CHAPTER 1

The Injection Molding Machine

Injection molding is a major processing technique for converting thermoplastics, and now thermosetting materials, into all types of products. Approximately 25% of the 13 billion pounds of thermoplastics sold in the United States in 1971 were injection molded, and about 36% (4320) of the 12,000 processing plants in the United States injection molded (1). Furthermore, in 1970 about 5000 injection molding machines were purchased in this country which brought the total of injection machines in-place to about 58,000. Since there were 130,000 processing machines, injection machines represent close to 45% of all processing units.

Sixty percent of the machines use a reciprocating screw, 35% a plunger (concentrated in the smaller machine sizes), and 5% a screw pot. This reinforces the fact that only 20% of those responding to the survey indicated that obsolescence was important.

The average plant had 12.5 machines. Custom molding plants tended to cluster in 12 machine units (12, 24, and 36 machine plants), as this is an economical management unit. The average age for smaller machines was 6.3 years, for medium size machines 5.0 years, and for larger machines 4.8 years. Also 52% of injection molders processed plastics by another method, and 20% used two or more different processes. In view of the high capital cost of injection machinery, it is surprising that for all plastic processing plants, 24% worked one shift, 18% two shifts, and 58% three shifts.

The process is not new. John and Isiah Hyatt received a patent in 1872 for an injection molding machine, which they used to mold camphor-plasticized cellulose nitrate (celluloid). In 1878 John Hyatt introduced the first multicavity mold. In 1909 Leo H. Baekeland introduced phenol-formaldehyde resins which are now injection moldable with the screw molding machine.

The experimental and theoretical works of Wallace H. Carothers led to a
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general theory of condensation-polymerization that provided the impetus for the production of many polymers, including nylon. At the end of the 1930's modern technology began to develop and great improvements in materials permitted injection molding to become economically viable. A similar advance in machine technology is developing now.

There are both advantages and disadvantages to injection molding.

Advantages of Injection Molding

1. Parts can be produced at high production rates.
2. Large volume production is possible.
3. Relatively low labor cost per unit is obtainable.
4. Process is highly susceptible to automation.
5. Parts require little or no finishing.
6. Many different surfaces, colors, and finishes are available.
7. Good decoration is possible.
8. For many shapes this process is the most economical way to fabricate.
9. Process permits the manufacture of very small parts which are almost impossible to fabricate in quantities by other methods.
10. Minimal scrap loss result as runners, gates, and rejects can be reground and reused.
11. Same item can be molded in different materials, without changing the machine or mold in some cases.
12. Close dimensional tolerances can be maintained.
13. Parts can be molded with metallic and nonmetallic inserts.
14. Parts can be molded in a combination of plastic and such fillers as glass, asbestos, talc, and carbon.
15. The inherent properties of the material give many advantages such as high strength-weight rates, corrosion resistance, strength, and clarity.

Disadvantages and Problems of Injection Molding

1. Intense industry competition often results in low profit margins.
2. Three shift operations are often necessary to compete.
3. Mold costs are high.
4. Molding machinery and auxiliary equipment costs are high.
5. Process control may be poor.
6. Machinery that is not consistent in operation, and whose controls are not directly related to the end product.
7. Susceptibility to poor workmanship.
8. Quality is often difficult to determine immediately.
9. Lack of knowledge about the fundamentals of the process causes problems.
10. Lack of knowledge about the long term properties of the materials may result in long-term failures.

Many of the above problems can be ameliorated if the processor understands the operation of the machines and the plastics processing principles discussed in this text.

MACHINE OPERATION

Figure 1-1 shows a reciprocating screw injection molding machine with a clamping capacity of 250 tons, using a 2-in. reciprocating screw which delivers a maximum of 13 oz of polystyrene per shot.

The machine basically is a tool for the following.

1. Raising the temperature of the plastic to a point where it will flow under pressure.
2. Allowing the plastic to solidify in the mold, which the machine keeps closed.
3. Opening the mold to eject the plastic.

Figure 1-2 shows a schematic representation of the clamping end of an hydraulic machine, and Figure 1-3 shows the injection end of an inline reciprocating screw plasticizing unit. The injection side of the mold is clamped to the stationary platen, and the ejection side of the mold is clamped to the moving platen. The mold has an empty space in the configuration of the part to be molded. This empty space is filled with melted plastic under high pressure.

The moving platen rides on four steel bars called tie rods (or tie bars). The clamping force is generated by the hydraulic mechanism pushing against the moving platen and stretching the tie rods.

Basic Principles Reciprocating Screw Machine

The steps of the molding process for a reciprocating screw machine with an hydraulic clamp follow (Figures 1-2 and 1-3):

1. Plastic material is put into the hopper. (The virgin powder is normally granulated to 1/8 to 3/16 spheres or cubes.)
2. Oil behind the clamp ram moves the moving platen, closing the mold. The pressure behind the clamp ram builds up, developing enough force to keep the mold closed during the injection cycle. If the force of the injecting plastic material is greater than the clamp force, the mold will open. Plastic will flow past the parting line on the surface of the mold, producing “flash” which either has to be removed or the piece has to be rejected and reground.
3. The material is melted primarily by the turning of the screw which converts mechanical energy into heat. It also picks up some heat from the heating bands on the plasticizing cylinder (extruder barrel). As the material melts, it moves forward along the screw flights to the front end of the screw. The pressure generated by the screw on the material forces the screw, screw drive system, and the hydraulic motor back, leaving a reservoir of plasticized
material in front of the screw. The screw will continue to turn until the rearward motion of the injection assembly hits a limit switch, which stops the rotation. This limit switch is adjustable, and its location determines the amount of material that will remain in front of the screw (the size of the "shot").

The pumping action of the screw also forces the hydraulic injection cylinders (one on each side of the screw) back. This return flow of oil from the hydraulic cylinders can be adjusted by the appropriate valve. This is called "back pressure", which is adjustable from zero to about 400 psi.

4. Most machines will retract the screw slightly at this point to decompress the material so that it does not "drool" out of the nozzle. This is called the "suck back" and is usually controlled by a timer.

5. The two hydraulic injection cylinders now bring the screw forward, injecting the material into the mold cavity. The injection pressure is maintained for a predetermined length of time. Most of the time there is a valve at the tip of the screw that prevents material from leaking into the flights of the screw during injection. It opens when the screw is turning, permitting the plastic to flow in front of it.

6. The oil velocity and pressure in the two injection cylinders develop enough speed to fill the mold as quickly as needed and maintain sufficient pressure to mold a part free from sink marks, flow marks, welds, and other defects.

7. As the material cools, it becomes more viscous and solidifies to the point where maintaining injection pressure is no longer of value.

8. Heat is continually removed from the mold by circulating cooling media
(usually water) through drilled holes in the mold. The amount of time needed for the part to solidify so that it might be ejected from the mold is set on the clamp timer. When it times out, the moveable platen returns to its original position, opening the mold.

9. An ejection mechanism separates the molded plastic part from the mold and the machine is ready for its next cycle. During the regular molding cycle steps 3 and 4 occur after step 7.

**Basic Principles-Plunger Machine**

A Plunger machine (Figure 1-4), which is discussed on p. 13, heats the material by conduction and convection only and has very different characteristics.

In a plunger machine, the cold granules in the rear of the cylinder are compressed as the plunger comes forward; thus the machine starts to fill the mold more slowly than a reciprocating screw machine in which the plunger acts directly on the plasticized material. As soon as the mold fills, the pressure builds up inside the mold.

In a plunger machine, there is a large pressure loss in the cylinder because of the nature of its design. Therefore, the pressure at the end of the plunger is considerably higher than the pressure at the nozzle. In a screw machine, the ram pressure and nozzle pressure are almost the same.

Figure 1-5 shows the injection end of a 16-oz. 425-ton clamp plunger
machine. The operator has his left hand on the safety gate, which has been extended upward for safety. He opens the gate and removes the parts with his right hand, lays them on the table for cooling and inspection, and separates the molded parts from the runner. In the rear is a multiple head drill press for post finishing operations. Next to the press are cabinets containing all the spare parts pertaining to that particular machine. A 1-ton hoist rides on an I beam that is central over the length of the machine. It is used for mold changes and repairs. Note the large nuts which hold the four tie rods to the stationary platen. The light signals an obstruction on the mold and is connected in parallel with a bell which is used when the machine runs automatically. A weighing device weighs the material for each shot.

To facilitate maintenance and the use of auxiliary equipment 110-V AC outlets were installed on the machine; thus wires were not put on the floor where they might get wet or become exposed. To the left of the outlets is a manually controlled valve which moves the whole injection carriage back for purging or nozzle change. The wheel next to it controls the injection pressure. The 10-hp motor and pump maintain the clamping pressure. The main motor
and pump are behind the machine. The gauges for the injection pressure, clamp pressure, pilot pressure, and oil temperature are found on a panel beneath the controls.

The wheel directly beneath the gate is used for "inching" or bypassing most of the oil to allow very slow movement of the machine for setup and checking. Immediately above the wheel is a gate safety limit switch attached in series with another one activated by the back of the gate. The gate also activates an hydraulic safety. This machine was subsequently converted to a two-stage screw-plunger machine.

Figure 1-6 shows a cutaway of a 2½-in. reciprocating screw 300-ton machine with an injection capacity of 24-oz. of polystyrene. As with all machines, the injection end is to the right of the operator. This permits him to open the safety gate with his left hand and remove the molded piece with his right.

The Injection Cycle

Figure 1-7 shows a schematic representation of a single cycle for a plunger-type machine and a screw-type machine. A plunger machine heats the material by conduction from the heated cylinder wall. A screw machine plastizices the material by the shearing action of the rotating screw.

Pressure is resistance to flow. Therefore, as the clamp ram closes, there is very little resistance to the flow of the hydraulic oil so that the pressure remains very low. As soon as the mold clamps resistance builds up quickly, the clamp pressure goes up rapidly and remains at a steady level until released; it then drops to zero, and the mold is opened.

Once the mold is initially filled, additional material is added to the mold by the injection pressure to compensate for shrinkage as the material cools. Adding too much material is called "over packing," which results in highly stressed parts and may cause ejection problems. Insufficient material causes short shots, poor surface, sink marks, welds, and other defects. Material will continue to flow into the mold as long as there is injection pressure, provided the gate has not been sealed by the material solidifying. Once the gate seals or the injection pressure ceases, no more material enters the mold, and the contraction of the cooling material causes a decay of mold pressure.

In any given molding operation there is a maximum residual cavity pressure above which the part cannot be satisfactorily ejected. The operator must adjust his time, temperature, and pressure controls to attain a residual pressure below this maximum.

Estimating Cycle Time

A molder will look at a plastic part and estimate its production, for example, as a 30-sec cycle or 120 shots per hour. He will be making a judgement based on
**Figure 1-6** Cutaway view of 2½-in. 300-ton reciprocating screw machine (British Plastics).
the design of the part, the material in which it is molded, the tolerance requirements, the machine on which it is molded, the mold, and, on occasion, even the operator. An hypothetical illustration for a screw machine follows:

Part weight = 210 g, GP-PS (general purpose polystyrene)
*Injection rate = 12 in.\(^3\) sec
  (for polystyrene 12 in.\(^3\) /sec \times 17.4 g/in.\(^3\) = 210 g/sec)
*Screw recovery rate (PS) = 40 g/sec
*Mold closing = 20 in./sec
*Mold opening = 26 in./sec

*Machine specification.
Calculation

Mold closing (10 in.) = 0.5 sec
Mold slow down = 0.5 sec
Mold filling time = weight part/injection rate = \( \frac{210 \text{ g/sec}}{210 \text{ g/sec}} \) = 1 sec

Injection hold timer = 5 sec
Clamp timer = 16 sec
(Screw recovery rate = 40 g/sec = 5.2 sec is less than clamp hold time so it will not restrict cycle.)

Mold opening plus ejection slow down = 2 sec
Part removal = 5 sec
Total = 120 shots/hr \( \approx \) 30 sec

The machine specifications assume that the hydraulic system is in good condition. Loss of pumped oil due to internal leakage can significantly slow the machine. The estimated injection hold timer and clamp timer (which controls the cooling time) settings are almost always based on experience with similar parts and materials. Attempts to compute them mathematically have not yet been successful (2).

Material Feed Control

In a straight plunger machine (Figure 1-4) the amount of feed can be controlled volumetrically. An adjustable chamber is filled with cold material every time the injection plunger reciprocates. This does not compensate for different particle sizes which change the bulk density, filling the chamber with different weights of material. An improved method uses a scale to weigh a predetermined charge of powder and dumps it, via a bucket, into the feed opening. A simple control system automatically compensates for incorrect feed (Figure 1-5).

Drying Material

The injection end has a hopper for holding the molding material. Some materials, such asnylons, polycarbonates, acrylics, acrylonitriles, and acetates, are hygroscopic and require drying before molding. Material is usually dried in an oven specifically designed for plastics. The oven is filled with trays so that the plastic can be spread out in thin layers, about 3/4 to 1 in. deep. Hot air is forced through the material by blowers. A small amount of warm air is bled out of the oven to prevent the accumulation of moisture. Raising the temperature of the air in the oven increases the diffusion of the water from the material. It also increases the capacity of the air to hold water. For example, at 70°F air holds 0.0158 lb of water per pound of dry air. At 175°F air holds 0.53 lb of water per
pound of dry air. Air entering at 100°F and 90% relative humidity contains only 0.038 lb of water per pound of dry air. For most materials the water equilibrium level is sufficiently high so that dehumidifying the intake air is unnecessary.

Fornylons and polycarbonates the statement above may not be true. In general the moisture content of nylon should not be greater than 0.28%. Above that level it will tend to react with the nylon during plasticizing and reduce the molecular weight, thus reducing the physical properties. Additionally, as with other materials, excess water results in splay marks and the possibility of internal bubbles caused by steam. Drying nylon at 175°F using intake air at 90°F and 70% relative humidity will give an equilibrium of 0.42% water. Trying to "dry" nylon as supplied by the manufacturer under these conditions would result in increasing the water content of the nylon to a point where it could not be molded properly. The air would have to be dehydrated by mechanical refrigeration or chemical desiccants that are regenerated by heating. Usually two sets are used, one in the oven and the other in the regenerating process. The length of time for drying depends on the type of material, its wetness, the circulation of the system, and the humidity and temperature of the makeup air. Normally 3 to 4 hr in an oven will dry the material (3).

Filtered hot air systems can be attached to the hopper to blow heated and dehumidified air through the plastic pellets. These are called hopper dryers. The intake air is filtered and dehumidified if required.

Hygroscopic material from the manufacturer in airtight containers can be used without drying if too much material is not placed in the hopper. Some machines are equipped with infrared heating devices to keep the material warm. A hopper dryer is always valuable when molding these materials.

In the extrusion process the removal of volatiles, including moisture, can be accomplished by using two screws in tandem on one barrel. A venting valve, connected to the atmosphere, is between them. The first section picks up material from the hopper and feeds it to the compression section where it is melted. The material is decompressed to atmospheric pressure at the point under the vent valve, thus permitting volatiles to escape. It is then recompressed and the balance of the screw acts like a single screw (p. 27)(3a, 3b). This removes the need for drying.

**Keep Foreign Matter Out of the Hopper**

Regardless of the care exercised by management there is a possibility of screw drivers, nuts and bolts, scales, and other metallic items entering the plasticizing chamber. These objects can cause major damage to the screw and barrel. A magnet is placed in the throat of the hopper to catch ferrous material, since this is the most common metal. Brass and copper are usually soft enough to be "molded" without damaging the machine.
TYPES OF INJECTION MACHINES CLASSIFIED BY INJECTION COMPONENT OR "END"

An injection machine basically consists of a clamping portion that contains the mold and the injection end which feeds, melts, and meters the plastic. Four major types of injection ends in use today follow:

1. The single stage plunger (Figure 1-4, 1-10) uses a plunger to force material over a spreader or torpedo. The heat is supplied by resistance heaters. The material is heated by conduction and convection.

2. The two stage plunger-plunger (two stage plunger or plunger into a "pot") type machine uses a single stage plunger to plasticize the material and force it into a second cylinder (Figure 1-8). The second cylinder shoots the material into the mold.

3. The two stage-screw plunger (screw-pot) is essentially similar to the plunger-plunger machine except that a fixed screw is used for plasticizing instead of a plunger (Figure 1-9).

4. A reciprocating screw (In-line screw) uses a rotating screw to plasticize the material (Figure 1-3). As the screw turns, the plasticized material is forced in front of it, pushing the screw back. The material is injected by bringing the screw forward, which then acts as a plunger. More reciprocating screws are sold than any other machine today.

Single Stage Plunger

Approximately one third of the machines in operation in 1972 are of the plunger type, even though very few are now being manufactured. Therefore, a limited discussion of its operation is presented.

The single stage plunger (Figure 1-4) uses a plunger to force the material over a spreader or torpedo. The heat is supplied by resistance heaters, and the material is melted primarily by conduction and also by convection. The flow in the cylinder is basically laminar, giving the least homogeneous melt of all plasticizing systems.

