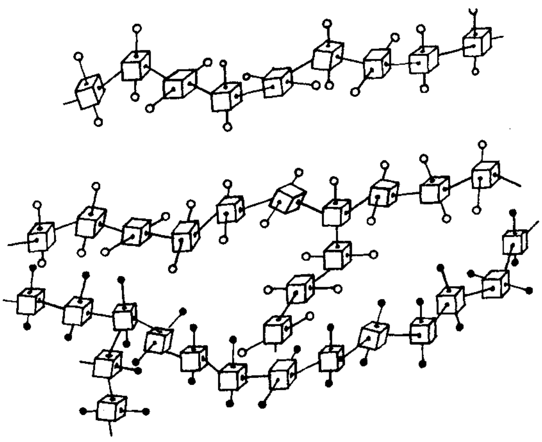

Fig. 5-19. Schematic representation of molecular structures of linear polyethylene (top) and branched polyethylene (bottom). Branching keeps the chains farther apart, reducing density, rigidity, and tensile strength. (*Courtesy Robinson Plastics Corp.*)

When ethylene molecules polymerize, theoretically they could do so to produce a straight line of carbon linkages, as shown in the top portion of Fig. 5-19. This would be a linear type of material. What happens when polymerization takes place is that the carbon atoms attach to each other in nonlinear fashion, branching out to form chains, as shown in the bottom section of Fig. 5-19. The amount of branching depends on the method of manufacture. High-pressure processes produce more branching than the low-pressure systems. To further understand the nature of the polymer molecule, it should be noted that the carbon atoms are free to rotate around their bonds and can bend at angles less than 180°. The effect of this swiveling and twisting is that the molecules and segments of the molecules become entangled with each other. The cohesive forces between the molecules consist of van der Waals type attraction. The other type of force in the polymer is in the carbon-carbon (C–C) linkages.

Properties of Linear and Branched Materials

With these simple concepts of molecule structure, it should be possible to predict the different properties of linear and branched materials:

Density. The linear structure of the polymer should permit the polymer molecules to come closer to each other, allowing more molecules to pack into a given volume (i.e., to be more dense). Obviously, the branching of molecules prevents this, so that they are less dense.

Yield. The higher the density is, the fewer the pieces of molded parts per pound of polyethylene that can be produced. This is not an unimportant consideration in material selection.

Permeability to Gas and Solvents. The branched materials physically create larger voids in the polymer, so that it is more permeable to gases and solvents than the linear or high-density material.

Tensile Strength. The linear materials, having molecules that are closer together, should have stronger intermolecular (van der Waals) forces than the nonlinear materials. Tensile strength is a measure of the strength of these molecular forces, and it is higher in linear materials than in branched. For example, a .96 resin has a typical tensile strength of 4300 psi and a .915 resin a strength of 1400 psi.

Percent Elongation to Failure. Because the linear molecules can entwine and kink more than the branched molecules, one would expect it to be more difficult to separate the linear molecules, so that applying a strong tensile force would rupture the molecule rather than cause it to flow and elongate. Branched material, having lower intermolecular strength because the molecules are farther apart and the van der Waals forces are weaker, would be expected to slide considerably more before rupturing. This is the case.

Stiffness. Linear polyethylene molecules, being closer together than the branched ones, have less room for segmental motion of the chains and bending of the backbone. Therefore, the linear materials are stiffer.

Heat Distortion. The heat deflection temperature under load is that temperature at which a specimen bar, under given conditions of loading to produce an outer fiber stress of 66 or 264 psi, will deflect 0.010. At a given temperature the molecular forces of attraction of a high-density material are greater than those of a low-density material because the segments are closer together. Therefore, it will take a given amount of heat energy to separate the linear molecules to such a distance that their attractive strength will be equal to that of the branched. The extra heat required means, in effect, that the linear material can absorb more heat for a given stiffness, so that its heat distortion temperature is higher. Typical heat distortion temperatures are: for a low-density polyethylene, 100°F; for a medium-density polyethene, 130°F; and for a high-density polyethylene, 160°F.

Softening Temperature. Similarly, the softening temperature of the high-density material is higher than that of the low-density material.

Hardness. Because linear molecules are closer together, the linear material should be harder. This is the case.

Resistance to Creep. Creep is the amount of flow (strain) caused by a given force (stress). As one would expect, the higher intermolecular force of the linear material make it more resistant to strain.

Flowability. Because of the stronger molecular attraction of the linear material, it should be more resistant to flow than the branched materials.

Compressibility. Because there is more open space in branched material, it should compress more easily than linear material.

Impact Strength. Because linear material has greater molecular attractive forces than the branched material, one normally would expect the linear material to have a higher impact strength, but this is not the case. Polyethylene crystallizes, and it is well known that impact forces travel along the interfaces of a crystalline structure, propagating breaks rapidly. Because the molecules in the linear material are closer together, they will crystallize more readily than those in the branched material. The higher crystallinity of the linear material is the reason for its lowered impact strength.

Thus, increasing the density of polyethylene increases its tensile strength, percent elongation to failure, stiffness, heat distortion temperature, softening temperature, and hardness; but increasing the density decreases the material's yield, permeability to gases and solvents, creep, flowability, compressibility, and impact strength.

Crystallinity

We were able to predict and understand the differentiating properties of linear and branched polyethylene simply by employing a conceptual catalog of the materials' physical states and by understanding some very simple principles. The same approach can be successfully used regarding crystallinity. Crystalline materials consist of a combination of amorphous sections and crystalline sections. When a crystalline polymer is melted; it becomes totally amorphous; the molecules are separated so that there is no longer an ordered structure. Large molecular segments vibrate and rotate to give a totally disordered structure. When the plastic cools, a point is reached where the forces of attraction are strong enough to prevent this free movement and lock part of the polymer into an ordered position. The segments now can rotate and oscillate only in a small fixed location. In an amorphous polymer the molecular configuration is the same throughout; the intermolecular distances are about the same and are controlled by the temperature. In a crystalline material the molecules are in an ordered structure, which takes up much less space than the amorphous state. Crystallization is indicated by a sharp decrease in volume; thus crystalline polymers show greater shrinkage than amorphous ones. Because the amount of crystallization varies with the material and molding conditions, it is much more difficult to hold tolerances in crystalline materials than in amorphous ones.

The molecular segments are much closer together in ordered crystalline lattices than in amorphous materials. To achieve a change in state, energy is required. For example, if ice and water are heated, the temperature remains the same, 32°F, until all the ice melts—the heat energy is being used to break up the crystalline structure. This also happens when polymer crystals break up into an amorphous condition. The fact that a crystalline structure has the molecules closer together with a corresponding increase in intermolecular forces, compared to the amorphous state, explains the properties of crystalline material.

As crystallinity results in a more compact structure, the density increases with crystallinity. The flexibility of a plastic depends on the ability of its segments to rotate; thus, crystalline structures, which inhibit rotation, are stiffer than amorphous structures. Because a crystalline structure has its molecules closer together, the tensile strength increases with crystallinity. However, the impact strength decreases with crystallinity, primarily because of the propagation of faults along the crystalline structure. Shrinkage will increase with crystallinity because crystals take up less space. The heat properties will be improved with crystallinity because the crystalline material must absorb a significant amount of heat energy before the structure is analogous to an amorphous material. Increasing the crystallinity brings the molecules closer together and increases the resistance to permeability of gases and vapors. Increasing crystallinity lowers the resistance to stress cracking, probably following the same mechanism as the lowering of impact strength. Crystalline materials warp more than amorphous ones, probably because the different densities within the same material set up internal stresses.

Flow Properties

We have been considering the static properties of polymers. An understanding of flow properties is essential in polymer processing, and they too are amenable to simple analysis.

Two investigators, Hagan and Poiseuille, independently derived the volumetric flow rate for a Newtonian liquid through a tube:

$$Q = \frac{\pi \times R^4 \times \Delta P}{8L \times \mu} \tag{2}$$

where:

Q = Volumetric flow rate
R = Radius of tube
L = Length of tube
ΔP = Pressure drop
μ = Viscosity

Inspection shows that the volumetric flow rate depends on three things. The first is the physical constants of the tube, $\pi R^4/8L$. A Newtonian liquid is extremely sensitive to the radius of the tube, but this effect is less important with plastic, as we shall shortly see, where viscosity varies with the shear rate (velocity). Second, the greater the pressure is, the higher the flow rate. Finally, the more viscous the material is, the lower the flow rate.

To maintain the same volume of material in the cavity shot after shot after shot, it is necessary to maintain the same pressure and viscosity conditions; this is the basis for automation. In plastics (viscoelastic materials) the viscosity is both temperature- and speed-dependent; so the speed of the plunger also must be controlled. This need for constant conditions is one of the main reasons why the use of a computer-controlled machine with feedback is extremely productive.

In rheology (the study of flow), the word stress is not used in the sense of a force acting on a body; instead it is a measure of the internal resistance of a body to an applied force. This resistance is the result of the attraction of molecular bonds and forces. When we say that we increase the shear stress to increase the shear rate, we really mean that we have to overcome increasing molecular resistance to achieve a faster flow rate. Shear stress is a measure of the resistance to flow of molecules sliding over each other; it is reported in pounds per square inch (psi). Force, which is measured in the same unit, is different from shear stress in two respects. Force acts perpendicular to the body, whereas the shear stress acts parallel to the containing surface. Pressure is force per unit area, while shear stress is resistance to force. Newton developed this concept of viscosity, using concentric cylinders. It can be explained more easily by imagining a stationary plate over which, at a distance X, there is a movable plate with an area A, moving at a velocity U, pushed by a force F. Neglecting the slip of the molecules on the stationary plate, we assume the velocity of the liquid at the stationary plate to be zero and the maximum velocity U to occur at the moving plate. The rate of change of velocity is the slope of the line connecting the velocity vectors, or du/dx. The force is therefore proportional to the area and velocity:

$$F = f \times A\,(du/dx) \qquad (3)$$

The proportionality constant (f) is called the viscosity and designated μ (mu) for Newtonian liquids or η (eta) for non-Newtonian liquids. Shear force or stress is represented by the Greek letter τ (tau) and shear rate by γ (gamma). Rearranging the terms, we have the following classical definition of viscosity:

$$\text{Viscosity} = \frac{F/A\ \text{(shear stress)}}{du/dx\ \text{(shear rate)}} \quad \text{or}$$

$$\mu = \frac{\tau}{\gamma} \qquad (4)$$

In a Newtonian liquid the shear force is directly proportional to the shear rate; doubling the unit force doubles the unit rate. In thermoplastic materials this is not the case; in the processing range a unit increase in the shear force varies and may even quadruple the shear rate. The viscosity is dependent on the shear rate and drops exponentially with increasing shear rate.

