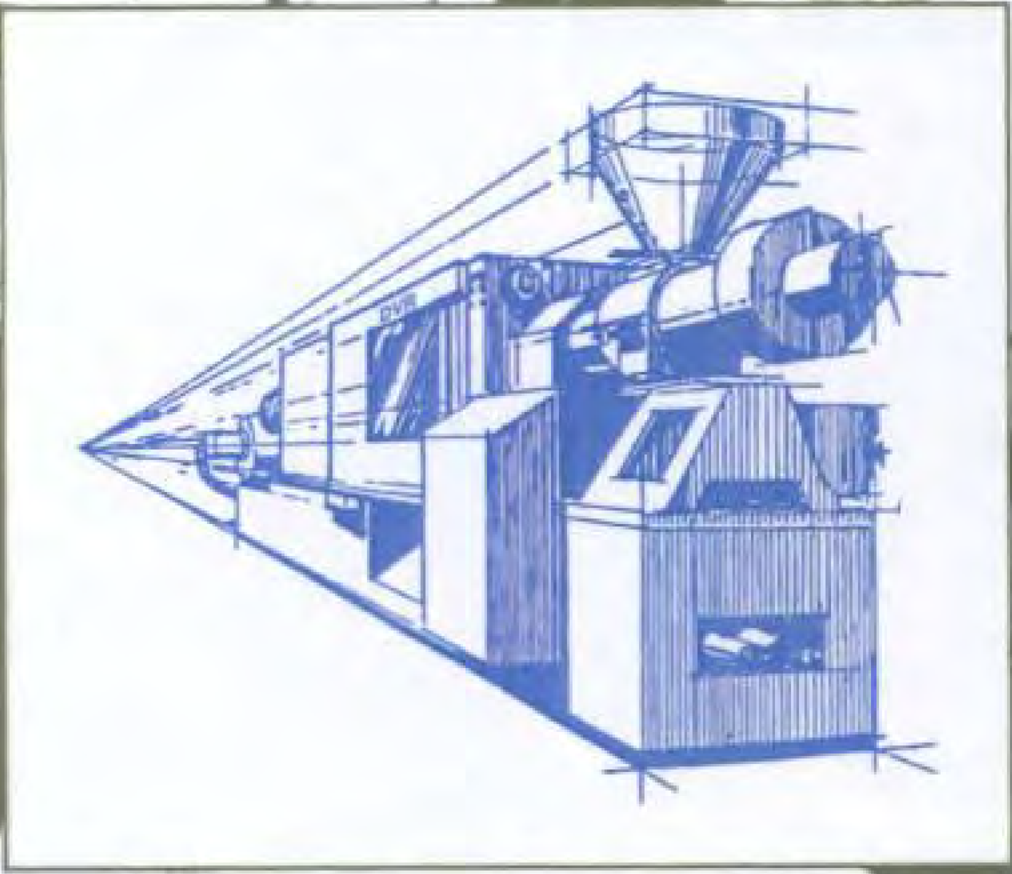

INJECTION MOLDING HANDBOOK

3rd Editio

Dominick V. Rosato
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Kluwer Academic Publishers

INJECTION
MOLDING
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THIRD EDITION

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Contents

In preparing this book and ensuring its completeness and the correctness of the subjects reviewed, use was made of the authors' worldwide personal, industrial, and teaching experience that totals over a century, as well as worldwide information from industry (personal contacts, conferences, books, articles, etc.) and trade associations.

THE ROSATOS

performance and mold products at the least cost, meeting performance requirements, and with ease (see the section on Molding Tolerances in Chap. 5).

Machine Characteristics

IMMs are characterized by their shot capacity. A shot represents the maximum volume of melt that is injected into the mold. It is usually about 30 to 70% of the actual available volume in the plasticator. The difference basically relates to the plastic material's melt behavior, and provides a safety factor to meet different mold packing conditions. Shot size capacity may be given in terms of the maximum weight that can be injected into one or more mold cavities, usually quoted in ounces or grams of general-purpose polystyrene (GPPS). Since plastics have different densities, a better way to express shot size is in terms of the volume of melt that can be injected into a mold at a specific pressure. The rate of injecting the shot is related to the IMM's speed and also the process control capability for cycling the melt into the mold cavity or cavities (fast–slow–fast, slow–fast, etc.).

The injection pressure in the barrel can range from 2,000 to at least 30,000 psi (14 to 205 MPa). The characteristics of the plastic being processed determine what pressure is required in the mold to obtain good products. Given a required cavity pressure, the barrel pressure has to be high enough to meet pressure flow restrictions going from the plasticator into the mold cavity or cavities.

The clamping force on the mold halves required in the IMM also depends on the plastic being processed. A specified clamping force is required to retain the pressure in the mold cavity or cavities. It also depends on the cross-sectional area of any melt located on the parting line of the mold, including any cavities and mold runner(s) that are located on the parting line. (If a TP hot-melt runner is located within the mold half, its cross-sectional area is not included in the parting-line area.) By multiplying the pressure required on the melt and the melt cross-sectional area, the clamping force required is determined. To provide a safety factor, 10 to 20% should be added.

Molding Plastics

Most of the literature on injection molding processing refers entirely or primarily to TPs; very little, if any at all, refers to thermoset TS plastics. At least 90 wt% of all injection-molded plastics are TPs. Injection-molded parts can, however, include combinations of TPs and TSs as well as rigid and flexible TPs, reinforced plastics, TP and TS elastomers, etc. (Chap. 6). During injection molding the TPs reach maximum temperature during plastication before entering the mold. The TS plastics reach maximum temperature in the heated molds.

Molding Basics and Overview

The following information provides a complete overview of the process of IM (Figs. 1-3 to 1-10). Continually required is better understanding and improving the relationship of process-plastic-product and controlling the complete process.

Injection molding is a repetitive process in which melted (plasticized) plastic is injected (forced) into a mold cavity or cavities, where it is held under pressure until it is removed in a solid state, basically duplicating the cavity of the mold (Fig. 1-11). The mold may consist of a single cavity or a number of similar or dissimilar cavities, each connected to flow channels, or *runners*, which direct the flow of the melt to the individual cavities (Fig. 1-12). Three basic operations take place: (1) heating the plastic in the injection or plasticizing unit so that it will flow under pressure, (2) allowing the plastic melt to solidify in the mold, and (3) opening the mold to eject the molded product.

These three steps are the operations in which the mechanical and thermal inputs of the injection equipment must be coordinated with the fundamental properties and behavior of the plastic being processed; different plastics tend to have different