The essentially laminar flow pattern can be shown by changing colors while the cylinder is in operation and cross-sectioning the extrudate at that time. The fin sections are clearly outlined as the material flows more slowly around them.

The plunger cylinder also transmits the pressure from the injection plunger to the molded material at the nozzle end. As mentioned previously pressure losses are considerable. Under flow conditions similar to molding pressure drops as high as 80% were recorded.

The pressure loss depends on the injection pressure, the barrel temperature, and to a lesser extent the design at the fin end of the torpedo. The major pressure loss occurs in the cold granular area.
Figure 1-8 Schematic drawing of injection end of two stage plunger machine (HPM Division of Koehring Co.).

Figure 1-10 shows a cross section of a typical straight bore cylinder. The heat is supplied by resistance bands separated into three zones, each controlled by its own thermocouple. The adaptor and nozzle have their own heating band under separate control. Cold material in granular form is compacted by the plunger and heated by the cylinder wall. It is spread around a torpedo which is rigidly supported at the nozzle end by an integral slab through which are drilled holes connecting the plasticizing chamber to the nozzle area. The rear of the torpedo is supported by several fins touching the bore of the heating cylinder. The torpedo is heated by conduction through the flange and fin area, both of which are in contact with the heated cylinder walls. This cylinder is easily cleaned by unscrewing the adaptor and hitting the fin end of the torpedo. A disadvantage of this design is the relative coolness of the fin end of the torpedo.

The second popular design has the torpedo attached near the fin section by a heavy flange, through which holes are bored for the plastic flow. This keeps the fin end warmer. Its disadvantage is its difficulty to disassemble and clean.
Efficiency calculations for the plunger machine. There is no acceptable way to rate the output of a plunger machine. Specifications are usually the
manufacturers optimistic evaluation under the best possible conditions. If this specification is important, it is best to consult with someone who has the identical equipment.

A rigorous analysis of the plunger cylinder including temperature and pressure measurements, temperature variations, and the effect of design factors on heater performance was given at the annual National Technical Conference of the Society of Plastic Engineers, Inc. in January 1955 (4). In analyzing the process the plastic was considered a tube with the cylinder diameter being the outside diameter and the torpedo diameter being the inside diameter. The heat transfer equations for an infinite slab will give sufficiently accurate approximations.

The material enters the chamber at a temperature \( T_0 \). The highest temperature it could reach at the nozzle end is the wall temperature \( T_w \). In practice the melt temperature \( T_m \) will be considerably lower. The efficiency of the cylinder can be expressed as the ratio of these two temperature differences.

\[
E = \frac{T_w - T_0}{T_m - T_0}
\]

(1-1)

\( E \) = heating efficiency

\( T_0 \) = temperature of entering material

\( T_w \) = temperature of cylinder wall

\( T_m \) = temperature of exiting material

The heating efficiency should not be confused with the machine efficiency. The latter is the ratio of the amount of heat acquired by the plastic over the amount of heat supplied by the electrical heaters.

While attempts have been made to use induction heating as a source of energy for injection molding thermoplastic (5,6), all cylinders for thermoplastics use electrical heating. Cylinders for injection molding thermosetting materials are usually heated with water on the barrel and electrically on the nozzle. The wattage of the heating elements of the cylinder are given for the purpose of connecting the machine electrically. It is assumed they are sufficient for the cylinder. Obviously a significant amount of heat is lost by radiation. To maintain a plastic temperature of 400°, which corresponded to an output of 6500 Btu/hr, a nonshielded cylinder required an input of 20,800 Btu/hr for a loss of 14,300 Btu/hr. Shielding with an asbestos lined aluminum cover reduced the heat loss to 6900 Btu/hr. This is a very significant reduction in operating costs. On the other hand, complete insulation of the heating cylinder is not desirable because of the difficulty of good temperature control.

Some of the factors that affect the efficiency and output of a plunger cylinder follows:

1. Thermal diffusivity. This is the rate at which a temperature change at one
point in a body travels to another point. It is defined as the thermal conductivity divided by the product of the density and specific heat.

\[ \alpha = \frac{K}{\rho C} \]

\( K = \text{thermal conductivity} \)
\( \rho = \text{density} \)
\( C = \text{specific heat} \)  \hspace{1cm} (1-2)

Since plastic is an excellent insulator, it will take approximately 4½ hr to bring the average temperature of a 4-in.-diameter cylinder of plastic to 80% of the wall temperature.

2. The length of time that the plastic is in the cylinder. This is the product of the number of shots stored in the cylinder multiplied by the time of a single shot.

3. The ratio of the surface area of the heated section of the cylinder to the volume of the plastic. Obviously the larger the surface area, the more material that can be plasticized. This can be increased by fluting the torpedo. However, the gain would be counterbalanced by the extra thickness of the plastic.

4. The thickness of the plastic. The thinner the plastic, the more rapidly the heat will be transmitted. If the torpedo is internally heated, the thickness of the infinite slab is effectively cut in half. If it is just heated from the outer wall by conduction through the metal, the effective thickness of the slab is between that of one heated on both sides and heated on only one side. A cylinder with an internally heated torpedo at an efficiency \( E \) of 0.8 plasticized 73 lb/hr. When the torpedo heat was turned off, the rate dropped to 39 lb/hr. The production rate of a nonheated torpedo with a large contact area near the fin is superior because of the better heat transfer into the torpedo.

5. The flow path. The flow path through the cylinder should be clear with minimum spots for material hangup. If all material does not move through at a reasonably uniform velocity, some material will remain in longer than others and contribute to a very wide temperature variation. This gives different densities in the material, causes large stresses in the molded part and can also degrade the material. Measurements show that the material that goes by the fin area (velocity is slowed down) is higher in temperature than the other material in the cylinder.

It was found that with no lubricant and a 20,000-psi ram pressure, the pressure drop was 16,600 psi. Adding 200 ppm of lubricants reduced the pressure loss to 7800 psi. Anything that will reduce the granular volume, such as torpedo heat and prepacking the cylinder, will reduce the pressure loss.

Alternatives to the Conventional Plunger Machine

A number of other methods were tried but did not achieve commercial
acceptance. They included a rotating torpedo with fins on it (7), the purpose of which was to introduce mixing and break up the laminar flow. A melt extractor (8) wherein the material was plasticized through a strainer-like device and sent into a shooting chamber was also tried. A third method was a vented reverse flow cylinder. The material made three passes through the cylinder in grooved channels. At the end of the second pass, gases were vented back to the cold material (8a).

Preplasticizing Machines

The single stage plunger machine has some severe limitations which are overcome by using a preplasticizing system (9). Here the material is melted in one chamber and transferred into a second chamber. In a typical two stage machine — plunger-plunger or screw-plunger — the plunger or screw plasticizes the material in one cylinder and transfers it into another cylinder where the material is forced into the mold by the direct action of another plunger on the melted material. In a reciprocating or in-line screw, the material is plasticized and forced in front of the screw, which is in effect another chamber. The material is injected by bringing the screw forward which acts like a plunger. A check valve on the front end of the screw is used with nonheat sensitive thermoplastics.

Preplasticizing gives rise to a number of significant advantages.

1. The two basic requirements of a plunger cylinder are in conflict. Effective heat transfer requires small clearances between the plunger and torpedo and a long cylinder to permit gradual and full heat transfer. Good pressure transmission requires large channels or clearance between the wall and the torpedo and a short cylinder. This conflict is overcome in a preplasticizing system by separating the two functions. The material is heated in one chamber and injected in another.

2. The melt is more homogeneous because it is mixed as it passes through the small opening connecting the two chambers. This significantly reduces the high temperature differential (150°F) and the resultant stresses often found in a plunger machine.

3. Better shot weight control is possible. The plasticized material forces the injection plunger back until it reaches a predetermined location. The amount of material to be injected, therefore, has been volumetrically determined on the material to be injected at the temperature of injection. This contrasts with weighing cold pellets to determine the charge in a plunger machine. Accurate shot weight control is important in that it prevents underfilling — with its shorts and sink marks — and overfilling with its packing and difficult ejection. The bulk factor, specific gravity, and temperature difference from shot to shot does not affect the accuracy of the preplasticizing feed.
4. The injection plunger exerts pressure directly on the material which is advantageous. The pressure on the material can be determined accurately by a pressure gauge in the hydraulic injection system. In contrast, the true injection pressure on a plunger machine can only be read with a pressure sensing device on the nozzle. The injection pressure in a preplasticizing machine can be controlled accurately and generally remains constant. In a plunger machine, the pressure will change depending on the compressibility and temperature of the granules at the feed end.

5. Faster injection is possible. This is very important in controlling the quality of the molded parts and the length of the cycle.

6. Injection pressures of 20,000 psi on the material are required. Because of the large pressure losses in a plunger cylinder, a condition not encountered in a two stage machine, the cylinder and hydraulic system of the plunger machine must be significantly larger and more costly to produce 20,000 psi at the nozzle.

7. It is relatively easy to increase the shot capacity, particularly in two stage machines. Increasing the volume of the shooting cylinder is very inexpensive compared to the massive cylinders that would be required for large shots in a plunger machine. For this reason most plunger machines now in use are in the 12 oz or lower capacities.

8. The lack of pressure loss in the injection system reduces the horsepower requirements and the cost of operating the machine.

9. A preplasticizing unit permits molding at lower pressure because of the rapid injection rate and the better homogeneity of the melt. This lowers the mold clamping force per unit area and permits a larger projected area of molding on the machine.

10. With proper design of two stage machines, plasticizing can take place throughout most of the cycle, yielding more pounds per hour per dollar of machine cost.

There are a number of disadvantages to preplasticizing systems, primarily concerned with the additional maintenance of the valves, shooting cylinders, and reciprocating portions and mechanism of an inline machine. Another disadvantage is the leakage around the injection ram. Leakage adversely affects the accuracy of the injection. In an inline screw the leakage is internal as it is past the check valve on the tip of the screw. In a two stage machine the leakage is less critical, but improper wiping of the plunger tip may cause material to hang up and degrade.

**Plunger-plunger Machine.** Figure 1-8 illustrates a plunger-plunger machine. The preplasticizing chamber is that of Figure 1-4. It is connected by a three way valve shown in the plasticizing position. As the stuffed plunger reciprocates,
plasticized material is forced in front of the injection plunger. The injection plunger moves back a predetermined distance until it hits a limit switch (not shown) which stops the preplasticizer. At the appropriate time the rotary valve is turned, and the injection plunger comes forward, filling the mold.

A two stage plunger machine will almost always give better results than a single stage one. A superior way to plasticize is to use a screw. There is no advantage in using a plunger as a preplasticizer. For this reason, the plunger-plunger type of machine is no longer being manufactured. Many plants have converted plunger preplasticizers either to screw plunger machines or to reciprocating screw machines. This is not particularly difficult to do (10).

HEATING CYLINDER AND SCREW CONSTRUCTION AND MAINTENANCE

Heating cylinders of injection molding machines have their internal bore finished either by nitriding or by adding another metallic liner. Cylinders for nitriding are made of a special steel with a high aluminum content and chromium and molybdenum. The steel is first hardened, and the surface must be completely cleared of all traces of decarburization. If this is not done, the nitriding layer will be very brittle and peel off in operation. The cylinder is heated from 930°F to 1200°F in an atmosphere of ammonia. This results in a thin case, approximately 0.020 in deep. This surface has to be finished further, and the final depth of hardness may be considerably less. The hardness of the lining decreases with its depth, thus wear further reduces the surface hardness and accelerates itself.

Corrosion resistance depends primarily on the chromium content of the steel which ranges from 9 to 32% in bimetallic cylinders compared to a maximum of 2% in nitrided cylinders. Field surveys indicate most bimetallic cylinders outlast nitrided cylinders by factor of approximately 3 to 1. Even though they are more expensive, the bimetallic cylinders are recommended for molding equipment.

Bimetallic cylinders are made in two ways. The sleeve can be made separately and shrunk into a prebored barrel. This method allows for higher operating pressures. The second way involves centrifugally casting the molten lining material at speeds to produce up to 75 G. While welding techniques can deposit lining material, they are not used for injection cylinders.

The major lining material used is manufactured by the Xaloy, Inc. Their standard material is used for abrasion resistance and their Xaloy 306® for corrosion resistance. The first is an iron based alloy and the second a nickel cobalt based alloy. They are cast either into a low carbon steel shell, 1020, or an alloy steel shell, 4140. The latter is strongly recommended, because it almost doubles the tangential bore stress. This figure is 51,000 psi for standard Xaloy in a 4140 shell and 38,000 psi for Xaloy 306. The standard lining has a hardness of 60-63 $R_c$ and the 306 a hardness of 48-52 $R_c$. The cylinder bore can be chrome
plated (11). Most screws are made from 4140 steel which are flame hardened and chrome plated. They can also be carburized and nitrided, or have a hard surface material, by spraying of metal. Worn screws can be rebuilt several times (12).

Why Cylinders Breakdown

Major causes for breakdowns of plunger cylinders follow:

1. Fatigue failure, which is primarily caused by thermal shock conditions aggravated by improper starting and stopping procedures.
2. Corrosion from the thermoplastics used.
3. Excessive molding of metal parts, screw drivers, and miscellaneous trash. Steel can be caught by the use of magnets. Other material damages are reduced by good management procedures.
4. Prolonged use of high injection pressure. Two stage injection pressure capability will substantially reduce this cause of failure.

Corrosion

With corrosive materials such as PVC, polycarbonates, and butyrates, the cylinder should be purged if there is to be a prolonged shutdown. Polystyrene is an excellent purging material, as is reground cast acrylic (see Ref. 13 for a list of manufacturers’ recommendations for purging).

Corrosion is a serious problem with certain materials (14, 14a, 14b). Chrome plating and chemically deposited electroless nickel coating minimizes the problem. Molding glass-filled thermoplastics in screw machines has caused considerable wear. It was thought the wear came from erosion at the feed end of the screw. Evidence has shown that wear occurs more in the return valve section at the front of the screw. This wear was probably caused by corrosion from the decomposition of the wetting agent between glass and plastic. The use of large runners and gates reduced the need for higher temperatures which in turn reduced this screw wear.

Cylinder Repair

Cylinders are repaired by disassembling and smoothing out surface imperfections to prevent material hangup. Small cracks can be welded and finished. Leakage from cylinders requires refitting. Occasionally a soft copper gasket will effect a seal.

Screw barrels seem to have less mechanical problems but are subject to considerable corrosion damage. This is due to the molding of corrosive materials which are difficult, if not impossible, to mold in plunger equipment. Wear
caused by the sliding of the nonreturn valve has not been a major problem. *Screws are relatively easy to disassemble and clean. The barrel is best cleaned with a wire brush attached to a long broom handle. Worn barrels can be rebored and the screw size increased to the necessary dimensions* (12).

**Purging and Startup**

By purging we mean the cleaning of one color or type of material from the barrel by forcing this material out with a new color or material. When a machine starts up from cold, enough time should be allowed for the heating cylinder to completely reach molding temperature. Many molders allow a "soak-in" period of 20 min after the pyrometers indicate molding heat. This substantially lowers the stress in the barrel when starting. Purging at start-up should be done under low pressure. In screw machines the pressure is only in front of the tip. When a machine is shut down, it should be purged until no more material comes out. The plunger should be left in the forward position.

**CYLINDER NOZZLES**

The nozzle is a tube which provides a mechanical and thermal connection from the hot cylinder to the much colder injection mold with a minimum pressure and thermal loss. There are three types of nozzles:

1. An open channel with no mechanical valve between the cylinder and mold.
2. An internal check valve held closed either by an internal or external spring and opened by the injection pressure of the plastic.
3. A cutoff valve operated by an external source such as a cylinder.

The land length in any nozzle is kept to a minimum consistent with the strength requirements of the nozzle. In nozzle construction (Figure 1-11) a straight hole is bored down the length of the nozzle. This bore is usually about 1/2 in. diameter as this permits quick melting and rapid flow. It is then tapered out to meet the diameter of the hole in the cylinder. Since this measurement is difficult to make, it is better to have the nozzle hole larger than the cylinder hole (if they cannot be perfectly matched) to minimize degradation and hangup. There should also be a small straight section so that if the nozzle is refaced the matching dimension will not change. There is a taper of about 1/2° to permit better sealing on the nozzle seat.

The nozzle need not be in one piece. Very often the tip is made replaceable by screwing it into the nozzle body. This makes replacement and repair considerably less expensive.
Nozzles that extend directly into the surface of a cavity are more properly considered under gating. As a general rule it is desirable to minimize the length of the sprue. The nozzle must be extended as long as possible. Therefore, heating bands have to be used and there must be enough clearance in the central platen area to permit them to extend into the mold.

There are many specialty nozzles such as one with a screen pack to trap small foreign matter that plug hot runner and insulated runner type molds. Reference 15 is an excellent source of information about nozzles.