This is shown in Fig. 5-20, which has arithmetic plots of the viscosity and shear rate and of the shear stress and shear rate. It can be noticed that in the latter graph, there is a Newtonian portion at the beginning and at the end of the curve. It is more practical to plot such data on log-log plots, which will characterize the flow properties of a material. The information is obtained by using rheometers. The most common one extrudes the polymer through a capillary tube while measuring the force and speed of the plunger; viscosity then is a simple calculation. Such an instrument is called a capillary rheometer. In looking at the viscosity/shear rate curves of plastics, it is obvious that to maintain the same viscosity one must maintain the same speed as well as the same temperature.

These flow properties can be easily understood with a conceptual illustration of how the molecules move. Figure 5-21 shows a representation of a number of different polymer molecules of the same kind. They are in a random pattern, their vibrations or movement being determined by their heat energy. This Brownian movement, named after its postulator, tends to locate the polymer segments in random positions, this being the lowest energy level. The plastic molecule is too large to move as a unit. Brownian motion occurs in segmental units of the polymer.

If a force is applied in one direction to a polymer above its glass transition point, it will begin to move in a direction away from the force. As it starts to move, the carbon–carbon chains of the molecule will tend to orient themselves in the direction of flow (Fig. 5-22). If the force is applied very slowly, so that the Brownian motion overcomes the orientation caused by flow, the mass of the polymer will move with a rate proportional to the applied stress. This is Newtonian flow and is the corresponding straight section at the beginning of the left curve in Fig. 5-22.

As the flow rate increases, two things happen. The chains move so rapidly that there is

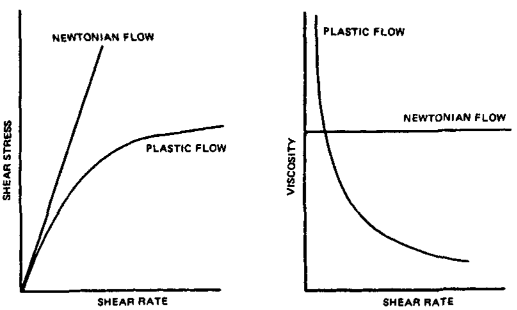

Fig. 5-20. Arithmetic plots of shear stress vs. shear rate and viscosity vs. shear rate for Newtonian and plastics materials. (*Courtesy Robinson Plastics Corp.*)

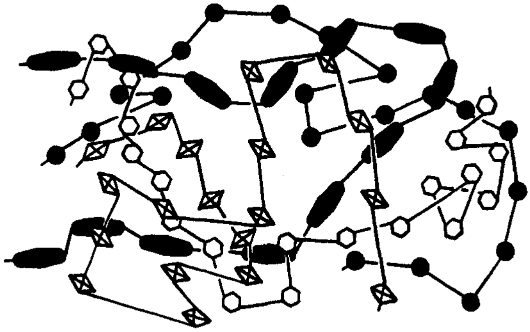

Fig. 5-21. Schematic representation of segments of polymer chains in their random position. This is a result of local vibration, thermally controlled, called Brownian movement. (*Courtesy Robinson Plastics Corp.*)

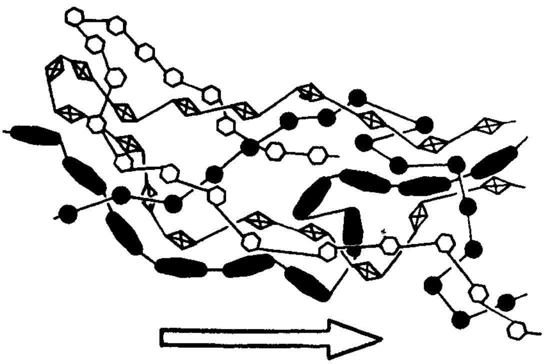

Fig. 5-22. Schematic representation showing the effect of a stress on the random structure of Fig. 5-21. Molecular segments tend to orient in the direction of flow. (*Courtesy Robinson Plastics Corp.*)

not sufficient time for the Brownian motion to have an appreciable effect; also, the molecules that are being oriented in one direction separate because their side chains untangle. This separation reduces the intermolecular forces exponentially (because they are van der Waals type attractions), permitting them to slide over each other much more easily. In other words, the increased shear rate (speed) is no longer proportional to the shear stress (force). A unit increase in shear stress will give a much larger increase in shear rate than would happen with a Newtonian liquid, where a unit increase in stress would give a unit increase in shear. The unit force, then, does two things: it accelerates the mass and separates the molecular segments. The proportion of each changes exponentially—this is the central portion of the shear stress/shear rate curve in Fig. 5-20, and is a characteristic of plastic polymer flow, where shear rate is no longer linearly proportional to shear stress. It is this central portion of the curve that is met in injection molding. As the flow rate increases, it reaches a final stage where all the polymer molecules have become oriented to their maximum level; there is no further untangling. Therefore, any increase in the shearing stress in this range will give a proportional increase in the shearing rate, and the material acts as a Newtonian fluid, which is indicated in the top portion of the curve in Fig. 5-20.

The basic difference between a Newtonian and a non-Newtonian fluid is in the length of the molecule. Newtonian liquids such as water, toluol, and glycerine all have very short molecular lengths. As is evident from the previous discussion, the rheological or flow properties of a polymer depend in some measure on its molecular structure. It is also evident that the flow properties are highly temperature-dependent, as the temperature is an indication of molecular motion and intermolecular distances. The relationship is exponential, and a plot of the log of the viscosity versus the temperature at a given shear rate is a straight line over narrow temperature ranges, describing viscous flow fairly accurately (Fig. 5-23). This type of information also has practical value. For example, if cavities were not filling out during the molding of cellulose acetate, increasing the temperature would not have a great effect on the viscosity or hence the filling. It would be necessary either to increase the pressure or to open the gate. On the contrary, acrylic material is very temperature-sensitive, and raising the temperature even a small amount will result in a considerable decrease in viscosity. This also means that temperature control of the material is more important for a viscosity/temperature-sensitive material such as acrylic than for cellulose acetate or polystyrene.

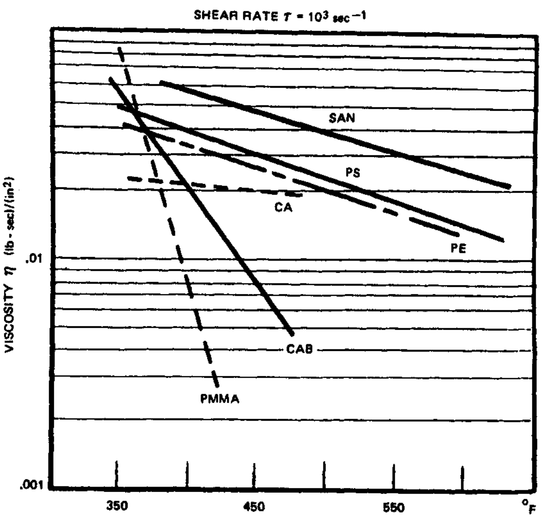

Fig. 5-23. Effect of temperature upon polymer viscosity. SAN—styrene-acrylonitrile; PS—polystyrene; PE—polyethylene; CA—cellulose acetate; CAB—cellulose acetate butyrate; PMMA—polymethyl-methacrylate (acrylic). (*Courtesy Robinson Plastics Corp.*)

From this discussion, the controlling parameters for consistent injection molding become evident. Equation (2) states that the viscosity and the pressure control the output in a given geometric system. We also have seen that the viscosity in thermoplastic materials depends on two conditions—temperature and rate of flow. The temperature of the material is controlled by the conditions of the heating cylinder, nozzle, and mold. Therefore, in order to have consistent molding, the temperature, the pressure, and the rate of flow must be controlled. It is not possible to have successful automatic molding or consistent molding without controlling the flow rate. When the machine is instrumented to make measurements, compare the measurements to a preset standard, and change the conditions during the molding to meet the standard, it is possible to have consistent automatic molding. That is what a computer-controlled machine with feedback provides.

Orientation

Orientation effects are very important. The term orientation means the alignment of the molecule and molecular segments in the direction of flow. The strength in that direction is that of the carbon–carbon linkage, whose disassociation energy of 83 kcal/mole is much greater than the 2 to 5 kcal/mole of the van der Waals type forces holding the polymer together perpendicular to the line of flow. Thus plastic that is oriented will be stronger in the direction of flow than perpendicular to it. The ratio will not be 83/5, as no material orients completely; but the greater the orientation is, the closer the material gets to this ratio. The second major implication of this concept is that the oriented plastic will shrink more in the direction of flow than it will perpendicular to it. Shrinkage is a result of two factors—a normal decrease in volume due to temperature change and relaxation of the stretching caused by carbon–carbon linkages. As there are more carbon–carbon linkages in the direction of the oriented flow than perpendicular to it, this phenomenon occurs.

Plastics do not all exhibit orientation to the same degree. Consider molding a rectangular plaque of clear polystyrene 2 inches wide and 6 inches long, 0.090 inch thick and gated on the 2-inch end. If the molding were held between crossed Polaroid filters, a colored pattern would be seen. This property is called birefringence and is used to measure orientation. The material front that flows past the gate is randomized, and freezes as such on the walls of the cavity. This section is totally unoriented. However, one end of the molecule is anchored to the wall, and the flow of other material past it pulls the other end of the molecule in its direction, giving a maximum amount of orientation. As the part cools, the orientation is frozen at the walls. The center of the section remains warm for the longest time, allowing Brownian motion to disorient many of its molecules. Therefore, the center section is the least oriented. This is shown by birefringence patterns.