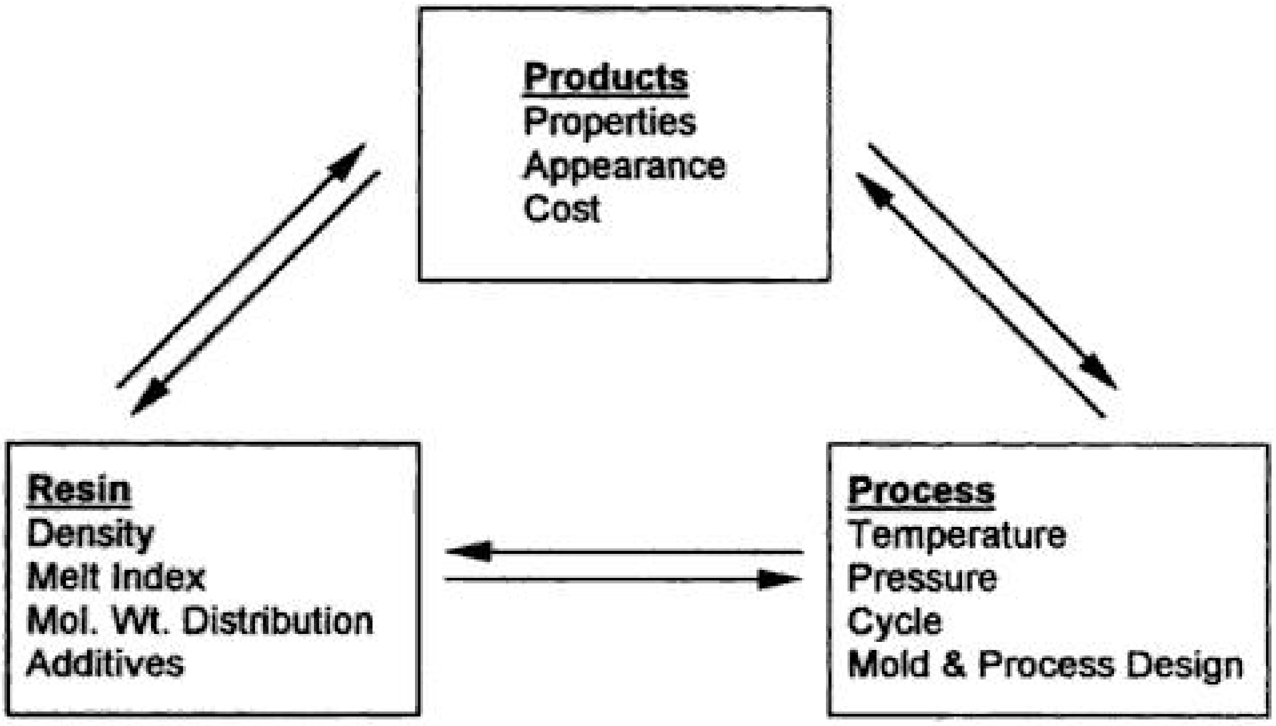


Fig. 1-8 Interrelation of product, resin, and process.

of heating–cooling cycles before appearance and/or properties are affected. Thermosets (TSs), upon their final heating [usually at least to 120°C (248°F)], become permanently insoluble and infusible. During heating they undergo a chemical (cross-linking) change. Certain plastics require higher melt temperatures, some as high as 400°C (752°F) (see section on Recycling in Chap. 6).

Extensive compounding of different amounts and combinations of additives (colorants, flame retardants, heat and light stabilizers, etc.), fillers (calcium carbonate, etc.), and reinforcements (glass fibers, glass flakes, graphite fibers, whiskers, etc.) are used with plastics. Compounding also embraces the mixing (alloying, blending, etc.) of two or more plastics that may be miscible or immiscible, with or without additives.

With TPs, the mold initially is kept at as low a temperature as possible, below the melting point of the plastic melt. This approach causes the injected hot melt to initiate surface freezing on the cavity wall, followed by formation of the solid product. After a sufficient cooling time, the mold opens and the part(s) are ejected. When processing TSs [from the injection unit (plasticizer)], the hot melt entering the heated mold initially remains below the temperature that would cause premature solidification due to its exothermic reaction.

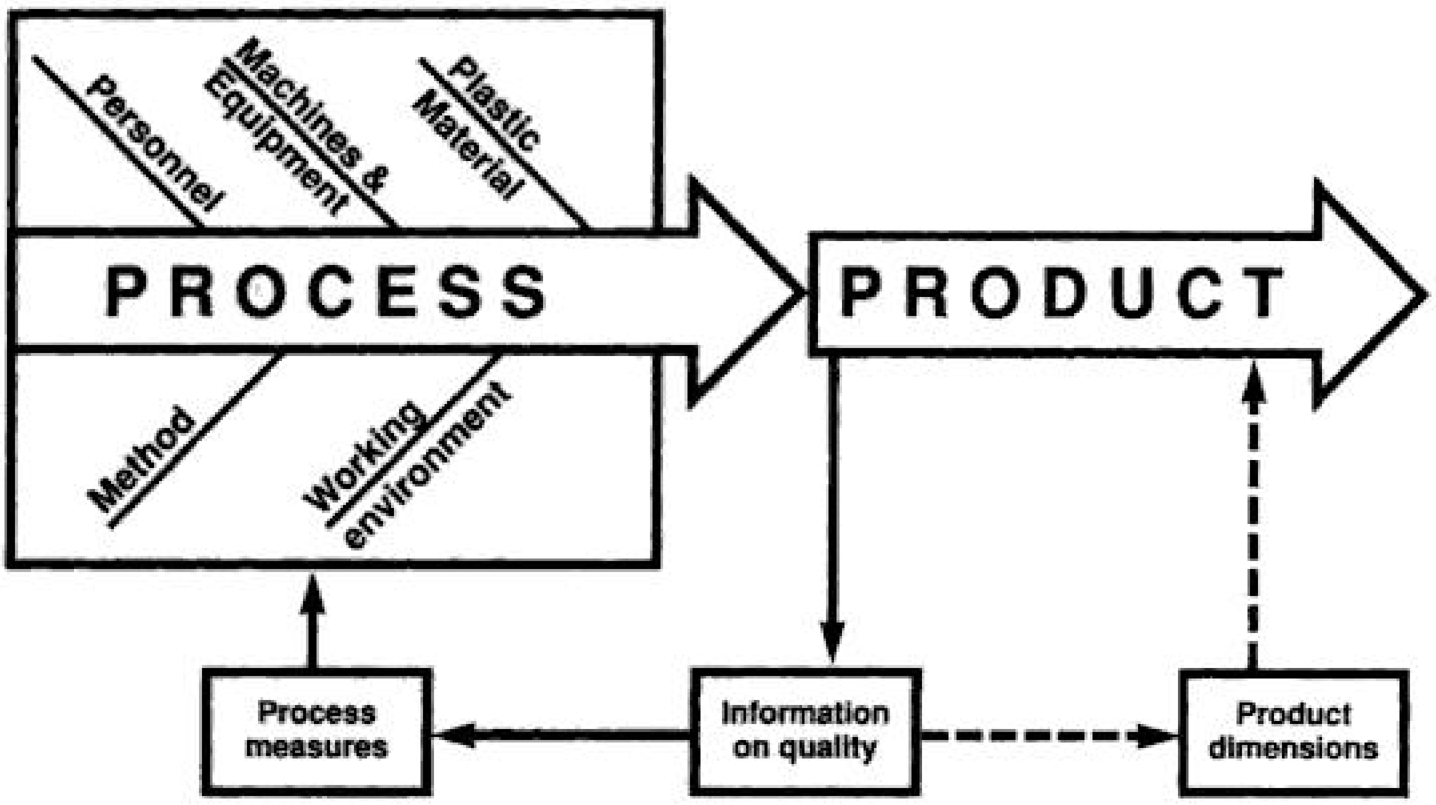


Fig. 1-9 Simplified processing steps.