Nozzles that shut off mechanically are necessary if the screw in a reciprocating machine is rotating while the mold is open. There are two types of self-operating valves both using the same principle. One type has a spring loaded ball-type check valve which is placed internally at the tip of the nozzle. Injection pressure opens the valve and the spring closes it. The disadvantages of this valve are the restriction of flow and the possibility of material hangup.

An antisuck back nozzle is designed to prevent material flowing backwards from the mold into the cylinder. This action, the reverse of the shut-off nozzle, is accomplished by using a ball without a spring which is forced forward while the mold is under pressure. As soon as the pressure is released any suckback or material ejection from the cavity will force the ball back against the seat.

Figure 1-12 shows a needle shut-off nozzle. An external spring forces a bar toward the mold. This bar is attached to a needle-shaped piston which seals off
the front of the nozzle. When injection pressure is applied, it hydraulically forces the needle back (compressing the spring) and permits the material to flow into the mold. When the pressure drops to a value determined by the spring, the bar forces the needle forward sealing off the opening to the mold. The pistons can valve has the disadvantage of possible leakage around the needle.

The third type of seal-off is obtained as the result of an external motion. The simplest and most expensive way is to use a flat faced nozzle and sprue bushing, and move the injection cylinder off center, sealing off the opening. A second method uses the sprue break motion of the machine to move part of the nozzle. This can take the form of a sliding seal in the nozzle or a linkage-operated sliding pin whose axis is perpendicular to the nozzle bore.

The most common method is to move an internal needle or slide valve by an hydraulic cylinder through linkages. It is preferable to operate the cylinders pneumatically, as a broken hydraulic hose in this area constitutes a fire hazard. As with all devices sealing off through molten plastic, wear and subsequent contamination can be a problem.

Nylon molding presents special problems in drooling. DuPont® developed a reverse taper nozzle (Figure 1-13) which, when coupled with enough heat and
good temperature control, gives clean sprue removal. If the temperature is too low, the material will seal in the nozzle, preventing the next shot. If the nozzle is too hot drooling will occur and the part may be damaged. The opening has a 10° taper for 1/8 in. with a 0.010 radius for strength. A 4° taper continues for 3/8 to 1 in. This is the point at which the sprue separates from the nozzle. A 1/8 to 3/16-in. hole extends for 1 to 2 in., ending in a taper which adapts itself to the cylinder bore.

Nozzle Alignment

If the nozzle does not seat correctly into the cylinder, streaking, burning, and black specks will appear. Additionally, material will hang up and possibly corrode the cylinder and nozzle. If the sprue tip is burned or discolored, the probable cause is misalignment or heat control. If a long streak of dirt occurs in the same place, it can be caused by a poorly seated nozzle, a foreign substance in the nozzle, a foreign substance in the barrel, or, least likely, a cracked barrel. Nozzles are kept streamlined to prevent pressure loss and hangup of material and subsequent degradation. Since the nozzle is a conveyor, restriction should be as limited as possible. A simple way to check restriction is to time the ram forward motion when the mold is on cycle. This time should be compared with the ram forward time for the same feed with the machine open, and it should be less than the ram forward time during molding. There is usually a 25 to 50% decrease, but if the time is the same, the nozzle is too restricted or foreign material is obstructing part of the passage. Pressure sensors are available which can be fitted into the nozzle. These are expensive at the moment but are
valuable in automatically controlling the molding cycle.

The opening leading to the mold, "0" dimension (Figure 1-11), comes in increments of 1/32 in. It should be slightly smaller than the opening of the sprue bushing so that the sprue can be pulled. If the hole is misaligned or the seat poor, plastic material can solidify around the 1/2 or 3/4-in. radius and cause the sprue to stick. Misalignment, which is the most frequent cause of nozzle damage can be checked by closing the carriage assembly with a piece of paper between the nozzle and sprue. If the paper is cut on one side misalignment is evident. Another way to check for misalignment is to rub an oil suspension of a blue pigment on the nozzle and close the machine. When the machine is backed away, wherever the nozzle touched the sprue, the pigment will be transferred. Ball swivel-type nozzles are available to compensate. A better solution to misalign-ment is to realign the press.

Control of Nozzle Temperatures

It is impossible to mold correctly without control of the nozzle temperature. If the nozzle is very short, many times the heat conduction from the cylinder will be enough to maintain it at the proper temperature. Usually nozzles are long enough to require external heat. The heating elements should be independently controlled, and never attached to the front heating bands of the cylinder. The cylinder requirements are completely different than those of the nozzle. Overheating the nozzle may burn or degrade the plastic. Underheating may result in a cold nozzle plugging up the cylinder.

Nozzle heating elements can be controlled with a variable transformer or proportional timer. The best way is to insert a thermocouple and use a controlling pyrometer.

The usual way of heating nozzles is with mica resistance heating bands. The life of these units is relatively short since they come in contact with hot plastic or they are mechanically abused. An improvement over the heating band is a tubular heater.

Cartridges inserted into the nozzle are now available and give longer life and up to four times the amount of heat. Hot circulating liquids are also used. This method gives better heat distribution but has the disadvantages and dangers of a circulating hot fluid. Inexpensive recorders are available to record the nozzle temperature. This can be very important in trouble shooting and precision molding. Thermocouples are also available to enter into the melt stream, but are basically used for research.

Lubricant Requirements

A lubricant should be used when screwing in nozzles. Molybdenum-type grease, graphite, silicone, and copper flake lubricants are used; the latter is preferable
because of its high heat and minimum contamination properties.

**SCREW PLASTIFICATION**

The use of a screw for preplasticizing and injecting material for injection molding is not new. A patent was granted in 1927 for a nonintermeshing twin screw extruder which fed directly into the mold. Maximum injection pressure for this type of system is in the order of 3 to 4000 psi. In 1932 a patent was granted for a stationary single screw extruding into a pot perpendicular to the screw. A plunger came down sealing off the screw and forcing the material into the mold. This is essentially the two stage screw pot system of today. In the early 1950s the inline system for preplasticizing was patented and in the middle of that decade the inline screw, as we know it today, became available.

The task of the injection molding screw (Figure 1-14) is to take cold pellets at the hopper end, compact the material in the feed section, degas and plasticize the material in the transition section, and pump it in the metering section.

**Characteristics of the Injection Molding Screw**

In an inline screw the barrel must be strong enough to maintain the full injection pressure. In a two stage screw it need only be as strong as required to maintain the pressure generated by the screw itself, rarely more than 8000 psi. In the

![Figure 1-14 Typical screw used in injection molding.](image)

- $D_B$ = diameter-barrel
- $D_S$ = diameter screw (nominal)
- $17.8^\circ$ = helix angle (one turn per screw diameter)
- $s = 0.250$ = land width
- $h_F = 0.350$ = flight depth (feed)
- $h_M = 0.105$ = flight depth (metering)
- $L = 50$ = overall length
- $\delta = 0.005$ = flight clearance (radial)
- $L/D = 20:1$ = ratio of length to diameter
- $3.3$ = $h_F/h_M$ = compression ratio
- $N = \text{revolutions per minute}$
event of a failure of the connecting valve between the screw and the shooting cylinder during injection, full injection pressure would be transmitted to the extruder. To ensure safety and to prevent damage to the barrel a safety plug is installed which will blow open before dangerous conditions can occur. A pressure transducer with an adjustable electrical contact can be used. The contact is connected with the control circuit so that the machine is automatically stopped when the pressure approaches the danger point. If it is set just below the safety plug setting, replacement, which can take several hours, is eliminated. The diameter of the barrel \((D_B)\), in turn, is determined by the nominal diameter of the screw \((D_S)\).

Screws used in molding machines have a constant pitch. The helix angle \((\theta)\) affects the conveying and the amount of mixing in the channel. Experience has shown that a helix which advances one turn per nominal screw diameter gives excellent results. This corresponds to an angle of 17.8°, which has been universally adopted.

The land width \((S)\) is 10% of the diameter. The radial flight clearance \((\delta)\) is the clearance between the screw flight and the barrel. It is specified considering the following effects:

1. The amount of leakage flow over the flights. This affects the output.
2. The temperature rise in the clearance. The heat is generated in shearing the plastic. The amount of heat generated is related to the screw speed and the nature of the material.
3. The scraping ability of the flights in cleaning the barrel.
4. The eccentricity of the screw and barrel.
5. Manufacturing costs.

For most materials, the radial clearance is the screw diameter times \(2 \times 10^{-3}\). Using a 2 1/2 in. extruder at 72 rpm the output with a 0.0025 radial clearance was 130 lb/hr; with 0.0055 radial clearance was 126 lb/hr; and with 0.0105 radial was 118 lb/hr (16).

The length of the screw \((L)\) is the axial length of the flighted section. An important criterion of a screw design is the ratio of the length over the diameter of the barrel \((L/D)\).

Long screws with a 20:1 \(L/D\) are used. Some of the advantages of a long screw are as follows.

1. The larger the \(L/D\) ratio, the more the shear heat can be uniformly generated in the plastic without degradation. For best performance in the metering section, a uniform melt is needed from the transition section. Because the shear rate is relatively constant over the channel depth, the conversion of mechanical energy to heat by shearing the plastic is distributed evenly through the material.
2. Only one velocity component is directed toward the screw forward direction. Another component causes lateral velocity in the channel which in turn causes circulation. The material near the wall flows to the screw root and back up again. The longer screw introduces a longer flow path resulting in about the same output as a shorter screw but with fewer pressure variations in the melt. The larger the \( L/D \) the more opportunity for mixing and consequently the better homogeneity of the melt.

3. As seen in (equation 1-4) the forward or drag flow is not affected by the length. The pressure flow or resistance to flow (equation 1-6) decreases with the length. The higher the ratio the more closely the pumping section approaches the theoretical output.

4. Larger \( L/D \) ratios have more frictional area. Beyond approximately 24 to 1 the increase does not justify the additional cost and maintenance.

The channel depth is an important specification relating to the output rate and melt quality. Since the feed section of the screw is basically a conveyor, the deeper the channel, the larger the volume between the flights, and the larger the output. However, there are other considerations one should be aware of in selecting the channel depth. In the metering section one such consideration is shear rate.

The shear rate is defined as the surface velocity at the barrel wall divided by the channel depth.

\[
\gamma = \frac{DN}{h}
\]  
\text{(1-3)}

where 
- \( \gamma \) = shear rate
- \( D \) = diameter screw
- \( N \) = rate of screw rotation
- \( h \) = channel depth

All materials have a maximum limiting shear rate, beyond which they degrade. The more heat sensitive they are, the lower the permissible shear rate. It is more desirable to decrease this rate by increasing the channel depth rather than decrease the screw speed. Increasing channel depth increases the undesirable negative output component, called the pressure flow [see (1-6)]. Pressure flow varies with the cube of the channel depth. Deep channels mean relatively poor circulation within the flight, poor mixing, and low thermal diffusivity which in turn result in increased temperature variation and lower homogeneity of the melt. The overall effect of flight depth on output is that the deeper the flight, the more rapid the decrease in output with pressure. A shallow screw, while it has a much lower output, is relatively insensitive to the back pressure setting of the molding machine. The flight depth in the metering section of five different 2 1/2-in. screws \( (L/D \ 20:1) \) designed for different materials are 0.075, 0.085, 0.100, 0.105, and 0.150. For a 3 1/2-in. screw \( (L/D \ 20:1) \) they are 0.095,
0.105, 0.120, 0.130, and 0.200.

The central section of the screw, which is approximately one fourth of the screw length, has the function of compacting the material. When the plastic enters the extruder, it is granular and full of air. When it leaves the extruder, it is a viscous liquid. This means that the volume of the screw channel must decrease somewhere to compensate for the increased density. This is done in the transition or compression section. In a 20:1 \( L/D \) screw it compromises approximately one fourth of the length or five turns. The compression ratio is defined as the volume of a unit length in the feed section divided by the volume of an equivalent length in the metering section. Since injection molding metering screws have a constant pitch the ratio of the channel depths is used, even though it is not precisely correct. For the 2 1/2-in. screw mentioned above the flight depths in the feed sections were 0.350, 0.320, 0.390, 0.350, and 0.420. The compression ratios for those screws were 4.6, 3.1, 3.9, 3.3, and 2.8, respectively. Compression ratios vary from 2 to 5 in screws used for molding. For the 3 1/2-in. screw they were 0.400, 0.350, 0.470, 0.400, and 0.520.

**Screw Conveying — Basic Principle**

If one puts some string in a jar of honey and pulls it out slowly, he sees the honey sticking to the string. Imagine an endless belt of string going through a vertical tube of honey. This tube has seals on the top and bottom, a reservoir on the bottom, and an outlet perpendicular to the tube at the very top. As the string is rotated upward, the friction of the honey on the string would cause an upward flow. The honey would be forced out of the top opening. The reason for the movement is that the honey is sticking to the string and sliding on the walls of the tube. In effect this is a friction pump identical in principle to the extruder, which is also known as an axial flow pump.

The string is now in the shape of a helix. The motion is relative to the barrel wall. Most of the motion using the 17.8° helix angle is in the direction of the barrel axis. The other component gives rise to circulation in the channel and promotes mixing. If the coefficient of friction between the plastic and the screw and the plastic and the barrel were identical, there would be no flow of material and it would just rotate as a plug within the flights of the screw.

To move forward the material must stick more to the barrel than the screw. It is the same principle as tightening a nut and bolt. If the nut is turned without holding the bolt, there is no relative motion. Such motion occurs only when one of the components is held. Obviously the larger the frictional difference between the plastic and the screw and the plastic and the barrel, the higher the output. (This is one reason too, why longer barrels are desirable.) A very useful determination of the effects of friction at different temperatures between steel and low density polyethylene, high density polyethylene, pyropropylene, ABS,
polystyrene, and ionomer resins is found in Ref. 17.

Figure 1-15 shows a graph of the coefficient of friction of polystyrene at different entering stock temperatures. Note the rapid lowering of friction at about 375°F. If the rear zone is overheated the coefficient of friction will be so low that a plug will form and feed will be blocked. On the contrary, the curve of high density polyethylene showed that a high barrel temperature at the feed will promote feeding. If ABS is preheated in drying to 200°F the coefficient of friction will probably cause feeding problems. If it is at 150°F, a broad latitude exists in the barrel temperature.

As more glass fiber and other reinforcements are used in injection molding, the molder will be forced to pay more attention to the feed system. The relationship of screw design, hopper throat and shape, feed hopper design, speed, effective back pressure, and the effect of forced feeding on the single screw extruder are important (see Refs. 18 and 19). Reference 20 evaluates the effect of particle size on molding. It was found that using beads of an average size of 0.004 in. gave better polymer melt, faster flow, and better pressure transmission than the conventional 1/8-in. beads. Some feed systems are now equipped with a variable opening of the hopper throat.

The feed section is located under the hopper and in the rear section of the screw. The flight depth is at its maximum, and the material from the hopper fills the flight of the screw. The feed section has a constant channel depth throughout its entire length. Since the conveying action is caused by the difference in friction between the plastic and the barrel wall and the plastic and the screw, the screw is always more highly polished than the barrel. Normally, the barrel temperature is higher than the screw temperature. Consequently, the material adheres to the barrel as it softens and slip upon the cooler screw. The material is then compacted in the feed section and begins to melt. The majority of the melting occurs in the compression or transition section. In most molding metering screws, the feed section is approximately half the screw length.

**Transition Section**

The transition or compression section where the channel depth is continually decreased completes the compacting and heating of the plastic granules. Here all the remaining air is released as a result of heat supplied by the cylinder heaters and mechanical energy supplied by the rotation of the screw.

Normally a transition zone encompasses approximately 25% of the screw length. When the material leaves the area under the hopper, it only partially fills the screw. After about four turns the material is fully compacted. The material touching the barrel melts by conduction (Figure 1-16). This melt (area 1) is scraped off by the forward or advancing edge of the screw where it starts a circulating pattern (area 2). Area 3 contains pellets which are sufficiently
Figure 1-15 Coefficients of friction for polystyrene (at 70, 150, and 200°F) sliding on steel surfaces (at temperatures ranging from 70 to 550°F). Polystyrene was Dow Chemical Co.'s Styrene 666U. Rapid reduction of friction between polystyrene at room temperature (70°F) and hot steel (over 375°F) can cause slippage on screw (Ref. 17).
warmed so that they stick together and adhere to the circulating melted mass of area 2. At the transitional sections between area 2 and 3 cold pellets are being melted and absorbed into area 2. Area 4 contains cold pellets which are conveyed as solids down the length of the screw.

Two types of heating are occurring. One is the convection of heat from the heater barrel. The second is the conversion of mechanical energy from turning the screw, into heat energy, by shearing the plastic.

It would seem logical that heating the screw would add more energy to the system and increase the output. This has been tried (21a) with significant output increases, lower temperature deviations, and of course, lower screw drive horsepower requirements. Boring the screw for the heater, maintenance, extra control parameter, and connection of the power leads may pose some problems. No field experience has been reported yet.