This behavior can be easily demonstrated by milling off one-third (0.030 inch) of the thickness. In effect, one section is highly oriented, and the center section, which has been exposed by the milling, is less oriented. If the milled piece is heated, the stretched carbon–carbon linkages should return to their normal position. Because the oriented section has the carbon–carbon linkages lined up more in one direction than they are in the less oriented sections, that part should shrink more. In effect, then, it would be acting as a bimetallic unit, one side shrinking more than the other, and the piece should bend over. This is what happens.

As the amount of orientation depends on the flow and on the forces that aid or prevent the motion of the molecular segments, it is easy to see what conditions can affect orientation. Anything that increases the mobility of the segments decreases orientation. Therefore, higher material temperatures, higher mold temperatures, and slower cooling would decrease orientation. Pressure on the material would limit mobility. Thus, low injection pressures and a short ram forward time decrease orientation. The use of a thicker part would decrease orientation because a longer time is needed for the center portion to cool with increasing thickness. We shall now examine some practical situations involving orientation.

Practical Applications. Consider molding a lid or cover 6 inches in diameter in a polyolefin

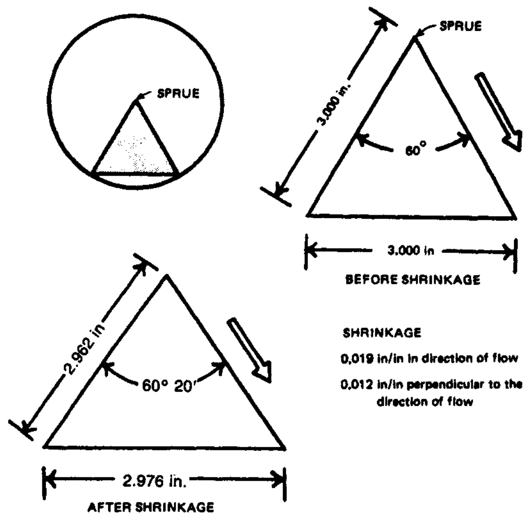

Fig. 5-24. Warping of center-gated polypropylene cover caused by the different shrinkages perpendicular and parallel to the direction of flow. (*Courtesy Robinson Plastics Corp.*)

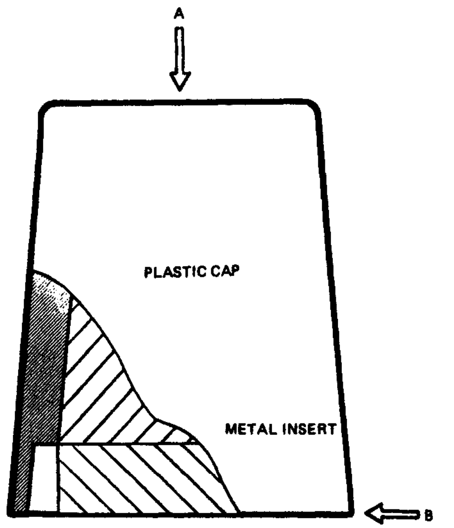

Fig. 5-25. Effect of orientation on a plastic cap molded with a metal insert. Gating at point A will give a cap strength along the walls. Gating at point B will give a cap strength in the hoop direction. (*Courtesy Robinson Plastics Corp.*)

(Fig. 5-24). The shrinkage in the direction of flow is 0.019 in./in., while the shrinkage perpendicular to flow is 0.012 in./in. The difference is caused by the different numbers of carbon–carbon linkages in the direction of and perpendicular to the flow.

Consider a 60° segment of the cover immediately upon molding. Each side will be 3.000 inches long. Upon cooling, the two sides in the direction of flow will have shrunk to 2.962 inches, and the segments perpendicular to flow will now be 2.976 inches. A simple trigonometric calculation shows the central angle is now 60°28′. The full 360° circle is now 362°48′. Obviously the extra material has to go somewhere. If it cannot lie in a flat plane, it will warp. If the thickness of the material and the ribbing provided enough strength, the part might not visibly warp, but it would be highly stressed. The way to minimize such warp or stress is to mold under those conditions that give the least orientation. Multiple gating also is effective, as is redesigning the cover.

Gate location affects the amount and the direction of orientation. Figure 5-25 shows a cap with a metal insert that was used as a protective guard over the fuse mechanism of a shell. The dimensions were controlled by a brass cap, which it replaced. The plastic was molded over a threaded metal insert originally gated at point *A*. After some time in the field, cracking developed around the metal insert. The main strength was in the direction of flow rather than in the hoop or circumferential direction. Because the thickness of the material could not be increased, the effects of orientation were used by changing the mold and regating at point *B*. The material flowed in the hoop direction and gave the maximum strength there. This slight difference was enough to prevent failure in the field.

Consider gating a deep polyolefin box (Fig. 5-26), using the thinnest possible wall section. Gating the box in the center (A) would give severe radial distortion for the same reasons illustrated in Fig. 5-24. It would be further complicated by the difference in flow length from the gate to point *X* and from the gate to point *Y*. The wall would have to be heavy enough to overcome this stress. Gating it diagonally with two gates (B) would give a radial twist, for the same reasons. It would be much less distorted than the center gate design and would require thinner walls for a stable part. It also would require a three-plate mold for the gating.

It would seem logical to gate on the edge of the *Y* portion, as shown in (C). This would be

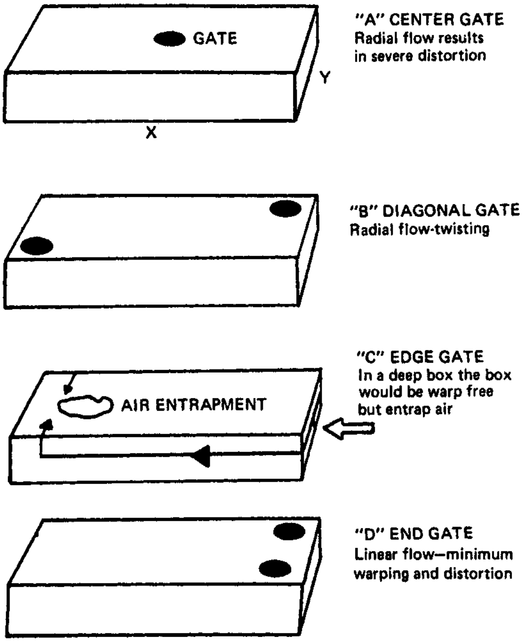

Fig. 5-26. Effect of gate location on a deep molded polyethylene box. (*Courtesy Robinson Plastics Corp.*)

true for a relatively shallow box. With a deep box, however, the material flows around the sides faster than over the top, and air is entrapped somewhere on the top, which virtually cannot be eliminated by venting. This still is not the best method of gating. The preferred method is shown in (D), where there are two gates on the top end of the box. This arrangement gives maximum linear flow without air entrapment and produces a part with the least amount of warp. In most instances, a satisfactory part could be molded with one gate located on the top end. Another possibility is to place two submarine gates near the top. For large parts, it is sometimes necessary to multiple-gate to ensure relatively even orientation patterns and flow lengths. The main problems that can be encountered are air entrapment and weld lines.

Warpage is the result of unequal stress in the molded part when the stress is strong enough to strain or distort the piece. Warping can be caused by the nature of the material, poor part design, poor mold design, and incorrect molding conditions. (See Chapter 11 for additional data.)

Shrinkage

When a plastic material is heated, it expands. Upon cooling to its original temperature, it will contract to the original volume, neglecting the effects of crystallinity, but this is not the only parameter. During injection molding an additional factor, pressure, is introduced. The material basically follows the equation of state: pressure times volume equals the gas constant times the absolute temperature, $PV = RT$. Mold shrinkage should not be confused with tolerance; tolerance is the variation in mold shrinkage rather than the shrinkage itself.

During injection molding, the following things happen: The hot material is injected into the cold cavity, initially under low pressure. Cooling starts immediately, as the parts in contact with the wall solidify. Because the specific volume (the volume of a unit weight of plastic) decreases with the temperature, the solid will occupy less room than the molten polymer. The material fills the cavity, and the pressure builds up rapidly. The pressure does two things: it adds more material to the cavity to make up for the decrease in volume of the material that is already solidified, and it adds more material to compensate for the decrease in volume that will occur when the rest of the material solidifies. If not enough material is put in, there will be excess shrinkage. If too much material is put in, there will be a highly stressed area at the gate. This process of material addition is called packing. The correct amount of material is found by trial and error. The effect of the machine pressure ceases when the injection pressure is stopped or the gate seals. A second, lower injection pressure is used until the machine is opened.

Overstressing of the gate section of an opaque part is impossible to detect during molding, yet highly stressed parts are much more likely to fail than less stressed parts. Thus it is one of the drawbacks of molding that quality cannot be immediately determined. This constraint is also a good reason why economic conditions should not force improper molding.

To decrease shrinkage, the molder should reduce wall thickness, increase injection pressure and injection forward time, increase injection speed, increase the overall cycle, raise the material temperature slightly, lower the mold temperature, decrease the molecular weight distribution, and usually increase the gate size.

Tolerance in molding is beyond the scope of this discussion. Suggested tolerances may be found on pages 821 through 844 or in the SPI Publication, "Standards and Practices of Plastics Molders." Controlling molding tolerance requires a good mold, a good machine, good management, and proper calculation of the price of the item. It is hardly necessary to point out that unneeded tolerances are costly. Good engineering specifies the minimum tolerances required for any application.

CORRECTING MOLDING FAULTS

Injection molding faults may appear when the molder is starting a new mold, after mold changes or repairs, while changing to a new material, or during the regular operation of a mold. The causes of these faults can be as follows: the machine, the mold, operating conditions (time, temperature, pressure, injection speed), the material, parts design, and management, the last of these being the most important.

In order to correct a fault, it first must be found. The purpose of quality control is to find the fault during molding, rather than to discover the error some hours, shifts, or days later when it has become history rather than a force influencing productivity and profit. Quality control should be a continuing ongoing process, starting with the ordering of the raw materials and molds and ending with the shipping of the finished part.

It is obvious that conditions of the machines, molds, auxiliary equipment, and work area contribute to preventing and correcting molding faults.

Poor communications and record keeping are other obvious sources of molding problems.