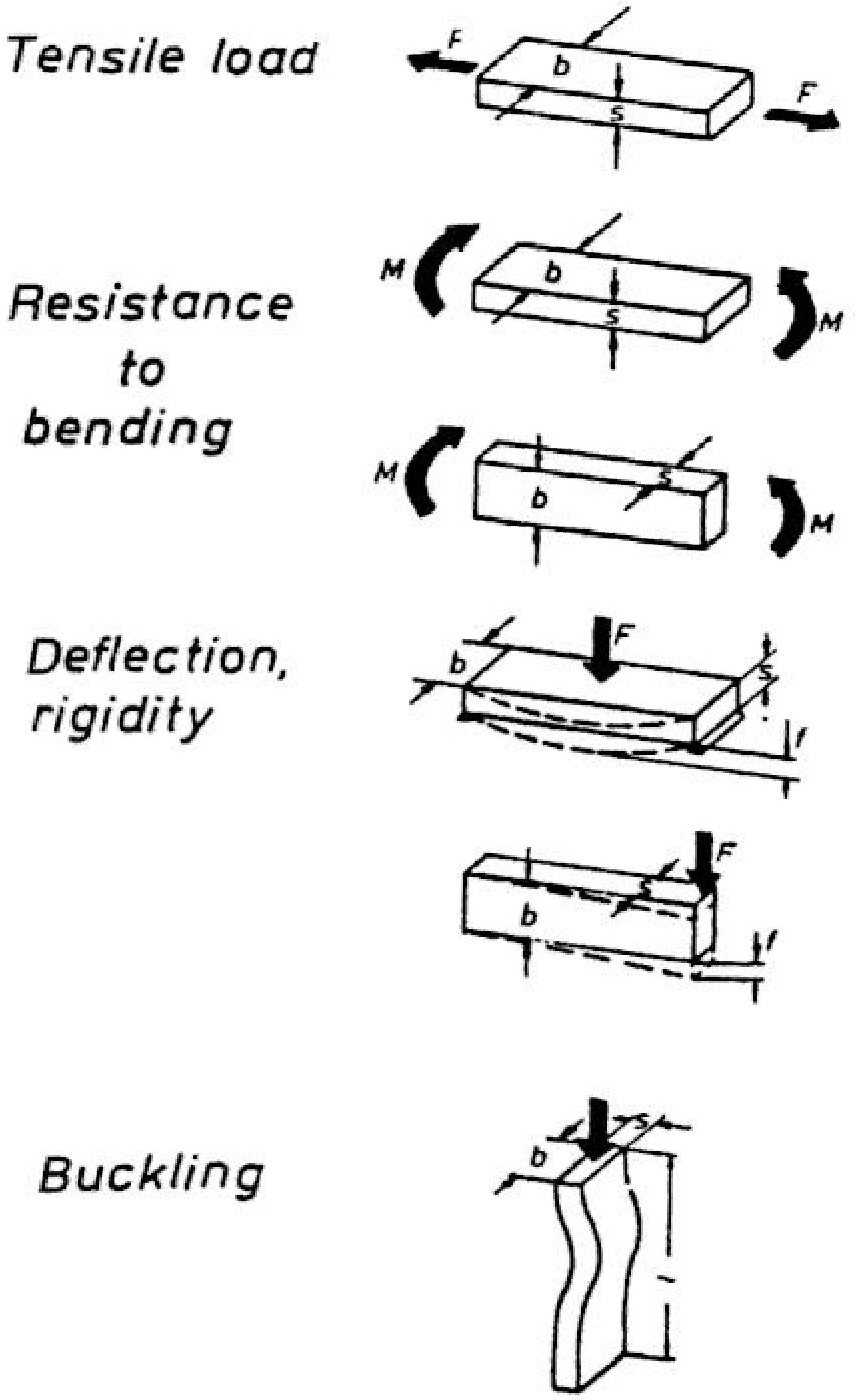


Fig. 1-18 Examples of mechanical tests.

displaying many types of shear–tension relationships. Together with the screw design, the deformation determines the pumping efficiency of the plasticator and controls the relationship between output rate and pressure drop through the melt flow to solidification in the mold cavity(s).

Plasticating

Plasticating is the process that melts the plastics. Different methods are used. The most common are the single-stage (reciprocating screw) and the two-stage. In Fig. 1-19, (a) and (b) show the ram (also called plunger) systems used in the original IMMs since the 1870s, and now used mainly to process plastics with very little melt flow, such as ultrahigh-molecular-weight polyethylene. They use a piston, with or without a torpedo, for plastication. Part (c) shows the single-stage reciprocating screw plasticator, and (d) the two-stage screw plasticator.

There are different IMM operating designs in use: all-hydraulic, all-electrical, and hybrid (combination of hydraulic and electrical). Each design provides different

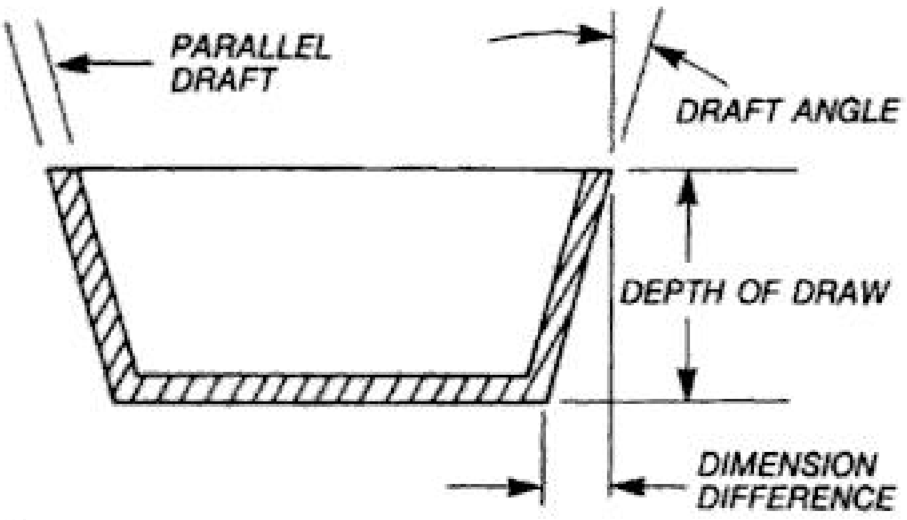


Fig. 1-22 Example of mold-cavity draft angle required to ensure removal of molded product during its mold ejection action.

require control of various parameters such as fill time and hold pressure (Chap. 4).

To simplify molding, whenever possible one should design the product with features that simplify the mold-cavity melt filling operation. Many such features can improve the product's performance and/or reduce cost. An example is choosing the mold-cavity draft angle according to the plastic being processed, tolerance requirements, etc. (Fig. 1-22). Figure 1-23 shows a situation where it is possible to eliminate or significantly reduce shrinkage, sink marks, and other defects (Chap. 8).

Processing

Processing steps are summarized in Figs. 1-9, 1-10, and 1-24 to 1-27. Different machine requirements and material conditions are considered in choosing the most efficient injection molding process. It is important to understand and properly operate the basic IMM as well as its auxiliary equipment. In particular, in practically all operations the screws must not be damaged or worn and the plastic must be properly dried. Special dryers and/or vented barrels are required for drying hygroscopic TP materials such as PC, PMMA, PUR, and PET (Chap. 10).

Use of TP regrind may have little effect on product performance (appearance, color, strength, etc.). However, reduction in performance can occur with certain TPs after even one passage through the IMM. Granulated TSs cannot be remelted but can be used as additives or fillers in plastics.

Many TPs can be recycled indefinitely by granulating scrap, defective products, and so on. During these cycles, however, the plastic develops a "time-to-heat" history or residence time. This phenomenon can significantly compromise processing advantages