As more material is melted, area 2 increases until finally at the metering section area 2 completely fills the flights. To keep the plasticizing process going there must be a constant source of cold material in area 4. The longer the plasticizing zone, the more material that can be plasticized in the screw until such time as there is no more cold material. Once the maximum length is reached, where all the unmelted particles have been plasticized when traveling at their maximum speed, a further increase in the screw length will not increase output. The other limiting factor would be reaching the maximum flow rate capacity of the metering section.
Since the same weight of material per unit cross section must flow through the whole length of the extruder, and since the bulk density of the unmelted portion is less than that of the melted portion, the unmelted portion must be moving at a faster rate. Normally this flow rate is larger than can be used by the melting mechanism. However, if irregular pellets are conveyed, agglomerates are formed that temporarily partially block the flow channel of the unmelted particles; screw output will be reduced, and pressure surges will occur. [A series of colored pellets were dropped at small intervals into a stream of clear extruding plastic (21). A series of colored photographs graphically show the flow of unmelted particles in area 4.]

It would seem logical that long (up to 5 diameters) transition sections increase output, reduce air entrapment, and reduce pressure temperature and output variations. This has been confirmed many times as, for example, in the evaluation of screws for nylon (22). The transition section serves as the feed for the metering section. Unless there is a relatively long feed section which is able to fill the metering section at discharge pressures over 1000 to 2000 psi, the efficiency of the pumping action in the metering section will be diminished giving lower output rates.

Surging will arise primarily as a result of excessive pressure development in the feed and transition sections which overdrive the metering section (23).

**Metering Zone**

The metering section of the screw acts as a pump, removing the material plasticized in the transition zone. There are two general theories for extrusion in this area, with the physical reality probably a combination of both. The adiabatic theory assumes that there is no heat conducted into the material or out of the material as it moves through the extruder. The temperature increase of the material is developed by the mechanical working of the material. The heat applied to the barrel only compensates for radiation. The isothermal theory assumes the material temperature to be constant the entire length of the metering section. No heat is applied to it and the barrel heat compensates for radiation. The heat generated by the mechanical working of the material is conducted out through the cylinder walls. The isothermal theory, with certain basic assumptions, have led to useful equations describing the output of the metering section (24). As mentioned later these have been refined so that they can accurately predict extruder performance by a computer program (25). An accuracy of about 85% is obtained using the following simplifying assumptions (26):

1. The material entering the metering zone is fully plasticized.
2. The material is isothermal implying no change in temperature, viscosity, or density.
3. The flow is steady state.
4. The flow is laminar.
5. The flow is Newtonian.
6. The material is incompressible.
7. The screw is of uniform pitch and untapered.
8. The curvature of the channel around the screw flights is ignored. The cross section is considered to be rectangular. The helix is unrolled and laid out flat.
9. The land volume is neglected.
10. The channel width is large, relative to the channel depth, so that the velocity distribution is uniform across the whole width of the channel. The flow can then be treated unidimensionally.
11. The transverse velocity which contributes to mixing rather than pumping is disregarded.
12. The radial gap is negligible.
13. The frictional effects of the side walls of the screw flights are negligible compared to the drag effects on the screw and barrel.

**Screw Output.** The output of the extruder ($Q$) is the result of three different types of flow. The transverse or circulating flow which contributes to mixing is not considered. The drag flow ($Q_d$) is the major component of the flow. It is the forward conveying action caused by the rotation of the screw relative to the cylinder. The layer of melt touching the stationary cylinder does not move very much. The layer adjacent to it is pulled by the screw and moves slightly faster. As we travel from the barrel surface to the screw surface, the speed increases until the layer at the screw root turns at the same speed as the screw. It is called drag flow because of the drag of the barrel surface on the plastic. The path of a particle within the stream is complex and can best be described as a spiral within a spiral.

Intuitively it should make no difference whether the screw rotates or the barrel rotates. For analytical purposes it is sometimes easier to visualize the performance of an extruder if the barrel was assumed to be rotating. This convention has been adopted by most authors.

The pressure flow ($Q_p$) is the component resisting flow in the system. It is sometimes called back flow which is a total misnomer. The material only flows in a forward direction. This has been shown most graphically in Ref. 27.

The output is also reduced by the material flowing between the clearance of the flight and the barrel ($Q_s$). Its influence is relatively small in well maintained extruders and is generally not calculated for injection molding applications. The output of the screw metering section (which is the output of the screw) therefore is:

$$Q = Q_{\text{drag}} - Q_{\text{pressure}} - Q_{\text{slippage}}$$
Drag Flow

\[ Q_{d1} = \frac{\pi^2}{2} D^2 \, N \, h \, \sin \theta \, \cos \theta \]  \hspace{1cm} (1-4)

where  
\begin{align*}
Q_{d1} &= \text{drag flow (in}^3/\text{min)} \\
D &= \text{barrel diameter (in.)} \\
N &= \text{screw speed (rpm)} \\
h &= \text{channel depth (in.)} \\
\theta &= \text{helix angle}
\end{align*}

Good results were obtained with a helix that advances one turn per screw diameter. This angle, \( \theta \), is 17.8\(^\circ\). Converting (1-4) into consistent dimensions

\[ Q_d = 3.1 \, D^2 \, h \, N \, \rho \]  \hspace{1cm} (1-5)

\[ \begin{align*}
Q_d &= \text{output (lb/hr)} \\
\rho &= \text{specific gravity}
\end{align*} \]

Inspecting (1-4) shows that the output is fundamentally a result of the geometry of the screw. It is in effect describing a positive displacement pump. Obviously the density of the material conveyed will be a nondesign factor in the output.

As an example, using a 2 1/2-in. screw with a flight depth \( h = 0.100 \), (1-5) becomes

\[ Q_d = 1.94 \, N \, \rho \]

For polystyrene with \( \rho = 0.92 \) (at 400\(^\circ\)F) and \( N = 100 \) rpm

\[ Q_d = (1.94) \, (0.92) \, (100) = 178 \text{ lb/hr} \]

For polyethylene \( \rho = 0.72 \) (at 400\(^\circ\)F) and \( N = 100 \) rpm

\[ Q_d = (1.94) \, (0.72) \, (100) = 140 \text{ lb/hr} \]

Pressure Flow

\[ Q_{p1} = \frac{\pi D h^3 \, \Delta P \, \sin^2 \theta}{12 \, \eta L} \]  \hspace{1cm} (1-6)

where  
\begin{align*}
Q_{p1} &= \text{output (in}^3/\text{sec)} \\
D &= \text{diameter of screw (in.)} \\
h &= \text{channel depth (in.)} \\
\Delta P &= \text{increase in pressure (psi)} \\
\theta &= \text{helix angle (17.8}\(^\circ\)) \\
\eta &= \text{viscosity (lb-sec/in}^2) \\
L &= \text{length metering section (in.)}
\end{align*}
With the specific gravity, $\rho$

$$Q_p = 3.14 \frac{Dh^3 \Delta P \rho}{\eta L}$$  \hspace{1cm} (1-7) \hspace{1cm} \text{viscosity (lb-sec/in.}^2\text{)}

$$Q_p = 2.2 \times 10^5 \frac{Dh^3 \Delta P \rho}{\eta L}$$  \hspace{1cm} (1-8) \hspace{1cm} \text{viscosity (poises)}

$$Q_p = \text{output (lb/hr)}$$

It must be emphasized again that (1-6) is resistance to flow and does not signify a physical motion toward the rear. In a given extruder, the pressure is highly sensitive to the viscosity. The viscosity range of plastics usable in an extruder is from $10^{-3}$ to $1.0$ lb-sec/in.$^2$. This is about $7 \times 10^3$ to $7 \times 10^6$ times the viscosity of water. The viscosity of water is so low that (1-6) would become very sensitive to pressure. This would make it unsuitable as a water pump. While temperature does not show in any of the output equations the density and particularly the viscosity are highly temperature dependent. The pressure loss ranges from 5 to 10%. It has been assumed that the feed and transition section have a flow rate equal to the metering section. If the flow rate there is less, the metering section will starve. If the flow rate is too high, high pressure will build up at the end of the transition zone and carry forward into the metering section. This may overcome the pressure flow component and even turn it positive. However, the quality of the melt is unacceptable.

For the same screw and materials, using $L = 10$ in., $\Delta P = 500$ psi:

For polystyrene $\eta = 0.02$ lb-sec/in.$^2$ at 1000 sec$^{-1}$

$$Q_p = \frac{(3.14) (2.5) (0.1)^3 (500) (0.92)}{(0.02) (10)} = 18 \text{ lb/hr}$$

$$Q_p = 10\% \text{ loss}$$

For polyethylene $\eta = 0.06$ lb-sec/in.$^2$ at 1000 sec$^{-1}$:

$$Q_p = 4.7 \text{ lb/hr} = 3.4\% \text{ loss}$$

*Leakage Flow*

$$Q_s = \frac{\pi}{10} \frac{D^2 \delta^3 \tan \theta \Delta P}{S \ I \ \eta}$$  \hspace{1cm} (1-9)

where $Q_s = \text{output (in.}^3/\text{sec)}$

$D = \text{screw diameter (in.)}$

$\delta = \text{flight clearance (in.)}$

$\Delta P = \text{pressure drop (psi)}$

$\theta = \text{helix angle (17.8°)}$

$S = \text{flight width (in.)}$
The injection molding machine

\[ L = \text{metering section length (in.)} \]
\[ \eta = \text{viscosity (lb-sec/in.}^2) \]

The slippage over the flights is normally disregarded in calculations. Its significance is that it demonstrates the importance of wear in a screw and permits the engineer to calculate the point at which maintenance is economic.

For a given screw all the constants can be lumped together and the output for the drag and pressure components can be written

\[ Q = \alpha N - \beta \frac{P}{\eta} \]  \hspace{1cm} (1-10)

where alpha and beta represent the respective constants. This shows that the only two variables under the control of the operator are the screw speed and the back pressure. The barrel temperature is also a variable but is controlled by the material temperature, directly related to the screw speed.

Almost all of the literature relates to extrusion which operates continually. Injection molding utilizes the screw for a fixed period of time. Therefore, to reach a given stock temperature, the screw can be run quickly at high speeds or more slowly at lower speeds, with the corresponding change of the barrel temperature. Slower screw speeds will normally give a better melt.

The other independent variable is the back pressure. Higher back pressure increases the homogeneity of the melt and as might be expected lowers the output, by increasing the pressure flow and the slippage. Higher back pressures usually improve the physical properties of the part (28). Problems of dimensional control, shrinkage, warpage, and color dispersion are often helped or eliminated by higher back pressure.

**Flow Patterns in the Screw Flights.** The flow pattern in the screw flights changes with the back pressure. Figure 1-17a shows a simplified schematic drawing of the flow of a particle in the flights with open discharge. The particle is moving in a circulatory motion from flight to flight. In addition it is moving forward along the axial direction of the barrel toward the nozzle. In the blocked flow (Figure 1-17b) there is a similar circulatory motion between the flights, but no forward motion because the open end is closed. Obviously there is the greatest mixing when the flow is blocked. The only time there is a plane of stagnation (0 velocity) is in blocked flow, when both the axial and transverse velocities pass simultaneously through zero at a plane two thirds of the distance up from the channel root. This should not occur in injection molding. The importance of this flow concept is that it shows that the more blocked the flow, the better the mixing in the screw. Changing the outlet orifice is in effect changing the \( \Delta P \) (1-6). The higher the pressure the greater the pressure flow and the lower the output. In injection molding this pressure corresponds to the back pressure setting of the machine. This is the reason that color dispersion is improved and homogeneity increased by raising the back pressure. Often
warpage and shrinkage problems can be overcome in this manner.

Reference 27 is recommended for an excellent analysis of the flow patterns in a single screw extruder. There are photographs which clearly show that under no circumstances does there exist a local velocity directed backwards along the screw axis. Reference 29 has a more detailed mathematical analysis of channel flow.

**Screw Conveying Considerations**

Almost all the early theoretical and experimental work was concerned with the metering section of the screw. Recent work, primarily by Tadmor, Klein, and Marshall has resulted in an understanding and mathematical formulation of the melting or plasticating section of the screw. Combined with further studies of the metering section, a computer program for a mathematical model of screw conveying was developed. The program which corresponds remarkably well with experimental data is being continually updated and can now simulate screw design and plasticating performance without any need for empirical information. In addition the program can produce such information as the effect of screw cooling on the pressure profile, absence of barrel cooling can be simulated, determination of the optimum location for mixing devices, and barrel temperature for maximum rate of melting and the mechanisms of the reciprocating screw. Since understanding screw plasticizing is essential to knowing injection molding, it is strongly urged that Ref. 25, and 30 to 37 be
consulted. Two books by the authors above (38, 39) give further information. The following section mentions some of the points made in Refs. 30-39.

**Melting Mechanisms**

The mechanism for melting is basically described in Refs. 21 and 35. The explanation of the mechanism was developed by putting in different colored particles into the screw, cooling the screw, disassembling, and unraveling the polymer.

Summarizing, the solid pellets are conducted from the hopper. They touch the barrel to form a thin film of melted plastic on the barrel surface. The relative motion of the barrel and screw drag this melt, which is picked up by the leading edge of the advancing flight of the screw. This flushes the polymer down in front of it, forming a pool which circulates. Heat is first conducted from the barrel through the film of plastic attached to it. Heat then enters the plastic by the shearing action, whose energy is derived from the turning of the screw. The width of the melted polymer increases as the width of the solid bed decreases. Melting is complete at the point where the width of the solid bed is zero.

It was found that the mechanism of melting does not immediately start in the first heating zone. One reason is that the barrel temperature there is kept below the melting point of the polymer to prevent plugging of the screw. Also even when the melting point is reached, the initial melt fills up some of the voids between the pellets before circulating. Until the thickness of the melt film on the barrel exceeds the radial clearance of the screw, the chances of circulation are minimal. This delay may continue until the material moves down 10% of the screw length.

The delay can be minimized by keeping the temperature as high as possible in the rear of the extruder, reducing the flight clearance, and preheating the material. Obviously the latter step will decrease the heat required from the screw for melting and give faster melting in the extruder. Care should be taken to prevent feeding problems caused by the temperature effect on the friction of the material to the barrel.

It was observed that the solid bed breaks up at certain points creating a gap which fills up with melted plastic. The external forces operating on the solid bed, such as the operating conditions, geometry, and physical properties of the polymer, create tensions which are larger than its tensile strength. This results in pieces breaking away and flowing into the channel of melted material. The bulk of the solid bed will continue to move ahead until another piece breaks away. This inherent unsteady state or condition is smoothed out in the relatively long transition sections of the screw. It should be noted that melting starts in the so-called feed section and often extends itself well into the metering section. If the screw is run at overcapacity, unmelted particles will appear in the extrudate.

Computer simulations, backed by experimental results, show that the length
of the melting zone is very much affected by the flow rate. Keeping all other variables constant and increasing the flow rate lengthens the melting zone, giving a less homogeneous product or even an incompletely melted polymer. This might logically be expected as the faster the solid bed moves in a given geometry the less time it will have to melt and disappear. Increasing the flow rate also increases the delay in the start of melting because of the time dependence of heat transfer from the barrel to the plastic.

**Output Rate and its Effect on Melt Properties.** Figure 1-18 (32) shows the effect of the output rate on the width of the solid bed. Low density polyethylene was extruded in a 2 1/2-in., 26 L/D extruder at a screw speed of 60 rpm and a barrel temperature of 400°F. Above the graph is a cross section of the extruder channel showing the depth and location of change. The material is fully plasticized when the solid bed width is zero. Curves 1 and 2 have a rate high enough so that unmelted particles appear at the nozzle end. It would appear that the maximum output for molding would be defined by curve 3, while a more homogeneous melt would come from operating the extruder under the conditions of curve 4. The table underneath shows the fraction of total heat required for melting which resulted from the shearing action of the screw. The fraction varies with the location on the barrel. The balance was provided by the barrel. The last column shows the shaft horsepower consumption for melting.

The effect of flow rate on melting is roughly linear. The effect of screw speed is the result of several factors. Keeping all other variables constant, an increase in the screw speed increases the shearing heat proportional to the square of the speed. It increases the cross channel velocity, which increases the rate at which the melt is being moved linearly. Both increase the rate of melting. Increased screw speed also reduces the delay in the start of melting. The first effect can be large enough so that the screw in Figure 1-18 can produce more heat than required by doubling its rpm. Practically, in injection molding, the improved melting rate caused by increased screw speed is counteracted by the reduced melt quality due to increased flow rate.

**Barrel Temperature Effects.** The effect of elevating the barrel temperature is not completely clear. While an increase in barrel temperature increases heat transfer, the increase changes the velocity profile of the interface between the solid bed and the barrel; this tends to reduce the rate of melting. It also tends to reduce the viscosity of the melted film on the barrel wall reducing the heat generated by shearing. Experience has shown that there is an optimum barrel temperature which is determined empirically.