Before an attempt can be made to correct faults, the machine must be operating consistently, and the temperature control and the mold operation must be consistent.

A single-cavity mold should fill evenly, as should a multiple-cavity mold. If one cavity fills first, the gate may seal off so that it will not be fully packed. The material destined for this cavity will be forced into other cavities, overpacking them. Shrinkages, sticking, and other problems result.

The machine should have a large enough clamping and plasticizing capacity. The plasticizing system should be appropriate for the job. The ejection system should be effective.

Most time functions are controlled by timers. If the mold is not run automatically, the major variable is the operator. The amount of time required to open the gate, remove the part, inspect the mold, and close the gate is variable. This factor often is a major cause of molding problems.

The temperature normally is controlled automatically. Poor design and malfunction of the temperature control system are not uncommon. In some locations, the voltage is not constant because of inadequacies in electrical power systems. Such inconsistency can be disastrous in the molding operation. The best way to recognize it is to use a recording voltmeter. Mold temperature should be controlled automatically.

The pressure also is controlled automatically. Sometimes, overheating will change the viscosity of the oil in the machine, thereby changing the operating conditions. This problem is difficult to detect, but an overheated machine is always suspect. A malfunctioning or worn screw tip will affect the injection pressure on the material.

A major variable in the molding process is the material, but this problem is inherent in the manufacturing process. Normally, there is little the molder can do other than recognize it. Changing materials will usually pinpoint this problem area.

Specific molding problems can be arbitrarily divided into several categories:

- *Short shots* are usually caused by the material solidifying before it completely fills the cavity. The problem usually is due to insufficient effective pressure on the material in the cavity. It can also be caused by a lack of material feeding to the machine. It may require increasing the temperature and pressure on the material, increasing the nozzle-screw-runner-gate system, improving the mold design, and redesigning the part.

• *Parts flashing* usually is caused by a mold deficiency. Other causes are an injection force that is greater than the clamping force, overheated material, insufficient venting, excess feed, and foreign matter left on the mold.

• *Sink marks* usually are caused by insufficient pressure on the parts, insufficient material packed into the cavity, and piece part design. They occur when there are heavy sections, particularly adjacent to thinner ones. These defects are predictable, and the end user should be cautioned about them before the mold is built. At times the solution lies in altering the finished part to make the sink mark acceptable. This might include putting a design over the sink mark or hiding it from view. (See Chapter 11.)

• *Voids* are caused by insufficient plastic in the cavity. The external walls are frozen solid, and the shrinkage occurs internally, creating a vacuum. Inadequate drying of hygroscopic materials and residual monomer and other chemicals in the original powder may cause the trouble. When voids appear immediately upon opening of the mold, they probably indicate a material problem. When the voids form after cooling, usually there is a mold or molding problem.

• *Poor welds (flow marks)* are caused by insufficient temperature and pressure at the weld location. Venting at the weld if possible and adding runoffs from the weld section may help. Increasing the thickness of the part at the weld is also useful. The material may be lubricated, or the mold locally heated at the weld mark. Poor welds have the dismaying proclivity of showing up as broken parts in the field. Flow marks are the result of welding a cooler material around a projection such as a pin. Their visibility depends on the material, color, and surface. They rarely present mechanical problems. Flow marks are inherent in the design of some parts and cannot be eliminated. This possibility should be explored thoroughly before the part design is finalized.

• *Brittleness* is caused by degradation of the material during molding or contamination, and it may be accentuated by a part that is designed at the low limits of its mechanical strength. Material *discoloration* results from burning and degradation; it is caused by excessive temperatures, and by material hanging up somewhere in the system (usually in the cylinder) and flowing over sharp projections such as a nick in the nozzle. The other major cause for discoloration is contamination, which can come from the material itself, poor housekeeping, poor handling, and colorants floating in the air.

• *Splays, mica, flow marks, and surface disturbances at the gate* are probably the most difficult molding faults to overcome. If molding conditions do not help, it usually is necessary to change the gating system and the mold temperature control. Sometimes localized heating at the gate will solve the problem. Splay marks or blushing at the gate usually is caused by melt fracture as the material enters the mold. Usually it is corrected by changing the gate design and by localized gate heating and reduced flow rates.

• *Warpage and excessive shrinkage* usually are caused by the design of the part, the gate location, and the molding conditions. Orientation and high stress levels are also factors.

• *Dimensional variations* are caused by inconsistent machine controls, incorrect molding conditions, poor part design, and variations in materials. Once the part has been molded and the machine conditions are set, dimensional variations should maintain themselves within a small given limit. The problem usually lies in detecting the dimensional variances during the molding operation.

• *Parts sticking in the mold* results primarily from mold defects, molding defects, insufficient knockout, packing of material in the mold, and incorrect mold design. If parts stick in the mold, it is impossible to mold correctly. Difficult ejection problems usually are the result of insufficient consideration of ejection problems during the design of the part and the mold.

• *Sprue sticking* is caused by an improperly fitted sprue-nozzle interface, pitted surfaces, inadequate pull-back, and packing. Occasionally the sprue diameter will be so large that it will not solidify enough for ejection at the same time as the molded part.

- *Nozzle drooling* is caused by overheated material. For a material with a sharp viscosity change at the molding temperature, such as nylon, the use of a reverse-taper nozzle or a positive-seal type of nozzle is recommended.
- *Excessive cycles* usually are caused by poor management. Proper records are not kept, standards are not established, and constant monitoring of output is not done. Other causes of excessive cycles are insufficient plasticizing capacity of the machine, inadequate cooling channels in the mold, insufficient cooling fluid, and erratic cycles.

PROCESS CONTROL

Process controls for injection molding machines can range from unsophisticated to extremely sophisticated devices. As this section will review, they can (1) have closed loop control of temperature and/or pressure; (2) maintain preset parameters for the screw ram speed, ram position, and/or hydraulic position; (3) monitor and/or correct the machine operation; (4) constantly fine-tune the machine, and (5) provide consistency and repeatability in the machine operation.

On-Machine Monitoring

There are different means available for monitoring injection molding machines. First, for clarity, let us separate *monitoring* from *controlling*. Monitoring means watching/observing—in our case, the performance of a molding machine. Traditionally, this is done in a variety of ways: by time and temperature indicators, screw speed tachometers, hour-meters, mechanical cycle counters, and the like. Controlling, on the other hand, means commanding the process variables to achieve the desired levels. Often, a control function is combined with monitoring in a single instrument. These devices may be called "indicating controllers."

This section will focus on monitoring as opposed to controlling: specifically, monitoring parameters such as cycle time, down time, rate, and totals, as opposed to temperature, pressure, and other process parameters.

Sophisticated "electronic stopwatches," or monitors, are available that take advantage of the fact that molding machines have numerous signals that are specifically indicative of the cycle. These signals can be utilized to trigger the electronic watch by direct electrical connection to molding machine contacts. With these direct connections, accurate cycle times are assured. For example, measuring from the injection forward relay (a frequent choice) can provide an accurate, continuous display of overall machine cycle times.

There are two proven benefits from monitoring the cycle time on a continuous basis:

1. Production can be maintained at the established optimum cycle time. Display resolution to .01 second quickly shows changes. For example, if a mechanical or hydraulic problem is developing, it can be detected before it progresses to a breakdown. If unauthorized people are meddling with machine settings, they can be observed. When changes are easily seen, unauthorized people are deterred from making them.
2. Product quality can be kept high because cycle variations due to the previously suggested potential causes are minimized. Further, material changes that contribute a small cycle effect but have a significant product effect can be picked up with continuous, accurate monitoring.

Implicit in maximizing these benefits is having the cycle time displayed on the machine. Many users post the standard cycle time in large numerals next to the digital display. This enables engineers, operators, mechanics, supervisors, foremen—anyone walking by the machine—to see and compare the current cycle with the desired one and to respond appropriately to deviation.

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In addition to monitoring overall cycle time, elapsed time displays can yield precise information about the individual elements that comprise the overall cycle. For instance, with a single-signal input cycle time display, the time a specific relay, switch, valve, etc., is energized can be measured and displayed. Other digital electronic stopwatches are available that accept input signals from two independent sources and can measure a variety of times between them.

An electronic stopwatch that accepts two input signals adds analytical capability beyond that available with one-signal input. For example, an engineer wants to set the optimum time for every element of a cycle. First, he or she must accurately determine where they are now. Then by "tweaking" the times down—while monitoring for verification—and checking product quality, the engineer can "set" each segment as fast as possible while maintaining good quality. If all active segments are optimized, and there is no "dead time" between segments, the cycle will, by definition, be as fast as it can be and still produce the desired product.

Note that "dead time" between active portions of the cycle must be eliminated. A dual-input digital display enables this to be done by switching between various signal sources in the machine. Once eliminated, dead time must also be kept out of the cycle in order to keep production up. By continuous monitoring of the most likely areas for dead time, it can be minimized. For instance, improper material additives have affected screw retraction adversely, to the extent of extending cycles because of screw slippage. With continuous monitoring of the retraction time, as measured between two limit switches or their equivalent, this problem could be detected quickly so the material could be changed as soon as it occurred.

The most sophisticated level of monitoring takes advantage of the evolution that has occurred in electronics. With the microprocessor, it is possible to add economical memory and multifunction capability to a machine display.

"Multifunction" means that in addition to the important "cycle-time measuring" component, additional data can be acquired, stored, and displayed. Unless it is separately available on the machine, all monitors of this type for injection molders should include a cycle measurement function. This may be either cycle time directly (in seconds or minutes) or production rate (in shots per hour, cycles per minute, etc.). The availability of a production rate display is important because in many companies the "shop floor language" is shots per hour, and a digital display of these numbers directly is more meaningful than a time readout; for example, the change in rate from 120 to 119 shots per hour compared to the cycle time changing from 30.0 seconds to 30.25 seconds. The successful use of monitors hinges on operating personnel understanding them as an aid to production. Therefore, the display should be scaled and read out in the user's particular terminology.