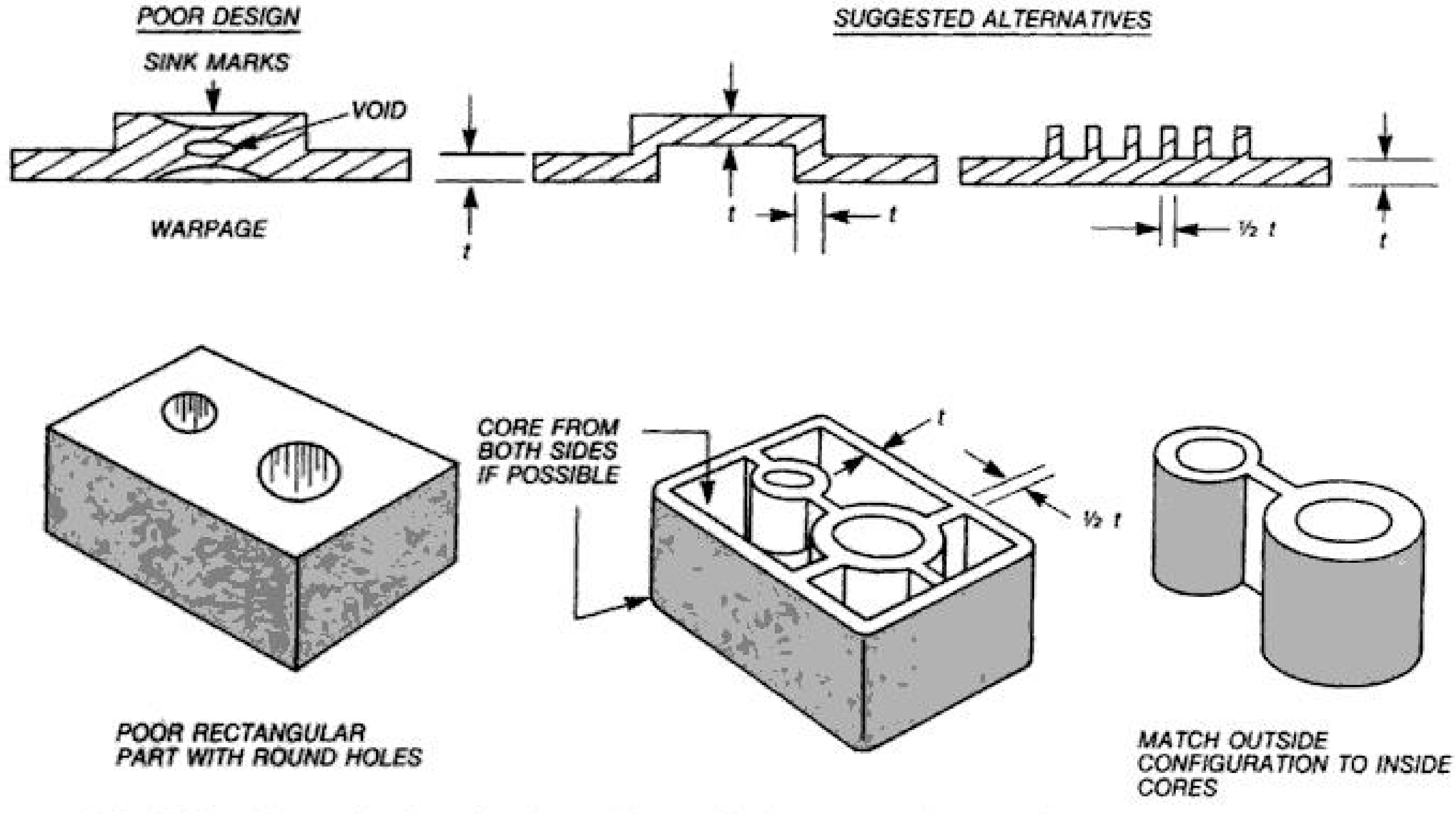


Fig. 1-23 Example of coring in molds to eliminate or reduce shrinkage and sink marks.

Fig. 1-28 Hopper feed control unit.

Control Guides

Adequate PC and its associated instrumentation are essential for product quality control (QC). The goal in some cases is precise adherence to a control point. In other cases, maintaining the temperature within comparatively small range is all that is necessary for effortless control (of temperature, time, pressure, melt flow, rate, etc.) that will produce the desired results (Chaps. 7, 9, and 13). Regardless of the type of controls available, the processor setting up a machine uses a systematic approach that should be outlined in the machine and/or control operating manuals. Once the machine is operating, the operator methodically targets one change at a time to achieve maximum injection molding efficiency.

With injection molding, as with all types of plastics processing, troubleshooting guides are established to take fast corrective action

Custom

The custom processor's facilities, like those in the metal-working field, may be called *job shops*. They process plastics into products or components used in other industries. For example, a manufacturer of injection-molded bottles may retain a custom processor to mold preforms. Custom processors typically have a close relationship with the companies for whom they work. They may be involved (to varying degrees) in the design of the product and the mold, they may have a voice in material selection, and in general they assume responsibility for the work they turn out.

Custom-contract There is a subgroup of custom processors known as *contract* fabricators. They have little involvement in the business of their customers. In effect, they just sell machine time.

Proprietary

A proprietary operation is one where the processor makes a product for sale directly to the public or to other companies. It usually has its own trade name.

Training Programs

Various training programs and seminars for processors and mold manufacturers are available worldwide. Information concerning processors' training programs is reviewed in Chaps. 2, 9, and 12 as well as other chapters. A tooling example is the apprentice training programs of the USA Tooling & Manufacturing Association (Park Ridge, IL). Their effective programs are based on well-planned services that involve properly supervised on-the-job training and classroom instruction. Such programs start with the development of a policy manual. One of TMA's most effective trainers is Northwestern Tool and Die Manufacturing Corp. (Skokie, IL).

Each training module includes a practical experience checklist, material checklist, practical experience record of hours, and safety checklist. Times on cutting tools include basics in equipment and their control operations (2000 h), lathe (800), milling (1000), grinder (1000), chrome plating (100), jig bore (700), honing (100), EDM (300), inspection tools (100), and so on.

The list of postsecondary schools devoting a significant portion of their funds to moldmaking and related programs is growing rapidly. As the industry continues to review the labor pool and come up short, and as undergraduate institutions fight over a shrinking market, education-and-industry partnering is increasing in urgency. As an example, the Moraine Park Technical College of Southeastern Wisconsin, an internationally known facility of the machine tooling industry, is a well-established school with a reput able program that, in conjunction with other area schools, has provided local industries a highly trained workforce for decades (410).

Processor Certifications

National skills certification programs by different organizations are in existence worldwide to certify the skills and knowledge of plastics-industry processor machine operators. Action by the different organizations continues to provide methods of improving these programs. As an example, the Society of Plastics Industry's Industries National Certification in Plastics (NCP) program has as its purposes: (1) to identify job-related knowledge, skills, and abilities, (2) to establish a productive performance standard, (3) to assess and recognize employees who meet the standard, and (4) to promote careers in the plastics industries. The examination includes basic process control; prevention and corrective action on primary and secondary equipment; handling, storage, packaging, and delivery of plastic materials; quality assurance; safety; tools and equipment; and general knowledge.

The Society of Plastics Engineers' Plastics Technology Certification was for plastics professionals who have the knowledge and ability to apply mathematics, the physical

2

Injection Molding Machines

Introduction

The injection molding machine (IMM) is one of the most significant and rational forming methods existing for processing plastic materials. A major part in this development has been by the forward-thinking machinery industry, which has been quick to seize on innovations and incorporate them into plastic molded products. The most recent examples are the all-electric and hybrid IMMs. A major focus continues to be on finding more rational means of processing the endless new plastics that are developed and also produce more cost-efficient products. A simplified general layout for an IMM is shown in Figs. 2-1 and 1-3.

For years so-called *product innovation* was the only rich source of new developments, such as reducing the number of molded product components by making them able to perform a variety of functions or by taking full use of material's attributes. In recent years, however, *process innovation* has also been moving into the forefront (Fig. 1-16). The latter includes all the means that help tighten up the manufacturing process, reorganizing and optimizing it. All activity is targeted for the most efficient application of production materials, a principle which must run right through the entire process from plastic materials to the finished product (Fig. 1-15 and Chap. 4).

Even though modern IMM with all its ingenious microprocessor control technology is in principle suited to perform flexible tasks, it nevertheless takes a whole series of peripheral auxiliary equipment to guarantee the necessary degree of flexibility. Examples include (1) raw material supply systems; (2) mold transport facilities; (3) mold preheating banks; (4) mold-changing devices, including rapid clamping and coupling equipment; (5) plasticizer-cylinder-changing devices; (6) molded-product handling equipment, particularly robots with interchangeable arms allowing adaptation to various types of production; and (7) transport systems for finished products and handling equipment to pass molded products on to subsequent production stages.