**Effects of Physical Constants.** The effect of the physical constants of the screw such as channel depth, taper, helix angle, and flight clearance are found in Ref. 32. Aside from flight clearance their effect cannot be changed by the molder. As the flight clearance increases because of wear, the length of the screw
Figure 1-18  Effect of throughput on solid bed profile at 60 rpm screw speed and 400°F barrel temperature for low density polyethylene extruded in a 2½-in. single screw plasticating extruder. The attached table shows the effect of throughput on (a) the consumption of shaft-power for melting and (b) on the fraction of total heat required for melting which originates in viscous heat dissipation (Ref. 32).

<table>
<thead>
<tr>
<th>Curve</th>
<th>Output (lb/hr)</th>
<th>Output (kg/hr)</th>
<th>(Heat by viscous dissipation) (Total heat for melting)</th>
<th>Power (hp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190</td>
<td>86.2</td>
<td>0.37–0.58</td>
<td>7.19</td>
</tr>
<tr>
<td>2</td>
<td>160</td>
<td>72.6</td>
<td>0.34–0.63</td>
<td>6.49</td>
</tr>
<tr>
<td>3</td>
<td>130</td>
<td>59</td>
<td>0.33–0.66</td>
<td>5.51</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>45.4</td>
<td>0.36–0.70</td>
<td>4.40</td>
</tr>
<tr>
<td>5</td>
<td>70</td>
<td>31.8</td>
<td>0.38–0.73</td>
<td>3.20</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>18.1</td>
<td>0.40–0.77</td>
<td>1.92</td>
</tr>
</tbody>
</table>

required for melting increases. For example, in extruding low density polyethylene in a 2 1/2-in. screw, a flight clearance of 0.5% of the barrel diameter requires a melting length 1.75 times the length required if there were no flight clearance. If the wear doubles this flight clearance to 1%, an effective length of 2.25 times the no-flight clearance length would be required.
**Peak Pressure.** The maximum pressure developed in an extruder is realized toward the end of the transition section before the metering section. This has been confirmed many times (23, 25, and 40) and particularly in Ref. 33. Curves are given comparing the actual measured pressures and the computer calculated ones. Figure 1-19 shows part of their results using a 2 1/2-in., 26 L/D, 3:1 compression ratio screw, extruding low density polyethylene. The location of the peak pressure does not vary significantly with the screw speed or output. The material starts to melt between 4 1/2 and 6 turns from the feed section. As would be expected, the slower screw speeds plasticize more slowly, with the point at which half the channel is filled with molten plastic being just before the transition zone.

**Temperature.** Temperature fluctuations and temperature profiles in the extruder have been accurately measured (25). Figure 1-20 shows the temperature profile for a screw similar to the one of Figure 1-18. Polyethylene was extruded at 375°F against a head pressure of 1230 psi. The top curve shows the barrel temperature, and the second the screw temperature. The shaded portion represents the maximum and minimum temperatures, with the line in between them the time-average temperature. Temperature fluctuations were

---

**Figure 1-19** Barrel pressures for extrusion of LD - PE, with start of melting and point where channel is half full of melted polymer (Ref. 33).
wide in the compression and metering zones, but rapidly diminished at the output end. When the screw was changed by tripling the metering length and correspondingly reducing the channel depth to 0.107, the profile changed radically. The longer, shallower, metering zone gave a very high back pressure, 6905 psi. The material was fully melted at the metering zone and gave a relatively uniform temperature. The shear heat developed caused the screw to rise 30° above the barrel temperature.

There is a relatively large amount of literature analyzing the single screw, which relates to theoretical considerations, experimental measurements, and the effect of the screw geometry and operating conditions on molding, and covers temperature profiles, pressure profiles, torque, and horsepower requirements. This literature is in addition to the previously mentioned references. A selected group are found in Refs. 41 to 49.

**Twin Screws.** Because of the heat sensitivity of some materials as well as
more precise production control requirements, there is renewed interest in low-shear screws for extruders and possibly for injection molding. Twin screws were used in reciprocating machines in the early 1960s, but they eventually gave way to the easier-to-make, more understandable, and less costly single screw.

The twin screw extruder with intermeshing screws rotating in the same direction is fundamentally a positive displacement pump. The material is transferred from screw to screw with relatively little mechanical energy converted into heat by shearing. Heat is supplied by the barrel. The output is controlled by controlling the amount of feed into the screw, which is always less than the capacity of the system. Because propulsion is almost entirely independent of friction and viscosity, the output, pressure, and material temperature are independent of the screw’s speed. Since screw speed determine shear rate, shear sensitive material such as PVC, can be extruded most successfully, without reducing the output. By contrast, a single screw might have to be operated at reduced speed because of excess shear heat and in so doing output is significantly decreased. The desired output and pressure in a twin screw would be determined by the amount of feed. Some of the disadvantages of the twin screw follow:

1. Difficulty of controlling the feed.
2. The necessity of completely purging the machine before shutdown so that the extruder can be started up without a long wait for the heat to soak through the steel into the plastic.
3. The complicated design of the transitional area from the end of the twin screws to the circular exit at the nozzle.
4. The biggest historical disadvantages of the twin screw assembly is the difficulty in designing adequate thrust-bearing assemblies because of the limitations imposed by the screws being close together. This problem which is more evident in the reciprocating screws than in two stage machines is becoming less critical with experience in twin screw design.
5. The cost of a twin screw machine is almost double that of a single screw.

Notwithstanding, the use of twin screws intermeshing and rotating in the same direction for injection molding machines will probably increase somewhat in the future. References 50, 51, 51a and 52 contain engineering analyses and comparisons of the two types of extruders.

RECIROCATING SCREW TIP ASSEMBLIES

The reciprocating screw machine uses the screw as a plunger. As the plunger comes forward the material could flow past the screw head and back into the flights. For more viscous materials, such as PVC, a plain tapered tip (Figure 1-21) on the front of the screw is sufficient to permit the screw to act as a
plunger. The rapid forward motion of the plunger does not let too much material leak back. Moreover, the plain tip is also good for molding heat sensitive material such as PVC, because this type of screw front provides the least opportunity for hangup and material degradation.

The less viscous materials require a check valve to prevent back flow over the screw tip. Screw tips, in either case, are a source of frictional heat, material hangups, intermittent malfunctioning, and high maintenance costs. The only way to eliminate them is to convert the machine into a two stage screw-pot, a situation which has other problems. Different valve types are listed below:

1. The ring type nonreturn valve. This valve (Figure 1-22) is a three part assembly. The check ring and seat are slipped on the main body which contains the tip. The assembly is then screwed into the reciprocating screw. The sliding ring fits snugly in the barrel. When the screw rotates the force of the plastic pushes the ring toward the nozzle end and permits the plasticized material to flow under it through flutes or grooves on the main assembly. The screw slides back until the amount of material necessary for the shot is plasticized. On the forward or injection stroke, the ring slides toward the seat and seals the rear of the screw from the front, so that material cannot leak by as the plunger comes forward.

If the fit of the ring is too tight it will cause excessive barrel wear. It will also increase the resistance of the screw to retraction, which is equivalent to raising the back pressure. This may not be desirable as extra stress is put on the threaded stud. A ring that is too loose allows excess leakage, and because of the high shear rate, degradation of the plastic. Plastics are not lubricants, which compounds the fitting problem. The abrasive action of some fillers accelerates wear in this type valve. Additionally, tramp metal can lodge between the seat
and the ring preventing seal off. It may be flushed through later but can leave a dent. When there is decomposition of the plastic in this area the trapped gas may etch the valve seat.

Wear on the ring can cause the ring to cock, resulting in severe erosion of the barrel. Wear also increases the pressure loss which increases the variation in shot size with all its resulting difficulties. If the ring valve does not close immediately, part of the material will flow back over the flights causing the screw to turn during injection. In any type of check valve, such rotation means the valve is not seating properly.

2. **Ball shutoff valve.** Some of the limitations of a sliding ring type shutoff are overcome with a ball shutoff, Figure 1-23. Such a valve should be guided so that it is not affected by gravity or centrifugal forces. It should have a short stroke and enough passage area so that the plasticized material can move without generating excessive frictional heat. It is advantageous to have a one piece design with a removable pin for ease of maintenance. Two piece units welded together are difficult to maintain and may cause problems at the joint. Ball-type nonreturn valves are easy to maintain, usually requiring only a relapping of the seat and a new ball. Their design is inherently more streamline than the sliding ring type. An excellent analysis of both types is found in Ref. 53.

3. **Other shutoff valves.** Neither shutoff valves are completely satisfactory, and new valves are being developed (54). One of the most interesting uses a body
Figure 1-23  Ball type none return valve for reciprocating screws in its plasticizing position.

which has a hole drilled in it at right angles to the screw. A large hole is drilled from the nozzle end and through the body to meet this hole. On the nozzle side of the body is a round disk covering this hole and floating on two stripper bolts. When the material is being plasticized its force coming out of the hole separates the disk from the body. When the plunger comes forward, the disk is forced back covering the hole. One of the advantages of this type of valve, aside from its low cost, is its ability to pass large pieces of foreign material without damage. It can be readily converted into a normally closed type of valve by putting springs on the stripper pins. A review of European nonreturn valves is found in Ref. 55.

SCREW DRIVES

One method of applying the driving force to the screw is to attach it to an electric motor through a speed-reducing, gear train with different speed ranges (56). A second method is to connect the screw to a nonvariable speed-reducing coupling which is driven by an hydraulic motor.

The Hydraulic Motor

The hydraulic motor is driven by an hydraulic pump (57, 58). Hydraulic motors
and pumps have either fixed or variable displacements. Fixed displacement pumps and motors are used for screw drives and have a constant torque output therefore, their horsepower varies with speed. This combination is the least expensive and simplest form of hyrdostatic transmissions. The maximum torque depends on the pressure setting of the controlling relief valve. Their running torque depends on the load imposed by the screw.

One of the outstanding features of the hydraulic system is the stepless control function. This characteristic is very important because of the importance of precise control over screw speed. Precise control is important because melt temperature and the time required to plasticize a given shot weight vary with screw speed. On the one hand, high screw speed is desirable, and on the other hand, slower screw rotation produces a more uniform melt temperature and degrades the material less. Good balance and control are more easily obtained with a stepless system.

Thus for many reasons it is desirable to plastify at the lowest possible screw speeds. The drive must supply enough torque to accomplish this, but not enough to mechanically break the screw. Changes in torque are needed because of the different processing characteristics of plastics (much higher torque is required to plasticize polycarbonate than polystyrene). It is desirable to have two torque-speed ranges for handling the different materials. If a material is being molded with a minimum torque, at a given speed, increasing the speed will increase the horsepower requirements.

The highest torque requirement is needed at the start of the rotation. This is primarily due to the inertia of the plastic material, that is, the viscosity. In addition, there is the inertial mass of the screw, coupling gears, and drive system. As the screw turns, the material is heated and the viscosity decreases, reducing the torque requirements.

Combinations of variable displacement pumps and motors will give different torque, horsepower, and speed operating characteristics. And the new high torque, low speed hydraulic motors, allow the elimination of the speed reducing unit found in many hydraulic systems.

The availability of high torque at low speeds by the electrical drive system is very useful in molding viscous materials. This can be achieved in hydraulic systems by having one pair of the gears in the speed reducing unit reversible. Another method is to use two motors attached to the same screw drive mechanism. They can be operated singly or together. When one motor operates it runs at full speed and lower torque. When both are used they share the available supply and run at half speed. This doubles the torque at the same horsepower input. For more on hydraulic drives, see Chapter 6.

**The Electric Motor**

The available torque of an electric motor drive is similar to the pattern described
above. An overload factor as high as 100% is available. An hydraulic drive, on the contrary, builds up its starting torque slowly and never can exceed its maximum operating torque. The maximum torque of the hydraulic system must be at least as large as the peak torque required to start turning the screw.

Thus a smaller electric motor can be specified for an electric drive as against an hydraulically driven screw of equal starting torque capacities. This, coupled with the higher efficiency of the electrical drive, results in significant operating economies.

This effect can be a mixed blessing. Suppose during operations that a heater band failed, or the pyrometer was set too low, or start-up was attempted at too low a temperature. Under these conditions, the availability of 100% torque overload may be excessive for the screw. At the worst, this could break the screw. There are a number of safety devices of varying degrees of effectiveness. None of these devices have the reliability and ease of operation of the pressure relief valve in an hydraulic drive system. This valve will limit the torque (which is controlled by the pressure supplied to the motor) to a safe value. Oil is by-passed through this valve to tank and the stalled screw and hydraulic motor will suffer no damage.

Electric drives do not have independent speed and torque controls. The speed is changed by gear trains. Since the input and output power is constant, the change in either speed or torque will inversely affect each other. This restricts finding the optimum molding conditions. The hydraulic system, on the other hand, has stepless speed control of the screw. It would be difficult to overstress this difference.

The rotating screw pushes the material in front of it, forcing the screw and injection carriage to the rear. The electric motor weighs considerably more than an hydraulic motor for comparable output. Therefore, the hydraulic system results in considerably lower back pressure at the “zero” setting of the back pressure valve.

Screws can be driven by special low-torque hydraulic motors which are either mounted outside directly on the screw or internally (Figure 1-6:27). A direct drive to the screw has no gears, speed reducers, thrust bearings, and develops minimum noise and vibration. No lubrication is required and maintenance is at a minimum. If the motor is inside the cylinder the maintenance is even less, but more difficult when it occurs.

**Drive Characteristics and Speed Reducers**

The majority of screws are driven by electric motors or hydraulic motors through a gear type speed reducer. Speed reducers are rated on a constant torque basis. One must be careful in selecting speed reducers. A speed reducer rated at 50 hp at 200 rpm, is good for only 12½ hp at 50 rpm. A speed reducer attached to an electric motor should not have a capacity larger than the strength of the
screw. It is much less expensive to strip gears than break screws. Of course, a properly designed and operated system will do neither. Hydraulic motors, if properly sized, cannot break the screw. Table 1-1 compares some of the important characteristics of the hydraulic and electric drives for injection molding screws.

**Torque.** The work done in a screw (melting the material) is done by rotating a screw in a stationary barrel. Under appropriate conditions, the polymer molecules slide over each other (shearing) creating heat. A second source of heat, but of much lower magnitude, occurs when the molecular chain is broken. The rotational force is called torque. It is the product of the

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Hydraulic</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>Low 60-75%</td>
<td>High 95%</td>
</tr>
<tr>
<td>Screw safety</td>
<td>Relief valve will prevent screw damage.</td>
<td>Overload protection difficult, particularly with small diameter screws.</td>
</tr>
<tr>
<td>Torque</td>
<td>Constant output. Infinitely adjustable. Must have maximum torque requirements built into the system even though it might be used only at startup.</td>
<td>Varies with screw speed. Excellent starting characteristics and at low screw speeds.</td>
</tr>
<tr>
<td>Speed</td>
<td>Stepless control easily adjusted. Gives best control of molding conditions</td>
<td>Limited number of speeds. More difficult to adjust and maintain.</td>
</tr>
<tr>
<td>Melt quality</td>
<td>Best</td>
<td>Acceptable</td>
</tr>
</tbody>
</table>
tangential force and the distance from the center of the rotating member. For example, if a 1 lb weight is placed at the end of a 1 ft bar attached to the center of the screw, the torque would be 1 ft × 1 lb or 1 ft-lb. Torque is related to horsepower:

\[
hp = \frac{\text{torque (ft-lb)} \times \text{rpm}}{5252}
\]

(1-11)

\[
hp = \frac{\text{torque (in.-lb)} \times \text{rpm}}{63,024}
\]

(1-12)

It is clear that the torque output of an electric motor of given horsepower will depend on its speed. A 30-hp motor will have the following torque at different speeds.

<table>
<thead>
<tr>
<th>rpm</th>
<th>Torque (ft-lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>87 1/2</td>
</tr>
<tr>
<td>1200</td>
<td>133</td>
</tr>
<tr>
<td>900</td>
<td>175</td>
</tr>
</tbody>
</table>

The speed of a given horsepower motor is built into that motor. Obviously, the higher torque unit (lower speed) motor will have a larger frame than the lower torque unit. The change in speed and torque can also be accomplished by changing the output speed of the motor by using a gear train. The change in torque will vary inversely with the speed.

**Screw Strength and Speed.** The strength of the screw limits the input horsepower. As input horsepower is increased, a point will be reached where the torque that can be provided will be above the yield strength of the metal screw. The strength of the screw varies with the cube of the root diameter.

Overpowering the screw will either degrade the plastic at excess speeds or shear off the screw at too low speeds. For a given horsepower, the slower the speed the higher the torque as shown in (1-11). For a 2 1/2 In. screw at 200 rpm the maximum permissible drive input is about 40 hp. For a 3 1/2 In. screw at 200 rpm it is 120 hp, and for a 4 1/2 In. screw at 150 rpm it is 180 hp. Table 1-2 shows the maximum horsepower per screw diameter that should be used on injection molding machines.