Additional data that may be compiled with these powerful monitors include totals, run time, down time, etc. "Down time" may be defined in several ways. It can be as simple as a machine set on the manual switch setting (for setup) instead of automatic or semiautomatic; or, as complicated as the monitor "learning" a good cycle and comparing every subsequent cycle to it, then accumulating down time for any cycle that is not at least 90% of the "good" cycle. The "learning" of the good cycle may be via a user-set switch identifying a desired cycle, or by the monitor calculating an average cycle. The ability to specifically accumulate and record down time on the machine changes a notoriously inaccurate data source—down time is usually guessed—to a precise record that is used to improve performance of machines and people.

Monitors may also be obtained with outputs to drive typical machine audio/visual alarms. These outputs can be energized when down time occurs, when a slow cycle occurs, or when a rate is below a standard the user inputs. (The latter type is only available with the most sophisticated type of monitor—one that communicates bidirectionally to a keyboard/computer.)

These more sophisticated, powerful monitors can provide multiple functions displayed on the machine; in addition, they can communicate directly with a centrally located computer. The central computer eliminates the manual collection of production data; it summarizes data, prints reports, calculates efficiencies and utilization, etc., automatically and immediately, not hours or days later.

Temperature Control of Barrel and Melt

The viscosity of the melt and the speed and pressure of injection determine whether an acceptable molded part is produced. Viscosity is a function of the temperature of plastics, and temperature is a result of the forces of screw rpm, back pressure, and externally applied heat. Injection machine control specialists are generally agreed that one-third of the melt temperature is derived from external heat. Closed loop temperature control thus deserves in-depth attention.

Many excellent instruments are available today as a result of reliable and cost-effective solid state and digital technologies. The temperature control result is, of course, no better than the quality of other components and installation practices employed on the machine. Too many times we find the advantages of a sophisticated temperature control (TC) instrument completely negated by poor installation techniques. Before deciding prematurely that the instrument is at fault, you should make the following checks:

1. Is the thermowell too big for the TC protection tube? Air is an excellent insulator.
2. Is there contamination inside the thermowell? Rust, scale, and residue prevent proper contact of the protection tube with the thermowell.
3. Is the TC junction partially open?
4. Are there oxidation and corrosion inside the protection tube?
5. Is the proper extension wire being used? Copper wire allows another thermocouple junction.
6. Is extension wire polarity observed? A single reversal will give a downscale reading; a double reversal will result in an erratic input to the controller.
7. Are wire terminations properly isolated? False cold junctions are a common problem.
8. Is the cold junction compensation at the extension wire termination on the controller working properly? A poorly positioned or poorly connected compensation component will allow the input to vary.
9. In the panel, are the thermocouple leads isolated from the ac wiring as required? Are the TC wiring and the ac wiring run in separate conduits from the control cabinet to the machine as required?
10. Is the control cabinet thermal environment within the specification of the controller? Excessive cabinet temperatures can cause a controller to drift.
11. Examine the power contactor. If it is a mechanical contactor, deterioration of the contacts can result in reduced power delivered to the heaters.
12. Are the heaters sized correctly? Modern temperature controllers can compensate for limited mis-sizing, but cannot substitute for proper design.
13. Heater bands must be secured tightly to the barrel; again, air is an excellent insulator.
14. Check the voltage being supplied to the heaters. High voltage leads to premature heater failure.
15. Inspect wiring terminations at the heater band; connections must be secure.

If the integrity of the heating system has been verified, your attention can now be turned to the advantages of modern temperature control instrumentation. To demonstrate the improvements made available in recent years, a comparison of the three basic instrument designs is helpful. Millivoltmeter designs can hold setpoint within 20 to 30 degrees; solid state designs can hold within 10 to 20 degrees; microprocessor-based designs typically hold setpoint within 2 to 5 degrees.

Microprocessor-based designs provide several distinct advantages. Already mentioned is the inherent ability to control the temperature at setpoint. Microprocessors do not drift; they either work perfectly, or they experience a catastrophic failure. They are absolutely repeatable, allowing the operator to duplicate a log of setpoint temperatures perfectly the next time that particular job is run. Microprocessors allow a natural avenue to provide digital displays of process information. Values are not subject to inaccurate interpolations and misreadings.

Microprocessors allow the implementation of PID (proportional, integral, derivative) control at little or no cost. PID has been shown to reduce process variations by as much as three or four degrees. Discussions of PID advantages are available from all major temperature control suppliers. (See Fig. 5-27, which shows a PID temperature controller.)

Microprocessor technology is relatively trouble-free—about six times more reliable than analog solid state designs, and about twelve times more reliable than millivoltmeter designs.

Another significant cost reduction effort, being implemented recently with excellent results, focuses on the controller output and power handling. Although an analog controller output accepted by a phase angle or zero angle SCR power controller is ideal in terms of power factor and heater life, it is a relatively costly arrangement. A more acceptable method, in line with cost restraints and providing very nearly the same advantages, is to use a controller with a solid state time-proportioned pilot duty output along with inexpensive mercury contactors or solid state relays. The controller output cycle time can then be reduced to ten seconds or less, thus approaching the same constant temperature and heater life advantages available with the more costly design.

Fig. 5-27. PID temperature controller. *(Courtesy Barber Colman Co., Loves Park, IL)*

Many more advantages are available when the microprocessor is used as the core component for temperature control. Automatic tuning, introduced recently, has already established an enviable track record. Its benefits fall into three major areas:

1. The unit will identify varying thermal behavior and adjust its PID values accordingly. Variables affecting viscosity include screw rpm, back pressure, variations in heater supply voltage, resin melt index, resin contamination, room ambient temperature, percent colorant, screw wear, barrel lining wear, heater and thermocouple degradation, percent regrind, hygroscopic characteristics, and feed zone instabilities.
2. Savings in management and maintenance activity will result from auto-tuned temperature control. Documentation of PID values for various jobs and machines can be eliminated. Individual operator preference for PID values that vary from the norm is precluded. Maintenance personnel are not required to dedicate a particular unit to a specific zone; instruments can be interchanged at will, and spares can be installed with no attention other than selection of the appropriate setpoint. A payback through reduction of overhead costs alone can generally be expected in six to eight months.
3. Energy saving is another major benefit. One customer study showed a 50% reduction in power consumed by the heaters, solely because the automatic tuning feature eliminates the cycling around setpoint normally associated with ineffectively tuned instruments.

Microprocessors also provide a means to communicate digital data to information collection stations. Although the economic feasibility of including the function with an individual temperature control instrument has not been demonstrated in the plastics industry, the feature is beginning to enjoy significant exposure on multiple zone injection machine controllers because of the low cost of adding another digital card to an existing rack. More commonly found on discrete controllers is an analogy communications output that provides a signal to remote recorders.

The ultimate implementation of the microprocessor has been its design in systems installations. Available systems include multizone temperature control and multipoint, multiloop control of sequence. Systems that depend on a single central processing unit (CPU) are available from many suppliers to control temperature, sequence, position, velocity, or pressure. Even more cost-effective are the total machine controllers, which control all machine parameters from a single keyboard. (See Fig. 5-28.) As compared to individual instruments, these systems typically reduce the per-zone cost of control, and provide unlimited future control flexibility as needs change. As production pro-

Fig. 5-28. Injection molding machine control panel. *(Courtesy Cincinnati Milacron, Batavia, OH)*

fessionals discover the need to manage the process at the least possible cost, machine control systems that can communicate with a central management computer are of increasing importance. Central control systems are available that can simultaneously receive information from the injection machine and transmit required parameter changes or complete job setups at the same time. Many injection machines can thus be interfaced with a single control location. If central on-line control is not justified, but one-way machine reporting is required, a choice of several management information systems is available.

PID Injection Pressure Control

A trend to faster-acting, more precise, and more energy-efficient hydraulic systems and components is one response by injection molders and machine builders to a business climate that demands higher productivity and more consistent product quality. Examples of this trend are found in the growing popularity of accumulators, which can deliver a large amount of oil at high pressure, making possible very high injection speeds without the need for an extremely large, energy-consuming pump; of variable-volume pumps, either single or multiple, which provide just the amount of flow that is needed at any point in the cycle, for energy-efficient molding; of servovalves, whose fast response is necessary to control the high injection speeds that the more efficient hydraulic systems can provide; and of multistep injection speed and pressure profiling, providing more sensitive control of the process so as to improve part quality.

One thing that all the above have in common is the tendency for changes in hydraulic pressure during a machine cycle to occur faster than ever before, and this in turn necessitates application of pressure controls that are responsive enough to keep pace. Fortunately, meeting this need does not require inventing new control technology, but rather, more thorough application of what we already have.

Hydraulic pressure-control logic is, in fact, the same as that used for temperature control; its more sophisticated form uses three modes of control, known as PID, for proportional, integral, and derivative (also called gain, reset, and rate, respectively). Each of these mutually interrelated modes of control has an adjustable "tuning constant" that permits the operator to adjust the sensitivity of the pressure controls to the dynamics of the particular machine's hydraulic system.

Some molders may not realize that these tuning adjustments are variables that are just as important to good process control as the set-points for the actual pressure values that the controller is asked to achieve.

Most commercial process-control systems for injection molding to date have not provided full PID pressure control—usually only proportional, or perhaps proportional-plus-reset (integral), control. Furthermore, these systems have commonly offered at most a gain adjustment, or else no tuning adjustment at all. Consequently, the concept of PID pressure control is probably unfamiliar to most molders, as is the role of tuning in obtaining the maximum benefit from three-mode controls.

Yet it is our feeling that, in order to get the kind of cycle-to-cycle repeatability that today's market demands and that today's microprocessor-based control systems are designed to provide, molders should understand the value of PID control logic and must know how to keep such controls properly tuned. Fortunately, current microprocessor know-how can make full PID control available at little or no extra cost, and makes tuning an easy task for the average setup person or technician.

PID Tuning: What It Means. The following is a brief explanation of the three control modes and their tuning constants. It is important to remember that the three terms are not independent, but mutually interactive, and that both the order and the magnitude of adjustments made to the tuning constants can affect the settings of the others.

• *Proportional control (gain):* With this type of control, the magnitude of the control output is proportional to the difference between the actual pressure and the desired pressure—

in other words, the magnitude of the error signal. The "proportional band" is the range of error above and below setpoint, within which the control output is proportioned between zero and 100%.