There are different types and capacities of IMMs to meet different product and cost–production requirements. The types are principally horizontal single clamping units with reciprocating and two-stage plasticators. They range in injection capacity (shot size) from less than an ounce to at least 400 oz (usually from 4 to 100 oz) and in clamp tonnage up to at least 10,000 tons (usual from 50 to 600 tons). Other factors when specifying an IMM include clamp stroke, clamping speed, maximum daylight, clearances between tie rods, plasticating capacity, injection pressure, injection speed, and so on, as reviewed in this chapter and Chap. 4. The

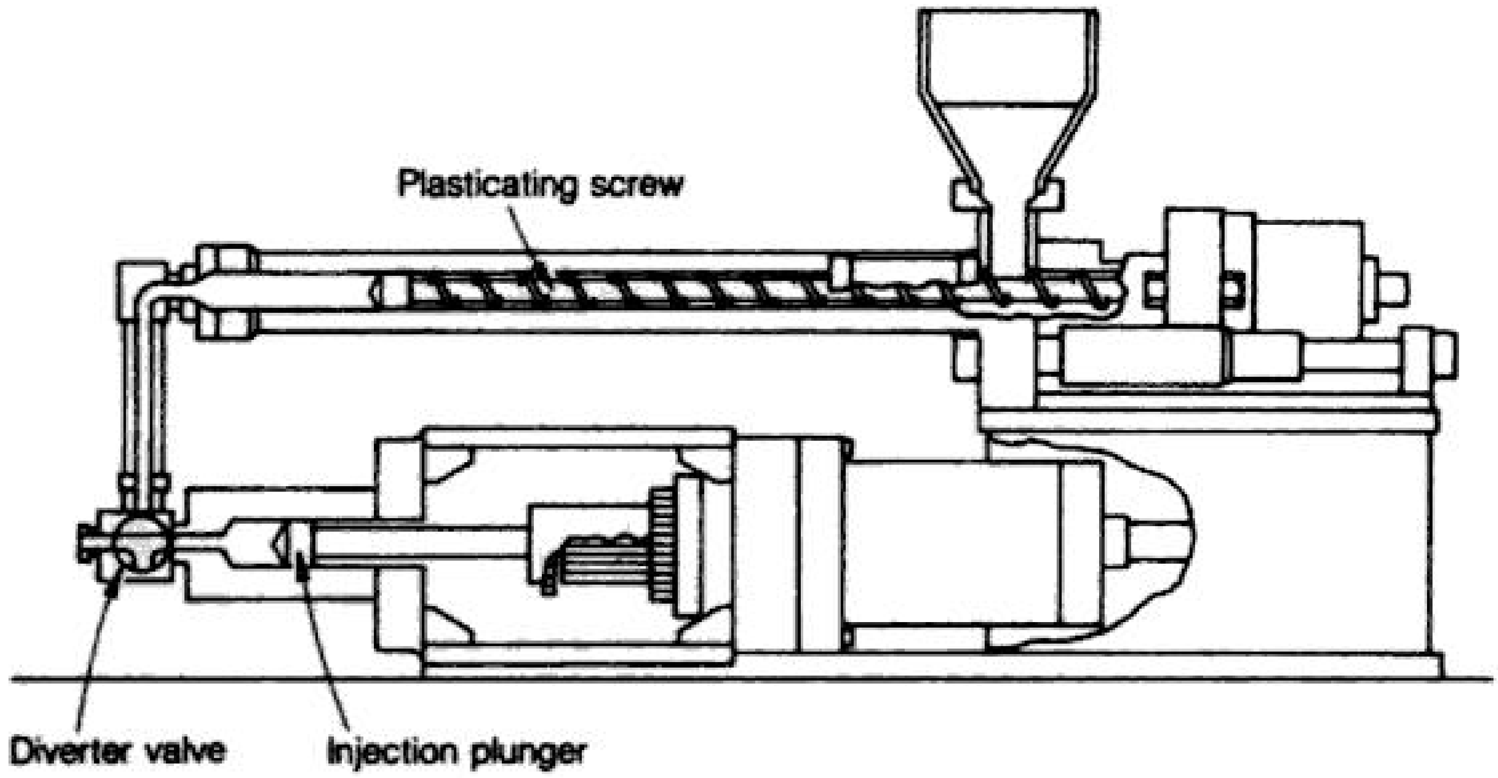


Fig. 2-5 Schematic of a two-stage screw IMM with parallel layup.

to enter the cavity prior to shot. However, for plastics with certain melt characteristics, melt flow problems can develop in this case. (Chap. 7).

At a preset time the screw acts as a ram to push the melt into the mold. Depending on the plastic's melt flow characteristics, the injection pressure at the nozzle is between 2,000 and 30,000 psi (14 and 200 MPa). The required pressure is determined by the plastic being processed and the melt pressure required in the cavity or cavities, taking into account pressure drops as the melt travels through the mold. While the shot is injected into the mold, an adequate clamping pressure must be used to keep the mold from opening (flashing) during and after the filling of the cavity.

Molds are designed to meet different requirements. They include hot runners or cold runners (for TPs or TSs) with different lengths of runners, gates, etc. (reviewed in Chap. 4).

Two-Stage Machines

Another very popular injection molding method uses a two-stage arrangement of screws. Such a machine is also called a preplasticizing IMM. The two-stage IMM uses a fixed plasticating screw (first stage) to feed the required melted plastic through a valve mechanism into a chamber, or *accumulator* (second stage). This screw does not require reciprocating action (as in a single-stage IMM), since it only conveys melts by means of some type of diverter mechanism (valve) into a *holding* (injection accumulator) cylinder (Figs. 2-5 to 2-7). When a sufficient quantity of melt has been transferred, the diverter valve again shifts to create a flow path over a prescribed time cycle from the accumulator cylinder into the mold. The second stage (ram injection stage) provides the pressure needed for the desired rate of injection of the melt (shot) into the mold cavity or cavities. After injection is completed, the diverter valve shifts to direct the melt flow from the first stage into the second-stage holding cylinder, and this operating cycle repeats. During all this action the first-stage extruder is continuously rotating; in practice this does not cause problems even when the melt flow is slightly restricted by being cut off from the second stage (1, 518, 525).

Thus the diverter or shuttle valve has three positions. One position is the closed mode, during which time the extruder is only preparing the melt. The next position directs the melt from the extruder into the accumulator (second stage). The third position directs a shot of melt from the accumulator into the mold cavity.

Injection Hydraulic Accumulator

The injection hydraulic accumulator is a device for increasing the speed of the melt an inherent limit on how far one can move the screw to obtain additional volume. These larger diameter screws are no problem to push with a hydraulic system, but are cost-prohibitive with the original electromechanical drive designs.

Other tradeoffs with the reciprocating design include that increasing the screw diameter to add volume limits the precision at the small end of the shot range. Because the stroke gets so short, it is difficult to have precision melt control. The reciprocating injection unit is usually oversized for the actual molding requirement because the effective diameter for plasticizing decreases with increasing screw stroke. As an example, it has become standard to size molding operations to 30 to 70% of a reciprocating injection unit's capacity. This sizing keeps the IMM in the best operating range for larger shots—typically 300 oz (8500 g), corresponding to a 150-oz (4250-g) two-stage unit process.

The two-stage unit design is a fundamental departure from the past reciprocating unit design. It frees the design of the injection function from dependence on the plasticizing function, because it uses an independent shooting chamber. This permits use of a smaller-diameter injection barrel and longer injection stroke for a given volume. The result is to make it easier to generate high injection rates, pressures, and volumes with smaller, precise, and proven electromechanical drives. The two-stage injection unit can shoot its full volume, unlike reciprocating units, which are usually sized twice as large.