The shear rate, (1-3) is directly dependent upon the screw speed. Excess shear rate will degrade the material. The shear rate is highest near the barrel wall. The maximum surface speed with present screw technology is about 150 ft/min. Some of the more shear sensitive materials limit the surface speed to 100 ft/min.
Table 1-2

<table>
<thead>
<tr>
<th>Screw in.</th>
<th>Diameter mm</th>
<th>Max. hp for Injection Molding</th>
<th>rpm for 100 ft/min (30.5 ms/min)</th>
<th>rpm for 150 ft/min (46 ms/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 3/4</td>
<td>44.5</td>
<td>7 1/2</td>
<td>220</td>
<td>330</td>
</tr>
<tr>
<td>2</td>
<td>50.8</td>
<td>15</td>
<td>190</td>
<td>290</td>
</tr>
<tr>
<td>2 1/2</td>
<td>63.5</td>
<td>40</td>
<td>155</td>
<td>230</td>
</tr>
<tr>
<td>3 1/2</td>
<td>88.9</td>
<td>75</td>
<td>110</td>
<td>165</td>
</tr>
<tr>
<td>4 1/2</td>
<td>114.3</td>
<td>150</td>
<td>85</td>
<td>130</td>
</tr>
<tr>
<td>6</td>
<td>152.4</td>
<td>200</td>
<td>65</td>
<td>95</td>
</tr>
</tbody>
</table>

**Screw Temperature.** The temperature increase of the material caused by shearing action is

\[ \Delta T = \frac{\pi D N \eta}{C h} \]  

(1-13)

where  
\( \Delta T \) = temperature increase of material  
\( D \) = diameter of screw  
\( N \) = rate of screw rotation  
\( C \) = specific heat of plastic  
\( h \) = screw channel depth  
\( \eta \) = non-Newtonian viscosity.

This relationship is not easy to use quantitatively because of the difficulty in accurately determining viscosity but is of value in explaining the parameters that affect \( \Delta T \) because of the following reasons:

1. The viscosity of polymeric materials is very sensitive to the rate of shear (discussed later). The shear rate is also dependent upon the rate of screw rotation, Eq. 1-3.
2. The viscosity is temperature dependent.
3. The mathematics are further complicated by the lack of knowledge of the mixing patterns in the channel.
4. Lastly, this equation only measures the frictional energy and not the heat received from the barrel.

Nonetheless, increasing speed of screw rotation increases temperature if everything else remains constant in an extruder. In a molding machine, the screw output is not continuous and the temperature rise is influenced by screw speed and also time of screw turning. Using a 1 3/4 in screw to injection mold a 0.96 density, 3.9 MI, polyethylene bowl weighing 130 g the following results were obtained (28):
In going from 24.5 to 66 rpm the required time of screw rotation falls in approximately that proportion. Going to 129 rpm reduces the time of screw rotation but nowhere near the extent expected. Among the reasons for this is the small time to receive conducted heat from the barrel.

**Horsepower Requirements.** If the back pressure is increased to 5100 psi, the time required increases from 14 to 38 sec at 66 rpm, and 10 to 20 sec at 129 rpm. The increased energy needed to raise the pressure came from the extra time of screw rotation.

The work done in screw plasticizing raises the temperature of the material to the molding temperature. The total energy required to do this would be the product of the specific heat, temperature change, and output. The screw also acts like a pump and the energy required for pumping is the product of the increase in pressure and the output. This can be expressed as follows:

\[
Z = C (T_P - T_f) Q + \Delta P Q
\]

where

\[
\begin{align*}
Z & = \text{power} \\
C & = \text{average specific heat} \ (\text{Btu/lb, } ^\circ\text{F}) \\
T_P & = \text{temperature plasticized material} \ (^\circ\text{F}) \\
T_f & = \text{temperature feed material} \ (^\circ\text{F}) \\
\dot{Q} & = \text{through-put} \ (\text{lb/hr}) \\
\Delta P & = \text{back pressure} \ (\text{psi})
\end{align*}
\]

If we disregard the energy required for pumping (\(\Delta P \times \dot{Q}\)), use a 30% loss factor for efficiency and heat provided from the barrel, and convert the expression into consistent units (1.15) becomes a good approximation of the amount of shaft horsepower required for a given output.

\[
hp = C (T_P - T_f) Q
\]

\[
= 0.00056 C (T_P - T_f) Q
\]

For example, high impact polystyrene has an average specific heat of 0.42.
How much horsepower is required to plasticize 1 lb/hr \((Q = 1)\) when the room temperature is \(70^\circ\text{F}\)?

\[
hp = (0.00056) \times (0.42) \times (400 - 70) \times 1 = 0.078 \text{ hp}
\]

This is equivalent to 13 lb/hr for each horsepower input.

Molding materials range from 6 to 14 lb/hr for each horsepower input.

The enthalpy is the same as the product of the average specific heat and temperature rise. Enthalpy tables for plastic are available (59), (1-15) might also be written as

\[
hp = 0.00056 \times (hp - H_f) \times Q \tag{1-16}
\]

\[
h_p = \text{enthalpy of plasticized material}
\]

\[
h_f = \text{enthalpy of feed material}
\]

\[
Q = \text{output (lb/hr)}
\]

For the previous example the enthalpies are 150 and 15, respectively; thus,

\[
h_p = (0.00056) \times (150 - 15) \times 1 = 0.076 \text{ hp} = 13 \text{ lb/hr}
\]

Using a 30-hp motor at a room temperature of \(80^\circ\text{F}\), what is the maximum output of low density polyethylene \((C = 0.8)\) at \(380^\circ\text{F}\)?

\[
30 = (0.00056) \times (0.8) \times (380 - 80) \times Q
\]

\[
Q = 223 \text{ lb/hr}
\]

Supposing the material temperature were raised to \(450^\circ\text{F}\). Would the output increase?

\[
30 = (0.00056) \times (0.8) \times (450 - 80) \times Q
\]

\[
Q = 181 \text{ lb/hr}
\]

Thus raising the material temperature lowers the maximum output. The molder therefore molds at the lowest possible melt temperature. This gives maximum screw output and reduces the time needed for reversing the process, that is, polymer cooling in the mold.

It is interesting to note that the output of the machine as defined in (1-14) is completely independent of the screw diameter. If, for example, a 2 1/2 In. and 3 1/2 In. screw, each having the same \(L/D\) ratio and the same input drive horsepower, were operated at the maximum capacity of the input drive, they will both deliver the same output (lb/hr). The plastic will remain longer in the 3 1/2 In. screw. Why then have large screws? The answer is found in (1-3), (1-11), and Table 1-2. Screw speeds must be kept low to prevent degradation. With a constant horsepower, the slower speeds can develop a torque high enough to shear the screw. Therefore, the higher horsepower required for higher output needs larger diameter screws to prevent screw breakage.

Thus it is obvious that in a screw machine, the horsepower rating available for screw rotation is a very important specification. Assuming similar efficiency for
different screw designs, the maximum output, which is a primary concern of injection molders, is largely determined by the horsepower rating of the screw. With this criteria, analyzing machine specifications of different manufacturers becomes more productive and interesting.

Finally, the amount of power consumed in shearing per unit screw length equal to one turn of a flight is

\[
Z = \pi^3 D^4 \frac{L}{h} \left( \frac{S}{\delta} \eta_L \right)^N
\]

(1-17)

where

- \( Z \) = power
- \( D \) = diameter
- \( L \) = lead (pitch length)
- \( h \) = channel depth
- \( S \) = flight land width
- \( N \) = screw speed
- \( \eta_C \) = viscosity in channel
- \( \pi_L \) = viscosity at land clearance
- \( \delta \) = clearance between flight and barrel

Again, since the viscosities are difficult to obtain, the purpose of the equation is to show the factors which affect power output.

**Advantages of Screw Plasticizing.** In a screw, the melting of the plastic is caused by the shearing action on the polymer between the barrel and root of the screw. As the polymer molecules slide over each other they convert the mechanical energy of the screw drive into heat energy. The heat is applied directly to the material. This process and the mixing action of the screw contribute to its major advantages as a plasticizing method. These advantages follow:

1. High shearing rates are obtained. As we see later these high rates lower the viscosity of the melt making the material flow easier.
2. Good mixing is developed resulting in an homogeneous melt. This usually means lower injection and hence clamp pressures.
3. Flow is nonlaminar.
4. Residence time in the cylinder is much less than in a plunger machine.
5. Most of the heat is supplied directly to the material.
6. Since relatively little heat is supplied from the heating bands compared to a plunger machine the cycle can be delayed for a longer period before purging, since the screw is not turning and little heat is being generated.
7. The action of the screw reduces chances of material hold-up and subsequent degradation.
8. Machine can be used with heat sensitive materials, such as PVC.
9. The screw is easier to clean than the plunger.
10. The screw is easier to purge than the plunger.

There is considerable literature comparing screw preplasticizing with plunger plasticizing and describing the operation of the in-line screw (60-63).

The reciprocating screw is the most popular injection end in the United States.

In the reciprocating machine, the material is fed from the hopper, plasticized in the screw, and forced past the one-way valve (if there is one) at the injection end of the screw. The material accumulates in front of the screw, forcing back the screw, the screw drive, and the motor. When the screw reaches a position, determined by the amount of feed required, a limit switch is contacted stopping the screw rotation. This happens while the previous shot cools in the mold. After that shot has been ejected and the mold closed, hydraulic injection cylinders bring the screw assembly forward and use the screw as an injection ram. The advantages of an in-line screw have been amply reported in the literature. Some of the advantages and disadvantages of the in-line screw can be deduced from the discussion of a screw-pot machine.

**Screw-Pot (Screw Plunger).** A screw-pot injection end is shown in Figure 1-9. It is essentially similar to the plunger-plunger machine (Figure 1-8) except that a fixed screw is used for plasticizing. The fixed screw need not be mounted vertically above the machine. It can be mounted at an angle or next to it on the same level. A ball type check valve is usually used between the screw and the front of the shooting cylinder.

A reciprocating screw could be used in place of a fixed screw. This permits continual operation of the screw throughout the whole cycle. It is primarily used in rapid cycling machines. For most applications it is less expensive to use larger cylinders and motors.

The screw pot and the reciprocating screw are both preplasticizing systems. Conceptually the difference is limited to the location of the pot which is in front of the reciprocating screw and a separate cylinder in the two stage machine. Although most machines sold today are of the reciprocating type, many molders have found significant advantages in screw-pot equipment. Some of them follow:

1. Because the screw does not act as the injection ram, lighter bearings can be used. There is no need for the heavy thrust assemblies found on reciprocating screws. Higher thrust assemblies could mean reduced maintenance costs.
2. The extruder barrel need only be strong enough to maintain the pressure of the material during plastification which is rarely over 10,000 psi. In contrast, the barrel for the reciprocating screw must contain the 20,000 psi used for injection.
3. There is less wear because the screw does not move.
4. A simple ball check valve can be used as the connection between the two stages. This is a trouble free and easy to maintain system. Furthermore, it
presents minimum flow resistance. The nonreturn valve at the tip of a reciprocating screw wears; sometimes it does not seat properly (preventing consistent molding), or sometimes causes wear in the barrel. In this valve material may hang up and degrade; it is also much more expensive than a ball check valve.

5. The connection between the two stages result in better mixing of the melt.

6. A very important advantage of a two-stage machine is that all the material goes over the full flights of the screw, receiving the same heat history. In a reciprocating screw only the first material in goes over the full length of the screw.

7. In a two stage machine, the screw pumps only against the injection ram which is floating in oil in the hydraulic cylinder. The reciprocating screw must push back the whole weight of the carriage and all the equipment on it. For this reason the shot size control is usually considerably more accurate in the two stage machine.

8. Extremely high injection pressures are available.

9. The size of a pot in front of a reciprocating screw is limited by the length of the feed stroke. If the screw goes too far back the material will not plasticize correctly. In a two stage machine there is no theoretical limitation. Thus a 2-in. reciprocating screw normally has a maximum shooting capacity of 13 oz while the same diameter screw can be readily designed to shoot 60 oz in a two stage machine.

There are a number of disadvantages of the two stage machine:

1. It requires two cylinders and two sets of heat controls.
2. It is slightly more difficult to clean.
3. It is slightly more difficult to set up.
4. It does not process high heat sensitive materials as well as a reciprocating screw.
5. Cylinders for molding thermosets and rubber are designed only for reciprocating screws.
6. It takes up more space than a reciprocating screw.

**Injection End Specifications**

A number of specifications for the injection end of the molding machine are common to all plasticizing equipment. The *injection capacity* (in.\(^3\)) is the maximum volume of material that can be injected in one shot. It is a measure of the geometry of the cylinder, plunger, and plunger stroke. It is sometimes given in ounces of polystyrene. To convert cubic inches to ounces of 1.00 density material multiply by 0.578. Multiplying by the density of the material in question will give the injection capacity in ounces of that material. For example,
polystyrene with a density of 1.06 is equivalent to 0.61 oz/in.$^3$ (0.578 x 1.06). This is a major machine specification. A 16-oz machine means that it will inject 16 oz (usually with polystyrene) per shot.

The injection rate (in.$^3$/min; oz/min) is the maximum rate at which the injection cylinder can eject fully plasticized material into the air, on a single shot basis. This is somewhat different than the speed achieved during molding which may be limited by the resistance to flow of the mold. The availability of a high injection rate is desirable since you can always adjust for lower rates if need be, but it is good to have the high rates when necessary. Injection rate should not be confused with the plasticizing capacity of the system, which is an indication of the maximum amount of moldable material produced in a given time.

An important quality of the machine is the amount of pressure that is placed directly upon the plasticized material. This injection pressure is easy to determine in a two stage machine or an in-line screw. It depends on the diameter of the screw or plunger, the diameter of the piston of the hydraulic injection cylinder, and the oil pressure. For example, a 2 1/2 in.-diameter reciprocating screw uses two 6-in.-diameter injection cylinders in a 2000-psi hydraulic system. The area of the injection cylinders is $2 \times 28.3 \text{ in.}^2 = 56.6 \text{ in.}^2$. The force on the injection plunger (Eq. 1-18) is $56 \text{ in.}^2 \times 2000 \text{ psi} = 113,200 \text{ lb}$. This is applied by the 2 1/2-in.-diameter (4.91 in.$^2$) screw upon the plastic material. The pressure applied on the material is $113,200/4.91 \approx 23,000$ psi.

In a straight plunger machine, the injection pressure on the material is usually given based upon the same factors. This is erroneous as there is at least a 30% pressure loss on the material from the feed end to the nozzle. A minimum pressure on the material of 20,000 psi should be available on general purpose machines.

**Screw Recovery Rate.** The major specification of the injection end is the screw recovery rate. This tells how many ounces per second are plasticized while the screw is running. The limitations of the manufacturer's specification and interesting data on the effect of screw speed and back pressure are presented in Ref. 66.

Through the efforts of the Injection Molding Professional Activity Group (PAG) of the Society of Plastic Engineers, the Society of the Plastic Industry adopted a standard, as of January 1, 1968 (67). In summary, a thermocouple, placed in the nozzle, is attached to a fast response temperature recorder. The temperature variations shall not exceed $10^\circ\text{F}$. The temperature of extrusion for polystyrene is $420^\circ\text{F}$, polyethylene $460^\circ\text{F}$, and nylon $540^\circ\text{F}$. For a given test, the shot size is 25, 50, 75, and 100% of rated injection capacity. The ejection rate for machines up to 30 oz is 1 1/2 to 2 oz/sec; for 30 to 150 oz, 3 to 4 oz/sec; and for machines over 150 oz 6 to 8 oz/sec. The screw running time is 50% of the total cycle.

When the temperature is stabilized, ten successive shots are taken recording
both their weight and the screw rotating time. The recovery rate is calculated by taking the average weight in ounces of the 10 shots and dividing it by the average screw running time in seconds. Before buying a machine one should ascertain the rating under this standard and make comparisons.

Table 1-3 gives typical injection end specifications for plunger, reciprocating screw, and screw plunger type machines.