Usually the proportional band is expressed in terms of its inverse, the gain. If the proportional band is set too wide (low gain), the controller will probably not be able to achieve the setpoint within the time frame of that segment of the cycle. On the other hand, if the proportional band is too narrow (high gain), it will cause violent oscillation of pressure around the setpoint, leading to intense machine vibration, shaking of hoses, and rapid movement of valve spools back and forth, all of which are hard on a machine's hydraulic system and can shorten the life of its components. In either case, inconsistent cycles will result.

The proportional band, or gain, setting is the most fundamental part of the tuning process, which strongly influences everything else. For that reason, it is usually performed first, although subsequent adjustment of the other tuning constants may require some readjustment of the gain.

• *Integral (or reset) control:* Unfortunately, it is a characteristic of purely proportional control that, in response to changing load conditions, it tends not to stabilize the process at setpoint, but rather, some distance away from it. Integral or reset control responds to this steady-state error, or "proportional droop," by shifting the proportional band up or down the pressure scale (without changing the band's width) so as to stabilize the process at setpoint. The amount of reset action to use, expressed in repeats per minute, is the second tuning constant.

• *Derivative (rate) control:* This type of control action responds to changes in error, or the rate at which the actual pressure approaches the setpoint. The faster the change in the magnitude of the error, the greater the rate control signal, and vice versa. It serves to intensify the effect of the proportional corrective action, causing the process to stabilize faster. Rate control's main effect is to prevent the undershoot/overshoot oscillation that may never be completely eliminated with proportional-plus-reset control alone. The amount of rate action, expressed in percent, is the third tuning constant, usually the last to be set.

Rate Control Necessary on High-Speed Machines. Until recently, it was not always necessary for an injection process controller to have rate or derivative control in addition to proportional and reset. Rate control has, however, become essential on newer, faster cycling machines with updated hydraulics.

For example, the high injection speeds of accumulator-assisted machines can create extremely fast changes in the conditions governing hydraulic pressure. In order to smooth out the resulting pressure fluctuations, rate control responds only to fast changes in hydraulic pressure, such as when the ram begins to feel resistance of the melt pushing through the runners and gates of the mold. Changing from one pressure setpoint to another, as in multistep injection profiling, can require the same fast stabilizing action; so the derivative control will help to bring about a faster setpoint change, with minimal overshoot.

A multiple-pump machine will experience a momentary drop in hydraulic pressure when the high-volume pump "drops out" and the smaller holding pump continues injection. This drop in pressure is sometimes so large that the injection ram will actually back up. Derivative control will help to lessen this short dip in pressure and smooth out the injection pressure curve.

Relating Process Control to Product Performance

Monitoring of the molding system can show the effects of mechanical and thermal strains. Strains are imposed upon the material as it is conveyed through the machine and mold. Instrumentation to sense, measure, and display changes in molding parameters helps the molder to determine process consistency.

Monitoring helps relate the process to the product. The sense molding parameters can show the relationship between pressure, temperatures, and position (movement) during the process.

Monitoring can also establish whether additional machine control is needed. The forgiving nature of the molding process and liberal product dimensions allow most parts to be produced with conventional "open loop" machine control systems. As product demands become more stringent, both dimensionally and physically, "closed loop" machine control may become advantageous.

Sensor Requirements. Any sensor used requires a power supply and an amplifier. A sensor is driven by an input voltage, usually called an "excitation" voltage. A resultant output signal is generated as the sensor responds to the monitored parameter. An amplifier is used to boost the output signal's strength. Increased signal strength or amplitude is needed for recording capabilities.

Sensors and electrical systems should be tested and calibrated before actual use. Variances do occur between sensors of the same type. Sensors should be maintained at a "zero" reference if precise monitoring or measuring is to be done. Electrical "drifting" destroys the accuracy of the information being obtained.

Molding Parameters.

Pressure.

• *Machine hydraulic pressure transducer:* A hydraulic pressure transducer is used to generate a signal. Monitoring the hydraulic pressure profile can help diagnose many machine problems. The hydraulic pressure transducer should be placed as close to the injection ram as possible; this location gives the most accurate pressure profile. Hydraulic pressure profiles can determine the following:

1. Hydraulic pressure relief valve setpoint consistency.
2. Timer accuracy for switching cutoff pressures.
3. Hydraulic back pressure setting during screw return.
4. Screw return time consistency.
5. Hydraulic pressure changes during injection, reflecting material viscosity changes.

• *Machine material pressure transducer:* Monitoring the material pressure can be done with a transducer in the machine nozzle. The material pressure profile will be similar to the machine hydraulic pressure profile. The pressure of the material and the hydraulics in the machine barrel become similar as the mold is filled. Sensing of material pressure at the machine nozzle can be done, but its usefulness is questionable.

• *Mold material pressure:* Material pressure transducers can be installed in the mold's runner system and in the cavity. Indirect and direct material sensors are available. The type of transducer selected depends upon the product configuration in the mold, mold construction, and type of runner system.

Pin-loaded-type material pressure transducers must be designed and installed with care. The use of pins to transmit material pressure can cause errors; the pins can stick, bend, and induce thermal effects during cure time. Location and pin diameter must be considered for monitoring. Because of the "select point" pressure sensing, the transducer output may be poor.

Direct material pressure transducers are now available. The accuracy of pressure sensing is much better, but there is a problem in selecting the location to sense and monitor the material pressure. Monitoring at a point located halfway into the cavity is a good general rule. Maintenance of built-in transducers should be considered when designing a mold.

The mold material pressure profile can determine the following:

1. Material filling time.
2. Material peak pressure consistency.
3. Machine nozzle contamination or freeze-off.

Temperature.

• *Machine barrel temperature:* Barrel temperatures are sensed and controlled with thermocouples (T.C.). One T.C. is needed for each zone that is being controlled. Usually three zones (front, middle, and rear) are sensed and controlled. The nozzle usually has its own control. For accurate temperature control and temperature setpoint, current-proportioning controllers should be used, not the time on–off type of temperature setpoint controllers.

Monitoring barrel temperatures can determine:

1. Temperature controller performance.
2. Barrel heater failure.

• *Mold temperature:* The control of mold temperature is usually done with an independent heater/chiller unit(s). The controller has temperature setpoints, and the mold usually balances out at some temperature around the setpoint. If the controller supply lines, mold water lines, and pressure losses are minimized, the control is acceptable.

Monitoring of the mold temperature is usually done with T.C.'s. Their accuracy depends on the T.C. placement. The T.C. location must be tried to determine the optimum location. This area of monitoring temperature in the mold is difficult because of the high thermal inertia in the heater/chiller/mold system.

• *Material temperature:* Material temperature can be measured in the machine nozzle. Commercial T.C. sensors are available to measure the material melt temperature. The T.C. devices are the simplest and most stable to install; infrared and ultrasonic systems are also available, but are much more complex.

Material temperature variances can exist in the melt because of screw mixing, barrel heating, and a varying shot-to-barrel ratio. Sensing the nozzle melt can show:

1. Material melt consistency.
2. A change in machine plasticating.
3. Heater failure on the barrel.

Position.

• *Machine ram position:* The ram position is monitored from a potentiometer mounted on the machine, either linear or rotary. The sensor indicates the ram during the molding process and can show the following:

1. Injection rate of material into the mold.
2. Consistency of ram profile during "open loop" or "closed loop" machine control.
3. Screw position during return to back position.
4. Screw return time consistency.

• *Machine tie bars:* Machine tie bars "stretch" when the mold is clamped. This mechanical strain or elongation can be measured with strain gauges, dial indicators, and linear variable displacement transducers (LVDTs). The LVDTs eliminate the need to drill holes in the tie bars or clamping on small indicating devices. Monitoring tie bar strain can show:

1. Balance of tie bar strain during clamp.
2. Mold clamp tonnage.
3. Machine/mold clamp tonnage changes occurring because of thermal effects of machine cycling and mold heating or cooling.

• *Mold part line:* Mold part line separation can be measured with indicator gauges and LVDTs. As material is packed into the mold, the part line can open. There is a direct relationship between machine clamp on the mold, material viscosity, and material injection rate. Monitoring for a mold's part line separation can show the following:

1. Dimensional changes in the product.
2. Mold flashing.

Display of Monitored Molding Parameters.

Analog Display. Analog devices include:

1. Chart recorder.
2. Voltmeter with a sweep needle.
3. Oscilloscope.

Analog signals are useful for seeing a continuous profile of the parameter being sensed. This profile is useful because it is time-related. Chart recordings show a continuous profile but are limited in the type of information that may be interpreted. Total span and peak changes are shown, but comparisons of one cycle to another are difficult.

Digital Display. Digital devices include:

1. Controllers with numerical setpoints.
2. Sensing devices with numerical readout display.

Digital monitoring devices give a numerical readout. The sensor's output signal is conditioned to give a discrete numerical readout(s). Data loggers are used to monitor multiple parameters digitally. Digitizing (displaying discrete numerical values at a certain rate) of analog signals can be a useful technique, but the rate at which information can be digitized must be considered. If any rapidly occurring events are being considered, this system can give erroneous or insufficient information.

CRT Display. Cathode ray tube (CRT) displays include:

1. Oscilloscopes (scope).
2. Storage scope.
3. Analog/digital scope.
4. Television.

Storage scopes can be utilized to monitor repeating cycles. A selected starting point is used to "trigger" the scopes. The storage scope display shows the excursion of a parameter over a period of time. A multichannel storage scope is very useful to relate more than one molding parameter on a single display.

Machine Control.

"Open Loop" Machine Sequence Control. In a conventional "open loop" machine sequence control system, input commands are set, and there is an unknown machine output response.

Monitoring of machine hydraulic pressure and ram position relates:

1. Screw return profile consistency.
2. Hydraulic pressure profile consistency.
3. Ram injection rate consistency.

An open loop machine control system *cannot* compensate for changes in material viscosity. Material viscosity changes result in:

1. Increased viscosity (increased stiffness)
   (a) Higher initial hydraulic pressure profile.
   (b) Slower ram injection rate.
   (c) Lower final in-mold material pressures.
2. Lower viscosity (more fluid)
   (a) Lower initial hydraulic pressure profile.
   (b) Faster ram injection rate.
   (c) Higher final in-mold material pressure.