The need for affordable high-pressure, large-shot injection with an electric drive led Milacron to look at new approaches rather than simply scaling up the size of a ball-screw, rack-and-pinion, or other linear actuator to accommodate the limits of a reciprocating screw. The two-stage unit evolved as a practical, effective way to dramatically extend the performance range of their electric IMMs, while meeting cost targets.

Drawing on its expertise in extrusion equipment, Milacron used a variant of its single-screw extruder to melt plastic and meter it into the injection (second-stage) barrel through a port in front. With extrusion as a separate function, plasticizing rates are sized to exact requirements. Injection control is much more precise than with the nonreturn valve in line with the injection screw plunger, which has to seat before control of the shot occurs. Its longer stroke of a smaller-diameter injection piston is what enables, as an example, the 150-oz (4250-g) two-stage IMM to do shots down to 4 oz (110 g). This shot is far smaller than would be possible with a 300-oz (8500-g) reciprocating screw. The industry's generally accepted practice is to avoid shooting less than 10 vol% of shot capacity for a reciprocating unit, since in such cases the screw stroke becomes so short that it is difficult to control.

The separate *extruder* allows molders to perform tasks that would be more difficult or impossible with a reciprocating unit, such as compounding glass fiber inline, changing the screw *L/D*, putting additives in the melt phase, and venting. The melt from the extruder is also more consistent and higher in quality, because each pellet (etc.) passes down the entire length of the screw, in contrast with a reciprocating screw, where some of the screw feed end may be behind the hopper.

While the two-stage IMM has its advantages, it created challenges to the machine designers. Most important was its handling of the melt, which made color change difficult. Also, heat-sensitive plastics could stick to the plunger tip. The electrically driven ball screw behind the injection piston (Milacron; patent pending for tip design) allows a new way to handle melt as it enters the shot chamber, overcoming these challenges. A screw-type tip is used on the injection piston. A one-way clutch rotates the tip while building a shot and retracting the piston, pushing melt forward over the tip (Fig. 2-10). Its first-stage extruder does not move melt directly into the front of the shot chamber at the piston tip; instead, the melt travels through the screw thread to maximize the mixing and forward flow. Depending on the shot size, this tip gives first-in–first-out, middle-in–last-out, or last-in–middle-out handling. Even when the piston tip is backed past the melt entry port, the rotation of the tip continues to wipe the plunger

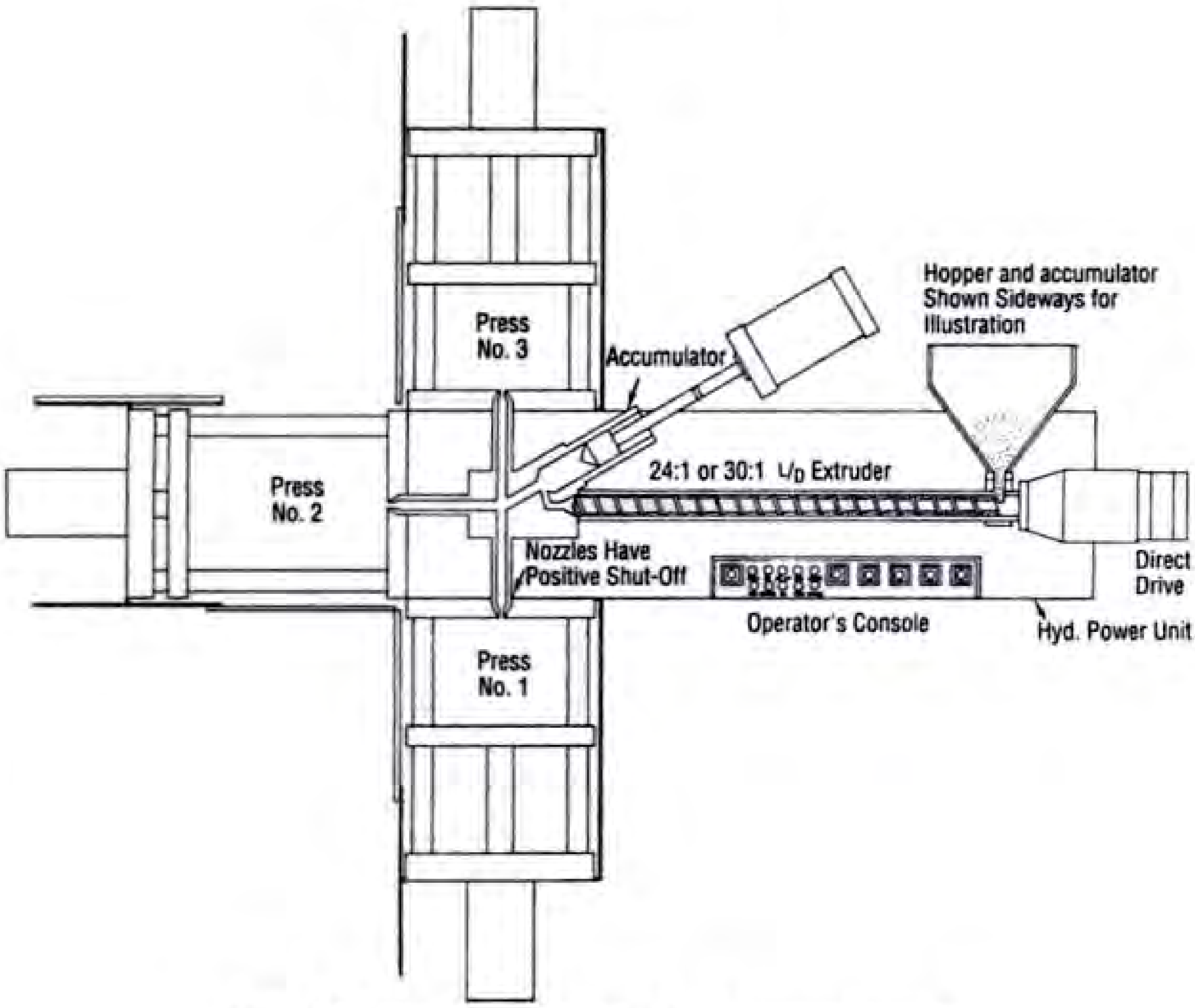


Fig. 2-14 Two-stage IMM with three clamping presses.

thermoplastics this cooling is accomplished by circulating a cooling medium, usually water, through drilled holes or channels properly located around the cavity. Thermoset plastics require heat, usually via electric cal-rods, in the mold to complete their solidification (chemical cross-linking).

6. The next step in the cycle is sending oil under controlled pressure to the return port(s) of the clamping ram, separating the mold halves.

7. As the moving platen returns to its open position, knockout or some type of ejection system (usually mechanical) is activated, removing the molded part(s) from the mold.

Examples of these hydraulic IMMs are shown in Figs. 2-15 and 2-16.

An example of advanced hydraulic technology is shown in Fig. 2-17. Two of these HPM 5,000-ton, 400-oz-injection-unit, two-platen, hydromechanical NEXT WAVE™ series machines were installed (1999–2000) in GM's Saturn plant (Spring Hill, TN) to mold interior parts and body panels for the division's new midsize LS sedans. To date the many existing IMMs at this 4-million-sq ft plant have been large toggle-clamp machines. The new IMMs include (1) parabolic platen design, leaving mold mounting surfaces flat and free of distortion, (2) retractable tiebars, (3) platen movement using very little oil, (4) GE Fanuc process control (similar to that used throughout the plant), (5) improved energy efficiency, and (6) 20 to 30% reduction in floor space compared to their existing machines.