<table>
<thead>
<tr>
<th>Injection unit</th>
<th>#1-10 Ounce plunger type 275 ton toggle clamp</th>
<th>#2-28 Ounce 2½” reciprocating screw 375 ton toggle clamp</th>
<th>#3-60 Ounce 3½” screw-plunger type 425 ton hydraulic clamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material injected</td>
<td>oz/shot 10</td>
<td>28.5</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>g/shot 284</td>
<td>809</td>
<td>2130</td>
</tr>
<tr>
<td>Material injected</td>
<td>in.³/shot –</td>
<td>52.6</td>
<td>134.0</td>
</tr>
<tr>
<td></td>
<td>cc/shot –</td>
<td>862.</td>
<td>2196.</td>
</tr>
<tr>
<td>Maximum injection rate</td>
<td>in.³/sec –</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>cc/sec –</td>
<td>246</td>
<td>574</td>
</tr>
<tr>
<td>Plunger displacement</td>
<td>in.³/min 34</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>cc/stroke 557</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Injection ram forward</td>
<td>in./min 360</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>mm/min 9144</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Plunger diameter</td>
<td>in. 2 5/8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>mm 67</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Screw diameter</td>
<td>in. –</td>
<td>2 1/2</td>
<td>3 1/2</td>
</tr>
<tr>
<td></td>
<td>mm –</td>
<td>64</td>
<td>89</td>
</tr>
<tr>
<td>Screw L/D ratio</td>
<td>–</td>
<td>20:1</td>
<td>20:1</td>
</tr>
<tr>
<td>Screw drive</td>
<td>Hydraulic</td>
<td>Hydraulic</td>
<td>–</td>
</tr>
<tr>
<td>Screw speed</td>
<td>rpm –</td>
<td>0-200</td>
<td>0-200</td>
</tr>
<tr>
<td>Injection stroke (maximum)</td>
<td>in. 11</td>
<td>8 1/2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>mm 279</td>
<td>216</td>
<td>–</td>
</tr>
</tbody>
</table>
Table 1-3 (Continued)

<table>
<thead>
<tr>
<th>Injection unit</th>
<th>#1-10 Ounce plunger type 275 ton toggle clamp</th>
<th>#2.28 Ounce 2½” reciprocating screw 375 ton toggle clamp</th>
<th>#3-60 Ounce 3½” screw-plunger type 425 ton hydraulic clamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection pressure on material</td>
<td>psi 20,000 1406</td>
<td>20,000 1406</td>
<td>20,000 1406</td>
</tr>
<tr>
<td></td>
<td>kg/cm²</td>
<td>1406</td>
<td>1406</td>
</tr>
<tr>
<td>Recovery rate</td>
<td>oz/sec –</td>
<td>2.9</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>g/sec –</td>
<td>82.</td>
<td>105.</td>
</tr>
<tr>
<td>Plasticizing capacity (poly-styrene)</td>
<td>lb/hr 120</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>kg/hr 54</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Hopper capacity</td>
<td>lb 150 68</td>
<td>110 50</td>
<td>200 91</td>
</tr>
<tr>
<td></td>
<td>kg</td>
<td>68</td>
<td>50</td>
</tr>
<tr>
<td>Heater load</td>
<td>kW 16</td>
<td>25</td>
<td>32</td>
</tr>
</tbody>
</table>

**Other Injection End Auxiliaries**

Below are some items found on many molding machines, some of which are essential and others helpful.

1. All molding machines should have a tachometer, so that the screw speed can be ascertained.

2. For those machines requiring it, a permanently mounted ladder at the hopper is useful. Plants using blended material can have a material blender which mixes in reinforcements with the plastic mounted directly over the hopper.

3. Some machines ride the injection carriage on chrome plated tie bars instead of on ways.

4. Some machines use rotary joints instead of hoses for connecting the movable carriage to the hydraulic oil supply.

5. The injection rate is a variable which should be controlled by a hydraulic flow control valve.

6. Two injection pressures, with at least 20,000 psi in the material available.
Flow (Intrusion) Molding

In flow molding, the material is extruded directly into the mold until it is filled. In practice, reciprocating machines are converted to flow molding machines by changing the hydraulic and electric circuits. The circuits are changes to allow the screw to come forward after extrusion and apply pressure to pack the material into the mold, as opposed to collecting the material in front of the screw and injecting an exact shot volume.

This technique is primarily used for molding heavy sections. Flow molding effectively extends the capacity of the machine.

Void elimination is the major problem encountered in conventional molding of heavy sections. The walls and the gate freeze too quickly to permit enough material to enter to compensate for shrinkage. In clear lenses, for example, the different densities cause distortion. Flow molding, combined with hot molds, keeps the plastic molten long enough to mold an homogeneous part. The author has molded a 30 1/2 oz large heavy section clear acrylic lens by flow molding using a 2 1/2-in. reciprocating screw on a machine whose normal capacity is 20 oz. The part required an exceptionally slow, controlled injection rate which could not have been done with conventional molding equipment.

Flow molding cannot be used effectively for thin walls. Because of the slow plasticizing rate of in-line screws, the material sets up too quickly to receive the benefit of the injection pressure at the end of the cycle.

Different Ways to Flow Mold. There are three ways of flow molding. The first is to start with the screw in the full forward position. The screw starts to rotate after the mold is closed and fills the mold. It continues extruding, producing a small cushion. Pressure is then applied to the injection ram to apply the final injection pressure.

The second method starts with a full barrel of previously plasticized material. The screw acting as a ram comes forward slowly and when it reaches its full forward point it starts to turn until the mold is filled. Then a small cushion is maintained and the hydraulic pressure is applied to complete the cycle.

The third method is to start with a full barrel and extrude until the point is reached where when the screw comes forward a small cushion will be left.

The last two methods allow for a more rapid filling cycle. In all instances, unless molding heat sensitive materials, the nonreturn valve at the front of the screw is desirable. Flow molding can be used with all materials, including crosslinked polyethylene, and FEP fluorocarbons and polyurethanes.

Other Methods of Melting Polymers

Because of the large volume of plastic manufactured by extruding devices, there is a continuing search for new methods. The plunger machine is in a sense an extruder. It has a number of disadvantages, the most important of which are
discontinuous output, long heating time, and air entrapment. Its advantages are high extrusion pressures which are independent of the temperature, and the low shear level. The disadvantages have been overcome by using two rams and a shuttle valve feeding into two separate reservoirs, each with their plunger (64). At the moment it is primarily a laboratory tool, but has potentials for injection molding.

When a viscos elastic material is introduced between a rotating and stationary disk, the material moves spirally and centripetally, heating up and plasticizing. It is extruded through an opening in the center of the stationary disk. This was first described in 1947 by Weissenberg. The advantages of this elastodynamic pump are its good heat transfer, degassing, mixing, nonpulsing flow, and short residence time. It is also a simple extruder to build. A Belgian machine using this principle appeared on the market in 1968. However, this machine has no commercial significance today.

A combination of the Weissenberg effect and the discovery of a lubrication phenomenon, in which an oil wedge capable of developing high pressures was developed between a journal and its bearing resulted in a hydrodynamic screwless extruder (65, 65a, 65b). The advantages claimed for this extruder are its simplicity, good heat transfer, low residence time, low shear, minimum thermal degradation, uniform pressure, high pressure capability, unlimited size, and rapid adjustments for operating conditions. The use of rapid impact to melt plastic is described in Ref. 74, 74a.

CLAMPING MECHANISMS

The clamping mechanism is a major factor in the cost of a machine and clamping force is a major machine specification (68). The two most common methods of clamping are to use an hydraulically operated toggle system or a fully hydraulic clamp. A toggle is a mechanical device used to amplify force. Figure 1-24 shows a common double acting toggle. The mechanical advantage can be as high as 50:1. In a molding machine it may consist of two bars joined together, end to end, with a pivot. The other end of one bar is attached to a stationary platen and the other end of the second bar to the movable platen. When the mold is open, the toggle is in the shape of a V. When pressure is applied to the pivot the two bars come into a straight line. The force to straighten the toggle is applied by an hydraulic cylinder. In a fully hydraulic system the force is supplied by an hydraulic cylinder alone.

Clamp Force Rating

The clamping force is rated in tons. For a hydraulic mechanism force is related to pressure and area by the following equation:
Figure 1-24 Double toggle clamping system.

\[ F = PA \]  

where \( F \) = force (lb)  
\( P \) = pressure (lb/in.\(^2\)) (psi)  
\( A \) = area (in.\(^2\))

For example, a press with an hydraulic clamp has a 20-in.-diameter clamping cylinder. Assume the maximum working line pressure is 2,000 psi. The clamping force is

\[ F = 2000 \pi (10)^2 = 628,000 \text{ lb} \]
\[ = 314 \text{ tons} \]

This press would be called a 300-ton press. Machines available today range from a 5.5-ton clamp for a machine whose maximum shot is 10 g, to a 5500-ton unit (69) that can mold 54 lb of polystyrene per shot. Machines with 10,000-ton clamps are being built (70).

When the molten plastic is injected into the mold, the pressure generated upon the material by the injection ram is preset by the operator; 20,000 psi is a
common maximum. This is opposed by the clamping force. If there were full pressure transmission through the material, a clamp force of over 10 tons/in.\(^2\) of projected area of molded surface would be needed to prevent the mold from opening. The projected area is the area of molded parts (including runners) parallel to the clamp-platen. Because of the hydraulic action of the machine, and the changes in viscosity and pressure transmission as the plastic cools in the mold, normal production can be conducted with 2 1/2 tons/in.\(^2\) of projected area. It is affected by the material, design of the part, speed of injection, and controls of the machine.

In both hydraulic and toggle systems, an hydraulic cylinder provides the force which causes the clamping action. This force is equally opposed by a stress in the tie rods. The amount of stretch is equal to the product of the load and the length of the rod, divided by the product of the cross sectional area of the rods, and the modulus of elasticity of steel (approximately 30 \(\times 10^6\) psi). A 3-in. tie rod on a 400-ton press will stretch approximately 1/16 in. Amplifying and measuring the deflection will give an accurate reading of the clamping force. This would only be necessary in a toggle machine. Clamping force in hydraulic machines can be read directly from the oil pressure gauge.

**Toggle Clamps**

In the mold open position of double acting toggle in Figure 1-24 the hydraulic actuating cylinder has retracted pulling the cross head close to the tail stock platen. This pulls the moving platen away from the stationary platen and opens the mold. It is difficult to stop the moving platen before the completion of the full stroke. Where this is important, nylon bumpers can be used as a mechanical stop. To close the mold the hydraulic cylinder is extended. The moving platen moves, starts slowly, reaches maximum speed at midstroke, and automatically decelerates as the crosshead extends and straightens out the links. A very small motion of the crosshead develops a large mechanical advantage causing the locking. (If the mechanical advantage were 50:1, a 300-ton press would only require a 6-ton hydraulic locking cylinder.) When the mold opens the full breaking force is developed as it utilizes the same leverage. This might be useful for molding.

There are a number of important advantages in a toggle system:

1. Because a much smaller hydraulic cylinder is required, there is significant economy in the size of the hydraulic equipment and, more important, in its operating cost. The savings are very significant over the life of the machine.

2. The second major advantage is the inherent speed of the design. Fully hydraulic clamps are available that move as fast as 2000 in./min. This is faster than most toggle machines. However, the cost of a fast moving hydraulic unit is considerably higher than the equivalent toggle system.
3. Another advantage of the toggle system is that it can be self-locking if it is designed to go "over center." Once the links have reached their extended position they will remain there until retracted. Most machines are live hydraulic or nonlocking. An hydraulic system requires maintenance of the line pressure at all times (71).

The toggle system used on molding machines has several disadvantages:

1. The toggle system doesn’t provide for any simple positive indication of the clamping force. It is therefore more difficult to adjust and monitor. Therefore the possibility of overclamping and damaging molds is real.

2. The clamping force may not remain constant. As the temperature of the mold and tie bars change, their lengths change, thus affecting the clamping force. In a hydraulic system this is automatically compensated by the compressibility of the oil.

3. It is difficult to control the speeds and force of the toggle mechanism as well as stopping and starting at different points.

4. The toggle system requires much more maintenance than the hydraulic system and is comparatively more susceptible to wear.

**Operating the Toggle Clamp.** To clamp properly the toggles must be fully extended. Therefore, the distance of the tail stock platen has to be changed to accommodate different mold heights. One way to do this is to have a chain which simultaneously moves the four locking nuts on the tail stock platen. A centralized die height adjustment with the addition of a moving back platen can also be used (Figure 1-6:6). The mold height adjustment screw (Figure 1-6:8) is moved by a crank (Figure 1-6:14), and the four tie bar nuts are not changed. The mechanism can be operated manually, electrically, or hydraulically.

Figure 1-6 shows the toggle system of Figure 1-24. The tail stock platen (Figure 1-6:2) is attached to the crosshead links (Figure 1-6:5) whose other ends are attached to the moving back platen (Figure 1-6:6). The hydraulic cylinder (Figure 1-6:1) has its piston (Figure 1-6:3) attached to the crosshead (Figure 1-6:4) which is supported on guide bars (Figure 1-6:13). As the cylinder extends the crosshead moves toward the injection end, forcing the toggles into a straight line and closing the mold. Some machines have four toggles, one on each corner of the platen.

The stroke of the moving platen is limited because the movement of the toggles is limited by the width or height of the platen. This can be overcome by attaching the hydraulic cylinder to the base with a pivot, the cylinder being parallel to the platens (Figure 1-25).

A further variation in the Monotoggle* (Figure 1-26) where the cylinder is attached to the toggles only. This permits longer strokes without loss of leverage.

*Copyrighted and patented (2969818); Improved Machinery, Inc.
The single toggle (Figure 1-25) may be activated mechanically instead of hydraulically. This is done by using a motor with a variable speed pulley attached to a fly wheel. On the fly wheel there is a spiroid pinion which is attached to a spiroid gear. The gear is connected to the toggle mechanism so that the rotation of the gear causes the toggle to extend or retract. The motion of the spiroid gear is controlled with a clutch and brake mechanism.

Hydraulic Clamps

Many of the smaller machines are available with either hydraulic or mechanical clamps. Most of the larger machines have hydraulic clamp systems. Some of the advantages of hydraulic clamping follow:

1. The clamping force is infinitely variable to its maximum.
2. The clamping force can be continually monitored by a pressure gauge on the hydraulic cylinder.
3. The clamping force can be changed at any time with hydraulic controls.

Figure 1-25  Single toggle clamping system.
Monotoggle © system, clamp opened

Figure 1-26 Monotoggle© system, clamp locked (Improved Machinery Inc.).
4. The speed of the ram in either direction can be infinitely varied below its maximum by hydraulic controls.
5. The stroke of the ram can be set by using a limit switch.
6. The machine stroke is not fixed and can be kept at a minimum.
7. The platen accelerates and decelerates smoothly.
8. The clamp can be stopped and started at will. This is useful in cam action and unscrewing molds.
9. Low pressure protection is easier to obtain hydraulically than with a toggle system.
10. The breakaway opening force and speed is adjustable.
11. Mold setup is quick. The stroke is adjusted by setting a limit switch and the pressure by the pressure control valve.
12. Since the moving parts of the hydraulic clamp float in oil, wear and maintenance are at a minimum. With proper care the only maintenance is the replacement of the chevron packing around the ram. By contrast toggles require forced lubrication, continual inspection and eventual replacement of the toggle pins and bushings.

Operating the Hydraulic Clamp. The major disadvantages of an hydraulic system are the higher initial cost, the higher operating costs because of the larger pump and motor, and the increased possibility of oil leakage (72). Most clamping systems use 2000 psi oil supplied from the pump. There are some systems where pressure intensifiers are used for pressures up to 8000 psi, which are held by check valves. Other intensifier systems use their own small pump. They are fed through flanges into the clamping ram to eliminate piping and leaks. Figure 1-27 shows the clamp and piping of a standard molding machine which uses a manifold to minimize interconnected piping. All valves, piping, and motors are readily accessible for adjustment and maintenance.

Hydraulic versus Toggle. Both toggle and hydraulic clamps work well. A comparison of their features, based on equivalent performance (clamp force and speed) is summarized below.

<table>
<thead>
<tr>
<th>Hydraulic</th>
<th>Toggle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Much higher original cost</td>
<td>1. Lower original cost</td>
</tr>
<tr>
<td>2. Higher horsepower needed therefore</td>
<td>2. Lower horsepower needed, more</td>
</tr>
<tr>
<td>more expensive to run</td>
<td>economical to run</td>
</tr>
<tr>
<td>3. Nonpositive clamp</td>
<td>3. Positive clamp</td>
</tr>
<tr>
<td>4. Unlimited stroke potential</td>
<td>4. Limited stroke</td>
</tr>
<tr>
<td>5. Direct readout of clamp force</td>
<td>5. No direct readout</td>
</tr>
<tr>
<td>7. Easy mold setup</td>
<td>7. More involved mold setup</td>
</tr>
</tbody>
</table>
8. Varies stroke to mold height
9. Clamp speed easily controlled or stopped at any point
10. Low maintenance as parts are self lubricated

8. Constant mold stroke
9. Clamp speed more difficult to control and stop
10. Higher maintenance costs

Other Clamp Systems

Neither the hydraulic clamp nor the toggle system were originally designed for molding machines. In the larger sizes it became impossible to reconcile a toggle

Figure 1-27 Clamp-end piping. The simplified piping arrangement employs a manifold to minimize interconnected piping. All valves, piping and motors are readily accessible for adjustment and maintenance. Full-time filtration of the hydraulic oil is provided (Farrel Corp.).
mechanism with the need for high clamp force, long stroke, platen size, and floor space. The simple hydraulic system, with its large power always available (even though not needed until the final clamp), was too costly and cumbersome. A number of systems were developed which overcame these limitations in varying degrees.