The ram injection rate is controlled by the metering of oil into the hydraulic injection ram cylinder. Material viscosity establishes the hydraulic pressure profile during mold filling and packing. The hydraulic pressure profile is a valuable parameter to monitor for establishing mold/machine consistency.

"Closed Loop" Machine Sequence Control. In a "closed loop" machine sequence control system, input commands are set, and corrections are made to the machine output response. The correction can be either of the following:

1. *Real time:* A sensed deviation is corrected in cycle, as quickly as the machine electrohydraulic valve and fluid system can respond.
2. *Adaptive:* A sensed deviation is adjusted for on the next cycle. The system's ability to adjust depends upon how sensitive the molding process is and controller capability to correct the deviation.

A closed loop machine control system *can* compensate for changes in material viscosity. This capability improves the consistency of initial mold filling but does not fully address final packing pressure in the mold.

The ram position is programmed to establish a material filling rate into the mold. The hydraulic pressure compensates for material viscosity changes during the controlled filling of the mold's sprue, runner, and cavity.

The final packing pressure is controlled by switching from the ram position (velocity) profile to a hydraulic packing pressure.

Control of the molding process is better, but actual improvement in the product is not always realized. Monitoring the molding system can help the molder to:

1. Improve mold setup consistency.
2. Resolve molding problems.
3. Determine the effectiveness of the equipment.
4. See the process working.

Adaptive Ram Programmer

The injection molding process has a number of variables in material and machine conditions that tend to change during production. All these variables affect the critical properties of the molded part. When material properties change or the machine drifts outside the ideally preset operating parameters, the operator must reestablish the conditions best suited for making the part. He or she is faced with a complex situation, as the interdependency of machine functions and material conditions requires a thorough understanding of the process, and a series of complex adjustments on the machine must be made to maintain part quality. Often the variables are not controllable to the necessary degree, and the operator has to contend with imperfect production and a high rejection rate.

The Spencer and Gilmore equation, developed a number of years ago, is now widely utilized to predict the relationships that must be maintained to keep the critical functions that affect part quality constant. This equation indicates that plastic pressure and volume are inversely related if temperature (or material viscosity) is constant. During molding, filling, and packing, the plastic temperature drops only slightly because of the short time interval involved. The material viscosity tends to change, however, as a function of composition or long-term temperature conditions of the machine.

The shrinkage of the plastic during mold cooling is primarily determined by the number of molecules in a given cavity under a given pressure. For this reason, cavity pressure controls have been utilized in an effort to control the shrinkage parameters of the part. As viscosity changes, however, it is important to adjust the plastic volume so that the number of molecules packed in a mold cavity will remain constant. In order to accomplish this, the precompressed shot size must be adjusted so that when the desired pressure in the cavity is reached, the total volume under pressure that exists between the tip of the ram and the cavity will be held constant. As the two parameters, pressure and volume, are highly interdependent, continual adjustments must be made (on each shot) following the trends in material parameters.

Another critical condition to be maintained is plastic flow rate. The Poiseuille equation for fluid flow (see above) shows the significance of pressure on flow rates. Plastic viscosity deviates considerably from constant during flow. The effect is to make flow behavior dependent upon pressure. As the operator desires to maintain the flow surface velocity for the plastic constant, or to adjust the flow in accordance with the requirements of the mold, the injection velocity together with material volume and pressure form the most important parameters that have to be controlled to maintain part quality.

Heretofore, individual parameters such as cavity pressure, ram oil pressure, and ram velocity have been measured and even controlled. The interdependence of these three functions, however, demands that a control system be utilized that can control all three parameters simultaneously, and is capable of automatic adjustments and decision making to maintain the equations in balance during the molding process.

Microprocessor Advantages

Microprocessor-based process controllers have been achieving more widespread acceptance as their cost has come down. Whereas a few years ago these controls were used only for applications that required their precise control, now we find advantages in their application on almost any job.

- *Setup time reduction:* Time for setup can be greatly reduced by the ability to record and store timer settings, limit switch positions, and pressure levels. The data can then be fed to the controller in seconds to preadjust the machine to the new setup.
- *Easier operator "tuning":* Since the microprocessor inputs can be located at the operator station, adjustments can be made without crawling around the machine.
- *Smoother operation:* This is achieved through ramping of the control signals. We can now eliminate many of the readjustments necessary as the machine temperature changes, simply by setting these ramps such that the time is longer than the response under conditions of start-up. Since the signal is now slower than valve response, the signal is always in control, yielding a more uniform cycle.
- *Less down time:* The constant monitoring of machine performance made possible with these systems can allow lower pressures and eliminate shock peaks, thereby extending component life. A properly applied system will also have fewer components to troubleshoot when a problem does occur, and diagnostic programs can be included.
- *Input energy reduction:* By programming the hydraulic system to respond to the varying demands of the circuit, we have the potential to reduce input power requirements.

GLOSSARY OF TERMS RELATED TO INJECTION MOLDING EQUIPMENT

There are three essential parts to an injection molding machine: the mold clamping device, the injection unit, and the mold. Accepted terminology is as follows:

Clamping system terminology—

clamping unit—That portion of an injection molding machine in which the mold is mounted, and which provides the motion and force to open and close the mold and to hold the mold closed during injection. When the mold is closed in a horizontal direction, the clamp is referred to as a **horizontal clamp.** When closed in a vertical direction, the clamp is referred to as a **vertical clamp.** This unit can also provide other features necessary for the effective functioning of the molding operation.

daylight, open (Fig. 5-29)—The maximum distance that can be obtained between the stationary platen and the moving platen when the actuating mechanism is fully retracted without ejector box and/or spacers.

daylight, closed or minimum mold thickness (Fig. 5-29)—The distance between the stationary platen and the moving platen when the actuating mechanism is fully extended, with or without ejector box and/or spacers. Minimum mold thickness will vary, depending upon the size and kind of ejector boxes and/or spacers used.

daylight, maximum closed (Fig. 5-29)—That distance between the stationary platen and the moving platen when the actuating mechanism is fully extended without ejector box and/or spacers.

daylight, minimum closed (Fig. 5-29)—That distance between the stationary platen and the moving platen when the actuating mechanism is fully extended with standard ejector box and/or spacers.

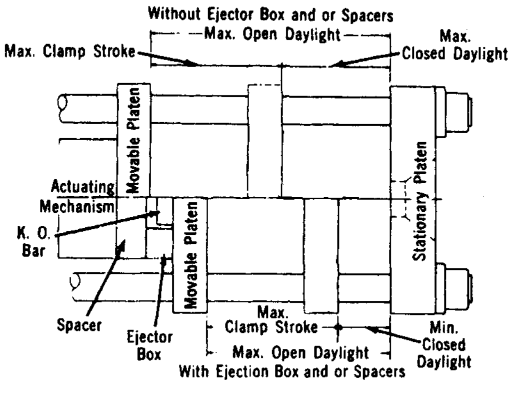

Fig. 5-29. Clamp die space nomenclature. *(All illustrations on injection molding courtesy SPI Machinery Division)*

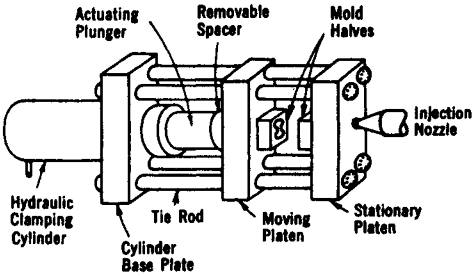

Fig. 5-30. Hydraulic clamp.

ejector (knockout)—A provision in the clamping unit that actuates a mechanism within the mold to eject the molded part(s) from the mold. The ejection actuating force may be applied hydraulically or pneumatically by a cylinder(s) attached to the moving platen or mechanically by the opening stroke of the moving platen.

full hydraulic clamp (Fig 5-30)—A clamping unit actuated by a hydraulic cylinder which is directly connected to the moving platen. Direct fluid pressure is used to open and close the mold, and to provide the clamping force to hold the mold closed during injection.

moving platen (Figs. 5-30 and 5.31)—That member of the clamping unit which is moved toward a stationary member. The moving section of the mold is bolted to this moving platen. This member usually includes the ejector (knockout) holes and mold mounting pattern of bolt holes or "T" slots. A standard pattern was recommended by SPI Standards Testing Method (Injection Machinery Division Standards, September 11, 1958).

stationary platen (Figs. 5-30 and 5-31)—The fixed member of the clamping unit on which the stationary section of the mold is bolted. This member usually includes a mold mounting pattern of bolt holes or "T" slots. A standard pattern was recommended by SPI Standards Testing Method (Injection Machinery Division Standards, September 11, 1958). In addition, the stationary platen

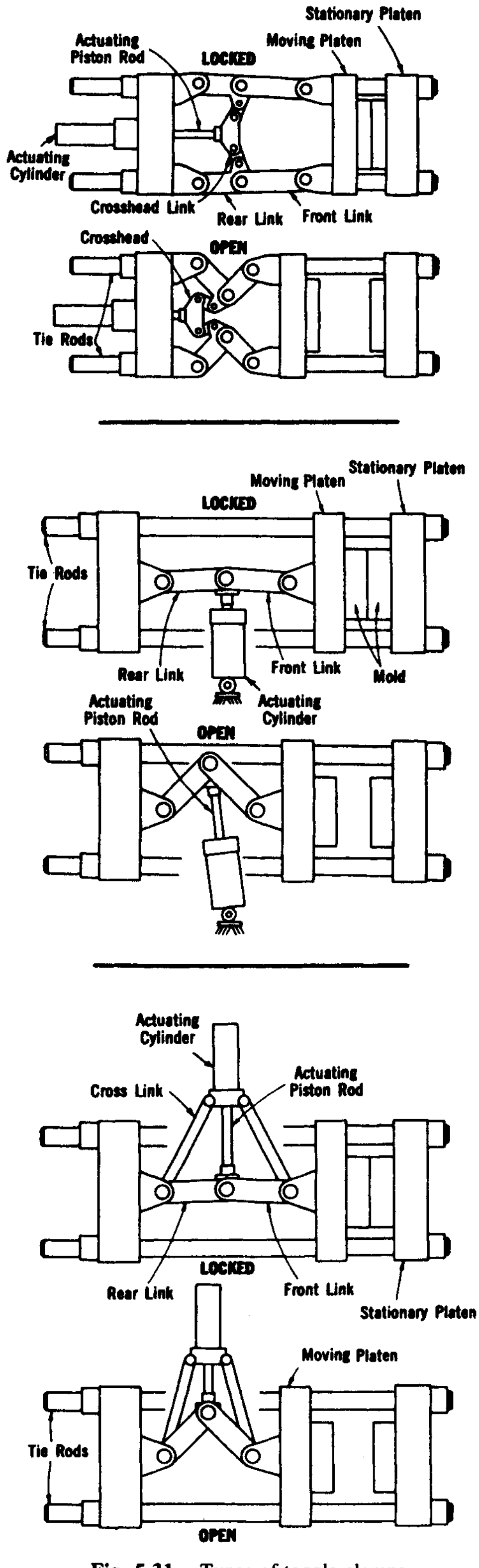

Fig. 5-31. Types of toggle clamps.