Reservoirs

The reservoir (or tank) provides hydraulic oil to the system for use in powering the various IMM actions. The reservoir must be sized to ensure that an adequate supply of oil is available to the system and also resulting from the design principle employed for discrete output of the manipulated variable mean that digital valves should not be employed as the final control element for closed-loop control of the process variables pressure and speed. Their use should be kept to open-loop control, where the advantages of this design predominate.

For similar reasons, digital hydraulic control elements are not suitable for closed-loop position control. The positioning of the mold and ejector in digital hydraulic machines does not achieve the accuracy of closed-loop position control. As in the case with digital temperature control, the digital measurement of position is becoming more common in high-quality injection molding machines.

There is still no standard approach for open- or closed-loop control of hydraulic functions. Nevertheless, it can be seen today that there will eventually be two attractive versions of digital systems:

- *Open-loop machine with digital hydraulics*. This version will find its greatest use in machines with sequential functions. It can meet stringent requirements with regard to reliability, while offering simple operation and needing minimal maintenance.
- *Digital closed-loop machine*. This version will find its greatest use in machines with simultaneous functions and automated equipment that requires closed-loop position control for high reliability and convenience of operation.

Both concepts represent good technical solutions for their areas of application.

Hydraulic Fluids and Influence of Heat

A hydraulic fluid is a liquid or mixture of liquids designed to transfer pressure (and thus power) from one point to another in a system on the basis of Pascal's law: pressure on a confined liquid is transmitted equally in all directions throughout the liquid.

The pressure due to excessive heat in the operation of machine-tool hydraulic systems, such as that of an IMM, can degrade the operation of the entire system. Heat affects five major areas of machine hydraulics, which in turn affect the cost and/or performance of the molded plastic product(s): (1) hydraulic-fluid life, (2) energy loss, (3) erratic operation of components, (4) formation and removal of sludge and varnish, and (5) operating conditions that cause overheating, which in turn causes leakage of check valves, relief valves, and so on.

Pumps

The hydraulic pump provides hydraulic flow and pressure to the system. It receives oil from the reservoir at low pressure and increases the pressure to that required by the system. Several different types are used. The most common are fixed- and variable-displacement pumps. Different designs are available, the most common being vane, piston, and gear types.

Variable-volume and variable-pressure compensating pumps are being used more frequently in an attempt to conserve energy. These pumps are capable of varying output to meet a particular flow requirement, or dispensing only enough flow to develop a particular pressure requirement. There is no single pump type that is perfect for every class and size of IMM.

Figures 2-19 and 2-20 show fixed and variable pumps. Fixed pumps can be single units or staged in multiple-pump configurations for powering large-clamp-tonage machines. Big machines theoretically could use multiple variable-volume pumps, but such systems would be rather expensive. Fixed-volume balanced vane pumps are quite popular and generally operate at 2,000 to 3,000 psi (13.8 to 20.7 MPa) with 90% volumetric efficiencies.

In vane pumps, a slotted rotor is splined to the driveshaft and turns inside the cam ring. Vanes are located in the rotor vane slots and follow the inner surface of the cam ring as the rotor turns. Centrifugal force and outlet pressure under the vanes hold them out against the cam ring, and they are enclosed by inlet and outlet support plates. The varying, continuous pressure under the vane area

Injection Molding: A Technology in Transition to Electrical Power

While incremental improvements will continue to be wrung out of hydraulic IMMs and molds, more significant advances in quality and productivity will result from the transition to all-electric molding machinery. This transition has barely begun, but it is likely to follow the same pattern it did in robots and machine tools (326).

Simply put, electric molding technology (EMT) eliminates so many variables from the process that a machine will produce more good parts per day at a lower cost. A reasonable body of experience and test data has been developed which documents these improvements. There are also significant operating advantages related to energy and environmental issues. Broadly speaking, three approaches to electric injection molding machinery have come to the forefront in Europe, Japan, and the United States. Each will be described, along with its rationale.

Where are the next major quality advances for injection molding likely to come from? Evidence from real-world applications suggests that EMT has the potential to significantly raise the standard of quality. Although EMT has a host of environmental and energy advantages in its favor, most early adopters of the technology are committing to it for reasons of quality and productivity. They simply get more parts per shift, and better ones.

The reason is that electric machines have a window of process capability that is inherently much tighter than what can be achieved for comparable cost with hydraulic machinery. EMT is the enabler for improved process repeatability, and in the long term will raise the industry's standard for machine performance. This tighter process capability translates into a variety of benefits, including less scrap, lower labor costs, and improved quality.

A technological sea change has been underway in injection molding machinery. With little fanfare, there was one company exhibiting EMT during the 1985 NPE show. Just 12 years later, there were at least twelve. The Japanese were racing to make the transition to EMT. At least seven Japanese companies started pursuing it, with Fanuc having a dedicated factory to build electric machines. Purchasing patterns in the United States and Europe indicate a significant increase in market acceptance, too.

Hydraulic machinery will always be strong Before we go further, it is important to note that hydraulic injection molding machines will continue to be strong contenders in the market. There will always be regional market preferences for these machines because of differing labor costs, work-force skill levels, and industrial infrastructures.

These machines also enjoy a cost advantage, so builders will continue to invest development money to provide better value. Finally, hydraulic machines will, at least for the foreseeable future, probably have a secure market in high-tonnage applications (primarily over 1,500 U.S. tons), because of the cost premium for high-power servomotors.

EMT offers many environmental, energy-reduction, and performance benefits, which largely drove development of the technology. Three designs from Japan, the United States, and Germany show how different machine builders have developed products that delivered these benefits to customers in conformance with specific regional market requirements. This is the same pattern of design proliferation that has occurred with hydraulic machinery and will continue as long as there are specific customer needs driving development.

Priority preferences The Japanese were first with an electric machine, because environmental issues are a high priority in that densely populated island nation. Compact size, low noise, and elimination of oil as an environmental and fire hazard led the Japanese to create the first commercially viable EMT. In a market dominated by precision mid- to low-tonnage machines and relatively small shot requirements, early electric drive technologies could most easily be adapted to injection molding in the Japanese market.