1. One of the earliest solutions was the use of a small diameter cylinder to move the clamping ram rapidly until the mold faces touched. This uses a relatively small amount of oil and, with large pumps, will give rapid motion. The main locking force is established by a large diameter cylinder which only need move a short distance. If the small cylinder is bored inside the large cylinder it is called a jack ram (Figure 6-19). If oil had to be pumped behind the large ram, obviously, the benefit of the jack ram would be lost. Instead of pumping, oil is supplied by gravity from the tank above the clamp or by suction if the tank is below the ram. Another way to do it is to have a large hole in the clamping ram. As the jack ram pushes the clamp ram forward the oil flows from front to back through the hole. Near the very end of the stroke a rod inside the clamp housing seals the hole allowing full clamp pressure behind the piston (73).

2. As the clamp capacity became larger and the stroke requirement longer, hydraulic clamps of this size became very expensive and unwieldy. A system was designed for injection molding machines which is commonly called “lock and block” (Figure 1-28). A small high speed rapid traverse cylinder is used to move the movable platen. A spacer which may be a hollow tube or rod is attached to the movable platen. At the end of the stroke of the rapid traverse cylinder the locking mechanism, an hydraulically operated movable plate, is inserted between the spacer and a large diameter short stroke hydraulic cylinder. The large clamp cylinder moves forward approximately an inch to provide the locking force. This type of “lock and block” mechanism requires a mold height adjustment.

All systems of this design, while losing a very slight speed advantage because of the three motions, gain in economy because of smaller hydraulic cylinder sizes, lower power requirements, and no huge toggle links requirement.

One of the disadvantages of this system is its long nonadjustable stroke with a corresponding waste of floor space and long stressed tie bars. To overcome this clamping units have been designed where the moving tailstock platen is not firmly anchored to the tie bars at all times (Figure 1-29). The rapid traverse cylinder moves the moving tailstock platen and clamping plate until the mold closes. The half nuts are closed over the tie bars, anchoring the moving tailstock platen. The large diameter, limited stroke main clamp cylinder extends giving the clamping force. To open the mold, the clamp cylinder is vented, the half nuts are released, and the rapid traverse cylinder retracted. This has the advantage of adjustable stroke, minimum stress length of the tie bars, increased rigidity, and smaller floor space. Careful engineering and maintenance is required to lock the
Figure 1-28 “Lock and block” hydraulic clamp.

Figure 1-29 Long stroke, rapid acting clamping system using one-half nuts to anchor the moving platen.
half nuts consistently in place.

3. Another system moves the movable platen with a small long stroke cylinder. The tie bars are completely out of the movable platen and are inserted at the very end of the stroke. They are locked by half nuts, hydraulically operated. Hydraulic cylinders at the end of each tie bar are located between the platen and lock. When they are extended they stretch the tie bars for clamping action.

Small single toggles can be used for rapid traverse of the platen. The clamp pressure is supplied by a large diameter short stroke cylinder. Since the toggle is only acting as a spacer it does not require the massive proportions that would be needed to generate large blocking pressures.

4. A very ingenious method (Figure 1-30) has the large diameter small stroke clamping cylinder moving on ways. A small cylinder lifts this main clamp vertically over the movable platens. The movable platens are activated by small diameter long stroke hydraulic cylinders. This system permits long strokes in a minimum tie bar length and uses minimum floor space.

**Vertical or Horizontal Clamp?**

Users of large presses must consider whether to buy a vertical or horizontal
press. One of the considerations is the space required. A 5000-ton horizontal machine occupies 720 ft². A 4000-ton vertical press requires 190 ft². Twelve feet are usually below floor level and 20 ft above it.

The size of the mold that can fit into a horizontal machine is limited by the spacing of the tie rods. There is a practical limit to this dimension. Vertical machines can be designed for much larger molds. Long strokes and large daylight are difficult to obtain in horizontal machines, but pose little problems for vertical ones. Parts can be too heavy to be removed by the operator. In horizontal machines the parts usually fall on a conveyor and are removed. (This procedure may sometimes damage the part). Vertical machines can also be unloaded automatically with such devices as suction cups, clamp assemblies, and air cushions to float the part out of the press. One of the disadvantages of the vertical machine is that the injection unit feeds from the side. If a part cannot be edge gated, a long hot runner system is used, a situation which can pose problems when using heat sensitive materials.

MACHINE SPECIFICATIONS

As noted before, a machine is classified by its clamping and injection ends. The clamping end is specified by its type (hydraulic, toggle) and its clamping tonnage; the injection end by its type (plunger, two-stage plunger, reciprocating screw, two-stage screw) and its shot capacity usually given in ounces of polystyrene per shot. If it is a screw machine, the specification includes the nominal diameter of the screw.

Clamp End Specifications

Tables 1-3 and 1-4 shows the specification for three machines, a plunger type with a toggle clamp, a reciprocating screw with a toggle clamp, and a screw-plunger machine with an hydraulic clamp. These specifications were taken from manufacturers' literature.

The Society of the Plastics Industry (SPI) has established patterns for tapped holes on the platens. They also have standardized the knock-out pattern so that molds are readily interchangeable from machine to machine and plant to plant. A discussion of the clamp end specifications may be helpful.

The clamping force (given in tons) has been discussed. The clamp stroke (given in inches), is the maximum distance the moving platen will move. It is desirable that this motion be fully adjustable to permit the minimum stroke required by the mold. On hydraulic equipment, the travel is stopped by a limit switch. Mechanical stops are helpful when mold stroke control is needed. The maximum daylight (inches) is the furtherest distance the platens can be separated from each other. The minimum mold thickness (inches) is the closest
| Table 1-4 Clamp end and general specifications for three different types of molding machines |
|-------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------|
| #1-10-Oz plunger type 275-ton toggle clamp            | #2-28-Oz 2½ In. reciprocating screw, 375-ton toggle clamp | #3-60-Oz 3½ In. screw-plunger-type, 425-ton hydraulic clamp |
| Clamping Force                                        | Short tons 275                                      | Short tons 375                                      | Short tons 425                                      |
|                                                      | Metric tons 250                                     | Metric tons 340                                     | Metric tons 387                                     |
| Break-away force                                      | Short tons 40                                       | Short tons 45                                       | Short tons 55                                       |
|                                                      | Metric tons 36.4                                    | Metric tons 41                                      | Metric tons 50                                      |
| Tie rod diameter                                      | in. 3 1/2                                           | in. 4 3/4                                           | in. 5                                               |
|                                                      | mm 89                                               | mm 121                                              | mm 127                                             |
| maximum                                               | in. 42                                              | in. 55                                              | in. 34                                              |
| daylight                                               | mm 1067                                             | mm 1397                                             | mm 864                                             |
| Clamp stroke (min.-max.)                              | in. 8–20                                            | in. 6–24                                            | in. 22                                             |
|                                                      | mm 203–508                                          | mm 152–609                                          | mm 560                                             |
| Minimum mold thickness                                | in. 6                                               | in. 8                                               | in. 12                                             |
|                                                      | mm 152                                              | mm 203                                              | mm 305                                             |
| Maximum mold thickness                                | in. 22                                              | in. 31                                              | –                                                  |
|                                                      | mm 560                                              | mm 787                                              | –                                                  |
| Distance between tie rods horizontal X vertical       | in. 16 1/2 X 18                                     | in. 24 X 20                                         | in. 24 X 23                                         |
|                                                      | mm 419 X 457                                        | mm 610 X 508                                        | mm 610 X 584                                        |
| Platen size, height X width                           | in. 27 X 27                                         | in. 36 X 32                                         | in. 39 X 36                                        |
|                                                      | mm 686 X 686                                        | mm 914 X 813                                        | mm 991 X 914                                        |
| Ejector type                                          | Mechanical                                          | Hydraulic                                           | Mechanical                                         |
| Ejector stroke maximum                                | in. 4                                               | in. 7                                               | in. 5                                              |
|                                                      | mm 102                                              | mm 178                                              | mm 127                                             |
| Ejector force                                         | Short tons –                                       | Metric tons –                                       | –                                                 |
|                                                      | –                                                   | –                                                   | –                                                 |
| Speeds                                                | Clamp ram forward in./min 925                       | Clamp ram forward m/min 23.5                       | Clamp ram forward m/min 925                       |
|                                                      | 1380                                                | 35.                                                 | 600                                               | 15.2                                              |

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distance that the two platens can come to each other while still maintaining clamp pressure. This can be further reduced by using a spacer or “bolster” plates. The minimum mold thickness is the difference between the maximum stroke and daylight. These are important specifications in that they tell how deep a piece may be molded and whether a mold of a given depth will fit in a machine.

The *clearance* between the tie rods (inches) is the determining factor whether a mold of a given length or width will fit into the press. For example, a press has 20 in. clearance vertically and 18 in. horizontally. Therefore, a mold
less than 20 in. wide, but over 20 in. long will fit vertically. A mold less than 18
in. high but over 18 in. long will fit horizontally. The length and width
dimensions of a mold are often determined by the side which is parallel to the
knock-out plate.

The *clamp speed* (inches per minute) is an important specification. Slow
clamp speed as well as excessive clamp motion means wasted productive time.
Losing 0.5 sec/shot on a machine producing 120 shots/hr will waste 110
productive hours per year.

The *knock-out stroke* (inches) determines the maximum knock-out
movement available. When molding deep draw pieces or using the knock-out
system for camming, long knock-out stroke is desirable.

Controls, hydraulics, knock-out systems, and safety, are all necessary com-
ponents of any injection molding machine installation. A brief description of
what is required is given below.

**Controls**

The electrical controls can be mounted in a separate enclosure (Figure 1-1) or on
the machine (Figure 1-6). The latter are less expensive to install in a molding
plant, take up less floor space, and are easier to move in the event the plant is
relocated. Separate panels remove the components from machine shock and
vibration, are roomier permitting easier maintenance and modification, and can
be located for maximum visibility to operating personnel. The area housing the
controls should be well lighted.

There are a number of conveniences found in some molding machines. The
heating and control circuits should be separate. This permits the molding
temperature to be reached at approximately the same time a repair is finished.
Symbols as well as labels should be put on the controls as some operators have
difficulty reading. There should be sequential signal lights for electrical and
hydraulic circuits for rapid location of malfunctions. Plug in components (relays,
timers, and limit switches) are available and desirable.

There should also be provision for extra instrumentation including heat
control units, timers, and relays. A nonresettable cycle counter can be attached
to the automatic ram forward solenoid control. A volt meter with long leads can
be permanently mounted in the control cabinet.

The manual control panel (Figure 1-6;20) is mounted on the machine for the
operator's convenience. It should be located so that he cannot possibly get hurt
when purging material. It should also be designed so that the controls cannot be
accidentally moved. Hydraulic gauges and controls (Figure 1-6;28; 29; 36) are
mounted for convenience in piping. It is very desirable to have multiple
hydraulic plug-in testing points to facilitate hydraulic maintenance. Additional
core pulling circuits are also desirable.
Hydraulics

Location of the hydraulic components and electric motors depend on the individual machine. Most oil reservoirs (Figure 1-6;16) are located in the base of the machine. Fully hydraulic large capacity clamps may have them above the clamping end. This helps the oil flow in by gravity. There should be an oil filtering system for continually filtering the oil. A magnet in the reservoir will collect the iron resulting from the normal wear and tear of the components. An oil temperature gauge should be installed on the machine preferably with a warning light if the oil goes above the predetermined temperature. The machine should be designed for easy maintenance, with as many components as possible readily accessible. Unfortunately this is not always the case.

Cooling water is needed because the hydraulic system generates heat. For example, a 16-oz capacity press running approximately 100 shots/hr required the removal of 25,000 Btu/hr through a heat exchanger (cooler). This is in addition to a substantial amount of radiation loss from the machine body. Provision for bringing water to and from the machine is therefore required. Water for cooling the hydraulic oil is usually supplied by a water tower or a well. Automatic throttling valves will control the amount of water going through the machine heat exchanger. (Provision is also required for mold cooling water. This can be tower water or more preferably, a mechanically refrigerated coolant). A fully hydraulic clamp usually requires lubrication only on the tie rods and the ways. Machines with toggle clamps require good lubrication. The trend is to automatic lubrication (Figure 1-6;12).

Knock-out Systems

The knock-out (K.O.) system is needed to eject the part from the mold. A separate knock-out plate in the mold changes its location relative to the rest of the mold. Attached to this plate are knock-out (ejector) pins or other devices which push against the molded parts as the mold completes its opening. This ejects the parts from the mold. On most machines there is an adjustable stationary ejector plate (Figure 1-6;7) to which are attached the ejector bars (Figure 1-6;17) which go through the movable platen. As the mold returns, the ejector bars go through holes in the back plate of the mold, contact, and stop the knock-out plate. The rest of the mold continues moving a predetermined distance and stops.

There are pins attached to the knock-out plate which project to the mold parting surface. They are pushed by the injection side of the mold as the mold closes. This forces the knock-out plate back to its normal position. Such pins are called push back or return pins. A much superior but more costly way to activate the knock-out system is by the use of hydraulic cylinders (Figure 1-6;18). This is an advantage since the knock-out system can be advanced or
retracted at any time with any speed or force. Hydraulic cylinders are particularly useful in cam action molds and insert molding.

Safety

The unprotected molding machine can be dangerous. People have lost limbs, fingers, and lives in the moving parts of the machine. A safety gate in front of and in the rear of the mold area is a necessary part of a safety system. The gate should be large enough and high enough so that it is impossible for anyone to get any part of his body in the platen area when the platen is closing. The safety gate should be permanently mounted on slides with enough clearance for hydraulic cylinders or other mold attachments. A mechanical safety operated by the gate drops a bar of steel between the platens so that the machine cannot close with the gate open even if there is an hydraulic or electric failure.

Guards should also be placed around the machine to prevent anyone from putting any part of his body in the toggle area or other moving parts of the machine. The gate should also be electrically interlocked. A machine must have electrical and hydraulic safety systems too.

The open feed section of the screw can also amputate fingers. A safety screen is difficult to design for this section. Hoppers that slide away from above the machine and which have material emptying chutes tend to minimize this danger and at the same time make the cleaning of the hopper easier. All the safety switches should have fail safe circuits and have provisions for testing.

In addition observe the following safety procedures:

1. At no time should any repairs between the platens be made with the motor running.
2. The heating cylinder should have a cover to prevent direct contact with the heating bands.
3. The purging controls should be located so that the operator is protected from spattering by overheated material. Clear plastic purging guides can also be used here.
4. Electrical locks should be provided so that no one can start the machine when mold or machine repairs are being made.

Occupational Safety and Health Act of 1970 (OSHA)

OSHA, which became effective on April 27, 1971, has the declared Congressional purpose to "assure so far as possible every working man and woman in the Nation safe and healthful working conditions and to preserve our human resources."

Each employer under the act has the general duty to furnish each of his employees employment and places of employment, free from recognized hazards causing, or likely to cause, death or serious physical harm; and the employer has
the specific duty of complying with safety and health standards, promulgated under this act.

Each employee has the duty to comply with these safety and health standards, and all rules, regulations, and orders issued pursuant to the act which are applicable to his own actions and conduct.

The standards can be roughly divided into two parts. One deals with standards applicable to almost all manufacturing operations. Examples would be maintaining aisles and passageways in good repair and clear of obstructions, and maintaining recognized fire prevention standards, such as fire extinguishers and keeping all material at least 36-in. below sprinklers. The second type would pertain to the particular industry.

Any employee (or representative, such as a union) who believe that a violation of a job safety or health standard exists which threaten physical harm, or that imminent danger exists, may request an inspection by sending a signed written notice to the Department of Labor.

Complete records of all injuries must be kept in a specific place and notice of this law must be posted throughout the plant.

The law puts the obligation for a safe plant directly upon the employer. Inspections, which are unannounced, see that the law is complied with; they do not tell the employer what to do. Therefore, penalties and fines are issued at the first inspection. This is contrary to most types of inspection, where a time is given to correct faults without any penalty.

Penalties of up to $10,000 may be assessed for each violation. A willful violation by an employer which results in the death of any employee is punishable by a fine of up to $10,000 or imprisonment of up to 6 months. A second conviction doubles these criminal penalties.

The plastics industry has one of the highest injury rates in industry and has been selected by OSHA as one of their early priorities. One would be well advised to become familiar with the requirements of this act. Providing a safe place has always been morally imperative. It now also becomes financially desirable. (76, 77, 78)

**SPECIAL TYPES OF MOLDING MACHINES**

Specific needs of plastics processors have led to the development of special types of injection machines modifications, four of which are described here.

1. *Off-center molding modifications.* Many times it is necessary to gate a molded part off center. Normally this would require an off center mold with the sprue bushing placed directly in the center of the machine. Another way of overcoming this off-center problem is to build either a three plate, hot runner, or insulated runner mold. The mold is placed centrally in the machine and the