usually includes provision for locating the mold on the platen and aligning the sprue bushing of the mold with the nozzle of the injection unit.

tie rods or beams (Figs. 5-30 and 5-31)—Those members of the clamping unit that join and align the stationary platen with the clamping force actuating mechanism and that serve as the tension members of the clamp when it is holding the mold closed.

toggle clamp (hydraulic actuated, mechanical actuated) (Fig. 5-31)—A clamping unit with a toggle mechanism directly connected to the moving platen. A hydraulic cylinder, or some mechanical force device, is connected to the toggle system to exert the opening and closing force and hold the mold closed during injection.

Injection system terminology—

injection plasticizing (plasticating) unit—That portion of an injection molding machine which converts a plastic material from a solid phase to a homogeneous semi-liquid phase by raising its temperature. This unit maintains the material at a moldable temperature and forces it through the injection unit nozzle into a mold.

plunger unit (Fig. 5-32)—A combination injection and plasticizing device in which a heating chamber is mounted between the plunger and the mold. This chamber heats the plastic material by conduction. The plunger, on each stroke, pushes unmelted plastic material into the chamber, which in turn forces plastic melt at the front of the chamber out through the nozzle.

prepacking—Also called "stuffing," a method that can be used to increase the volumetric output per shot of the injector plunger unit by prepacking or stuffing additional material into the heating cylinder by means of multiple strokes of the injector plunger. (Applies only to plunger unit type injection machines.)

reciprocating screw (Fig. 5-33)—A combination injection and plasticizing unit in which an extrusion device with a reciprocating screw is used to plasticize the material. Injection of material into a mold can take place by direct extrusion into the mold, or by reciprocating the screw as an injection plunger, or by a

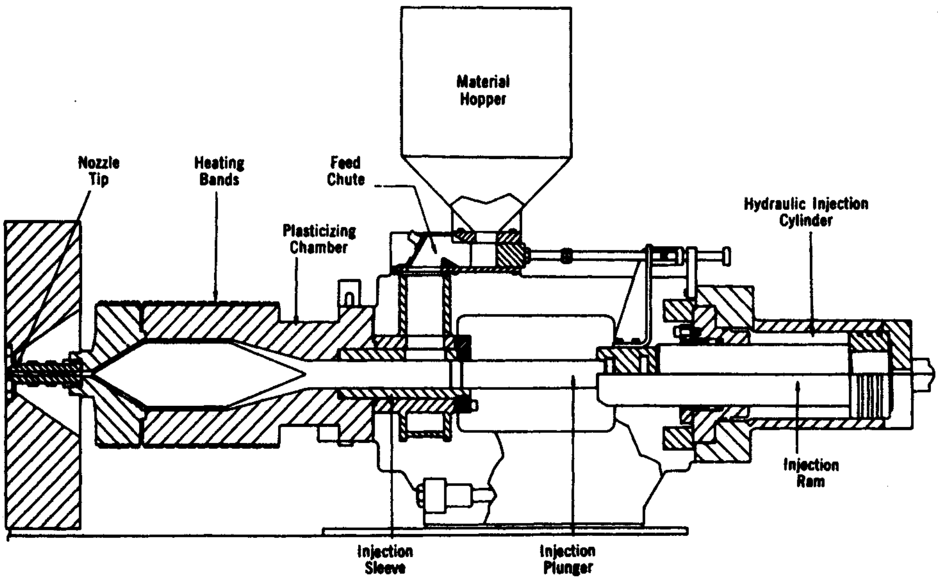

Fig. 5-32. Plunger unit.

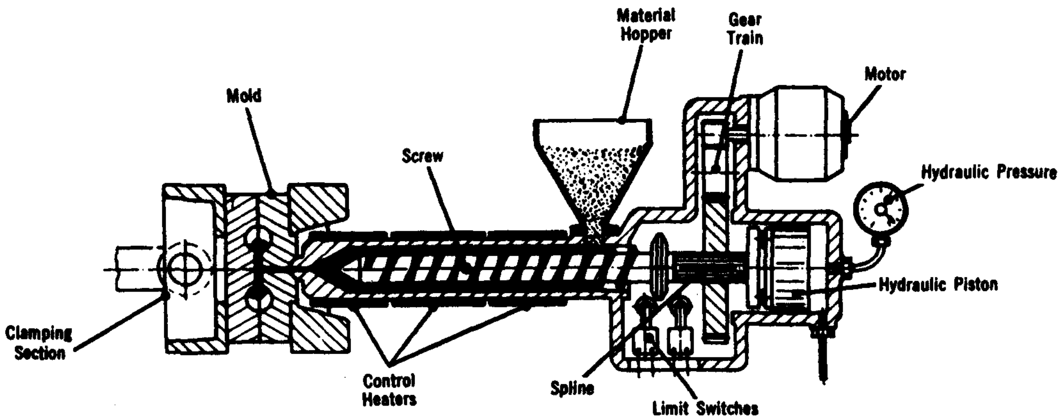

Fig. 5-33. Reciprocating screw unit.

combination of the two. When the screw serves as an injection plunger, this unit acts as a holding, measuring, and injection chamber.

two-stage plunger unit (Fig. 5-34)—An injection and plasticizing unit in which the plasticizing is performed in a separate unit. The latter consists of a chamber to heat the plastic material by conduction and a plunger to push unmelted plastic material into the chamber, which in turn forces plastic melt at the front of the chamber into a second stage injection unit. This injection unit serves as a

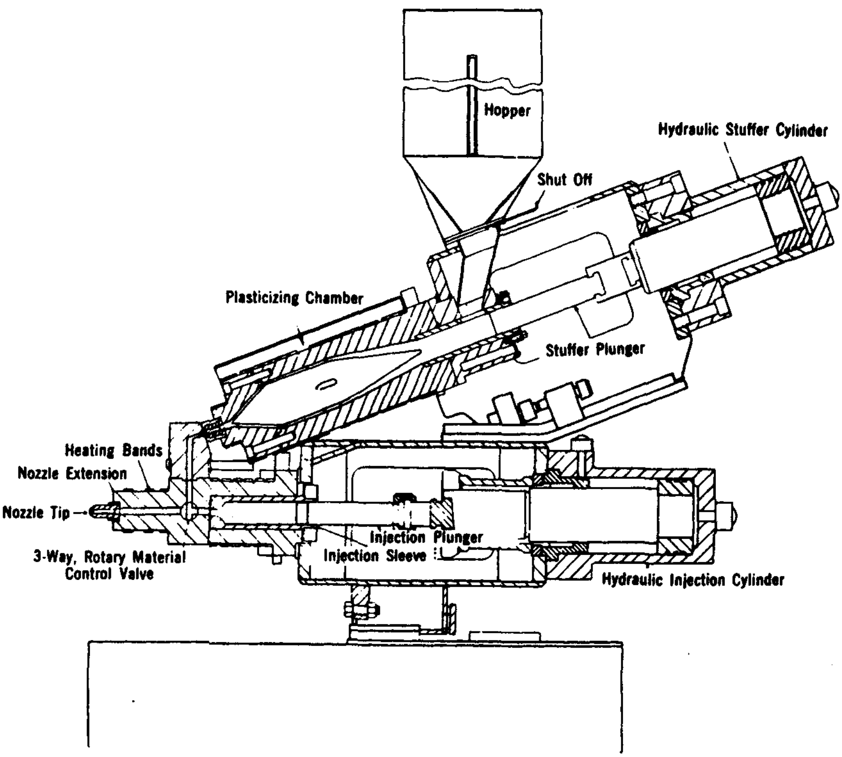

Fig. 5-34. Two-stage plunger unit.

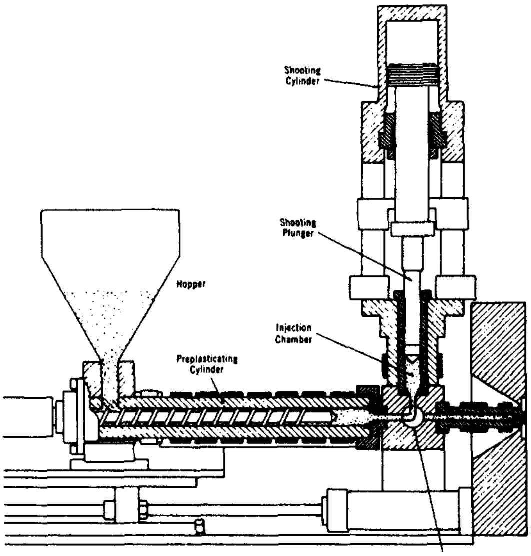

Fig. 5-35. Two-stage screw unit.

combination holding, measuring, and injection chamber. During the injection cycle the shooting plunger forces the plastic melt from the injection chamber out through the nozzle.

two-stage screw unit (Fig. 5-35)—An injection and plasticizing unit in which the plasticizing is performed in a separate unit which consists of a screw extrusion device to plasticize the material and force it into a second stage injection unit. This injection unit serves as a combination holding, measuring, and injection chamber. During the injection cycle a plunger forces the plastic melt from the injection chamber out through the nozzle.

See also molding definitions in Chapter 1.