are imperative. The fabrication of acrylic sheets therefore predominates in the acrylic casting process. Cast acrylic resins also account for most of the embodiments used for decorative or study purposes. In this case, hard polymers of ethyl or methyl methacrylate are used. Rods and tubes are also prepared from acrylic castings.

2. Casting of Nylon

The nylon casting process consists basically of four steps. These are the melting of the monomer, which is usually lactam flakes, the adding of the catalyst and activator, the mixing of the melts, and the casting process itself. Cocatalyzed anionic polymerization is currently the most widely used nylon casting method. The cocatalysts are strong bases and their salts with imides and lactams.

Since absorbed water can cause catalyst decomposition and hence incomplete polymerization and since lactam monomer flakes are highly hygroscopic, the melting of monomer is carried out under appropriately controlled temperature and humidity conditions. All additives are also completely dried and then mixed with the monomer in stainless steel vessels while flushing with inert gas under thermostatically controlled temperature. Molds can be of the single type fabricated from silicone rubber, epoxy, or sheet steel or the more expensive tool steel used in tight tolerance cast-to-size parts casting.

The nylon casting process is relatively more economical and is a more practical technique for the production of large and thick parts than comparable extrusion and injection molding processes. In addition, the crystallinity and molecular weight of cast nylon are higher than those of extruded or molded nylon. Consequently, cast nylon has a much higher modulus and heat deflection temperature, improved solvent resistance, and better hygroscopic characteristics and dimensional stability.

IX. PROBLEMS

11.1. A small business entrepreneur is considering buying an extruder for a 2-in. (ID) PVC pipe production. A two 8-h/d shift operation for a 300-day work year is planned. If the extruder is to be operated to produce 20 ft of pipe per hour and pipe thickness is 0.5 in., suggest the power rating for the electric motor appropriate for this extruder. PVC has a density of 1.44 g/cm^3.

11.2. Explain the following observations.

a. When complicated shapes are to be extruded, they are usually made from amorphous polymers rather than crystalline polymer.
b. Under comparable thermal conditions, extrusion rate is generally higher with amorphous polymers than crystalline polymers.
c. Many extruders are now equipped with dehumidified hopper driers.

11.3. The following table shows some thermal properties of three thermoplastic polymers. Compute the screw output for each polymer material if the screw drive power input is 60 hp and the mechanical efficiency is 75%. Assume that the heat requirement for molding the materials is satisfied by the viscous dissipation and feed temperature is 77°F.

Polymer	Avg Molding Temp. (°F)	Specific Heat (Btu/lb °F)	Heat of Fusion (Btu/lb)
Polystyrene	500	0.45	0
Polyethylene	440	0.91	104
Nylon 6,6	530	0.63	56

11.4. For a 2.5-in.-diameter screw at 200 rpm the maximum permissible drive input power is 40 hp. What is the maximum permissible drive input power for a 4.5-in.-diameter screw at (a) 150 rpm; (b) 200 rpm.

11.5. A syringe 6 in. long, 1 in. in diameter, and 0.1 in. thick is to be injection molded. The stress generated in the mold cavity and core material as the mold is filled with the plastic melt is 180,000 psi. Estimate the change in volume of the syringe if the mold cavity and core materials are made of:

a. Steel
b. Copper
c. Aluminum

Assume that the volume change is due essentially to the change in the core diameter.

11.6. For crystalline polymers, high mold temperatures result in enhanced tensile strength but reduced clarity of the molded part. Explain.

11.7. Decide which of the two processes (continuous extrusion blow molding or intermittent extrusion blow molding) is more suitable for the production of bottles from:

a. Polyethylene
b. Poly(vinyl chloride)

Explain the basis of your decision.

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