In the European market, speed and precision are high priorities, along with

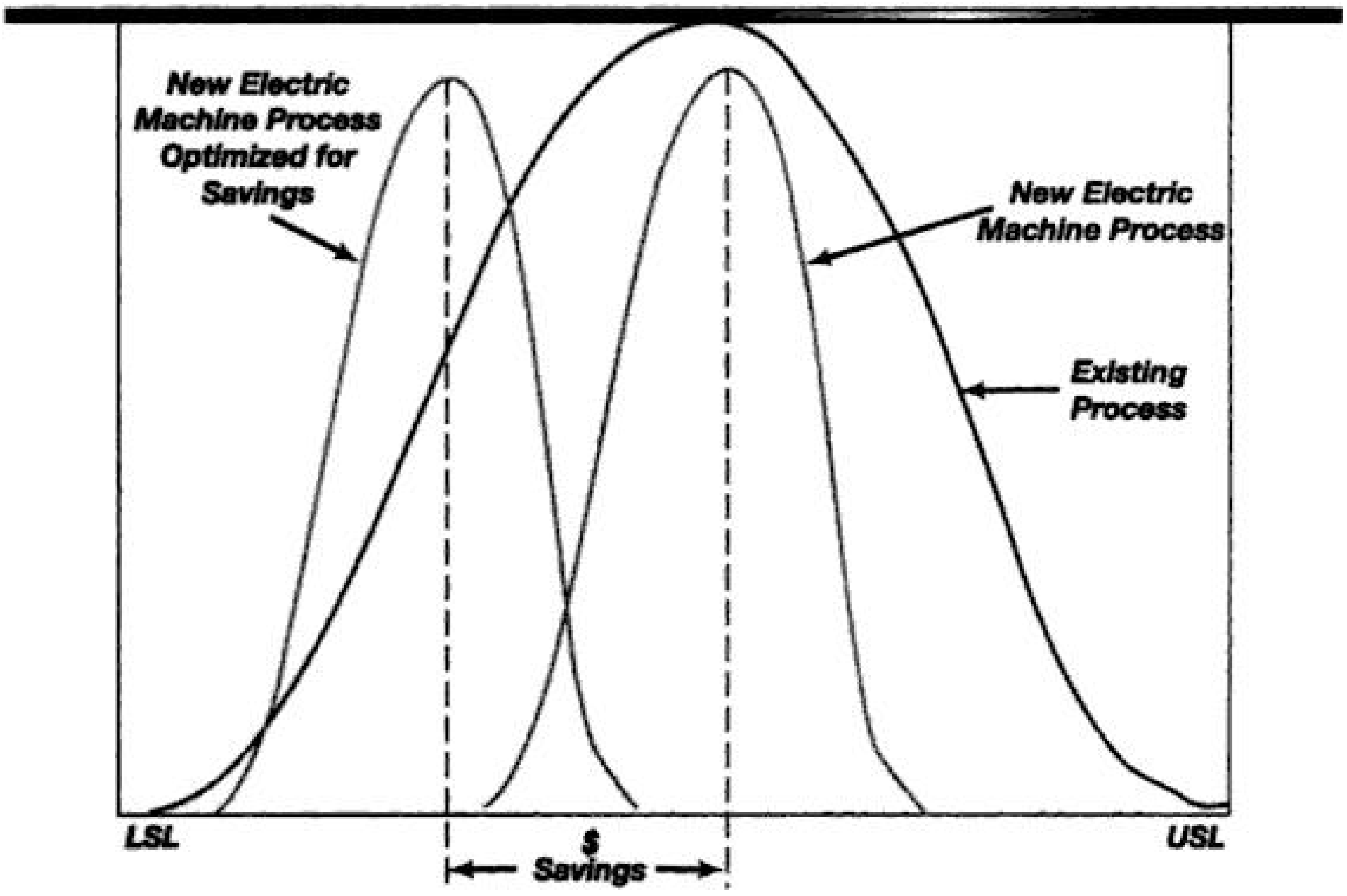


Fig. 2-25 Comparing the economics of good parts for electric vs. hydraulic IMMs.

process control (SPC) studies on parts already made. One graphic result of a process capability study is a bell-shaped curve, which many processors with SPC backgrounds use. As Fig. 2-25 shows, the tighter window of the electric machine's process capability allows operations to be moved confidently toward the lower specification limit where savings accrue in material, scrap, energy, and so on. In simple terms, the curve for an electric machine is much steeper, allowing upper and lower control limits to be moved in tighter. The curve for a hydraulic machine is flatter, dictated by the variables of hydraulic power (Chap. 13).

This higher process capability appears to be inherent in electric machine design. Even general-application electric machines have process capability that is significantly better than Hunkar class 1. Table 2-1 provides typical Hunkar test results from a series of 60 shots on a 300-ton U.S.-designed general-purpose Elektra IMM used for molding pipe elbows.

With a more capable process, molders can produce more good parts per day, adding to their profit margin and competitive advantage in the market. This occurs because:

1. It provides quick startup and setup without oil preheating.

2. Mold setup parameters can be determined once, then used on reruns with little or no adjustment. EMT reduces the art in molding, just as computer-controlled servoelectric

Table 2-1 Hunkar test results for molding pipe elbows

Parameter	Max.	Min.	Range	Hunkar Class 1
Cycle time (sec)	38.95	36.70	0.25	0.40
Hold time (sec)	7.02	7.01	0.01	0.04
Fill time (sec)	2.83	2.81	0.02	0.06
Plasticate time (sec)	11.14	10.92	0.22	0.30
Peak pressure (psi)	11,289	11,145	135	400
Hold pressure (psi)	8,549	8,542	7	80
Back pressure (psi)	1,688	1,665	21	100

Fig. 2-30 The Japanese-designed Roboshot electric IMM is extremely compact and quiet.

classifications do not have walls around them. They simply represent notions that many molders and machine makers can recognize. Molders can, and do, adapt to using machines in applications that may not be ideal for the job. This is also true for hydraulic machinery.

Molders want choices, and there will be many choices in electric machines, as there are in hydraulics. The same type of design proliferation, specialization and overlap seen in hydraulic machines will occur in electric machines to match the perceived needs and wants of customers. This is a plus for the industry.

An example of new designs entering the market is the all-electric Powerline 330 (Fig. 2-33) with advances in performance, size, and simplicity. This is a step forward

Fig. lapanese
Roboshot IMM.

costs. Examples of these hybrid operating systems are many.

One common technique is to direct hydraulic fluid to a booster tube to move the clamp ram forward. Oil fills the main area by flowing from the tank through the prefill valve to the main area. As the ram moves forward, a slight vacuum is developed in the main area, pulling fluid from the tank into the chamber. Once the clamp is closed, the refill valve is closed, trapping the oil in the main cylinder area. High-pressure fluid is put into this area, compressing this volume of oil and thus raising the pressure. A pressure control valve that closely controls the clamp tonnage thereby controls the maximum pressure. The tonnage is the maximum hydraulic pressure times the area it pushes against.

To open the clamp, hydraulic fluid is directed to the pull back side of the cylinder while the prefill valve is open, with fluid from the main cylinder being returned to the tank. One of the major advantages of the straight hydraulic clamp is its very precise control of the clamp tonnage.

Clamping Pressures

Depending on what plastic is being molded, the IMM clamping force may be from less than 20 tons to thousands of tons. The different plastics require different pressures applied on their melt in the mold cavity, ranging from 2000 to 30,000 psi (14 to 207 MPa). The average machine uses a range from 100 to 400 tons, but large machines that provide thousands of tons of clamping pressure are needed to mold large products.

A force is also required to open the mold; it is usually much less than (say 20% of) the clamping force. One has to ensure that adequate pressure is available for that purpose. Resistance exists due to the solidified melt in the cavity or cavities. Usually this requirement is not a problem unless the mold cavity shape is very complex and the mold was not properly designed for ease of ejecting the product.

Clamping systems have been predominantly hydraulic. Also becoming popular are all-electric drive systems and hydraulic–electrical hybrid systems. The mechanical mechanisms include toggle and straight ram systems among others. Each of these different systems has its advantages.

Pressure forces The pressure force, also called the clamping force or locking force, is the force, in tons, that is exerted to hold the two platens or mold halves together when melt under pressure fills the mold cavity.

Pressure measurement Different methods are used for pressure measurement, depending on the type of clamping system used. They include: (1) use of a pressure transducer between closed platens, (2) summation of the tie-bar forces, (3) measuring the force in a toggle mechanism, and (4) determining the force from the oil pressure in a hydraulic system or the electric power used in an electrical system. Measurements in the tie-bars, usually via some type of electrical strain gauge, offer the additional advantage of monitoring the forces in the individual bars. Thus, uneven loads or overloading of individual bars caused by unbalanced or worn molds, as well as other problems, can be identified quickly to avoid major problems.

Pre-close clamping Often one closes the mold to some point near the fully closed position before and after final closing. This permits bumping, improved parison pinch areas for blow molding, mold safety measures, etc.

Clamping actions IMMs can provide *close slowdown* clamping action. This means slowing down the moving platen for an adjustable distance before the mold faces come into contact. There may also be a *close low-pressure clamping system* to lower the clamp closing force in order to minimize the danger of mold damage caused by molded parts caught between the mold halves. A *clamp-opening-stroke interruption* is a complete stop of the clamp opening stroke to allow auxiliary operations before completion of the opening stroke.

The maximum distance over which the opening and closing mechanism can move a

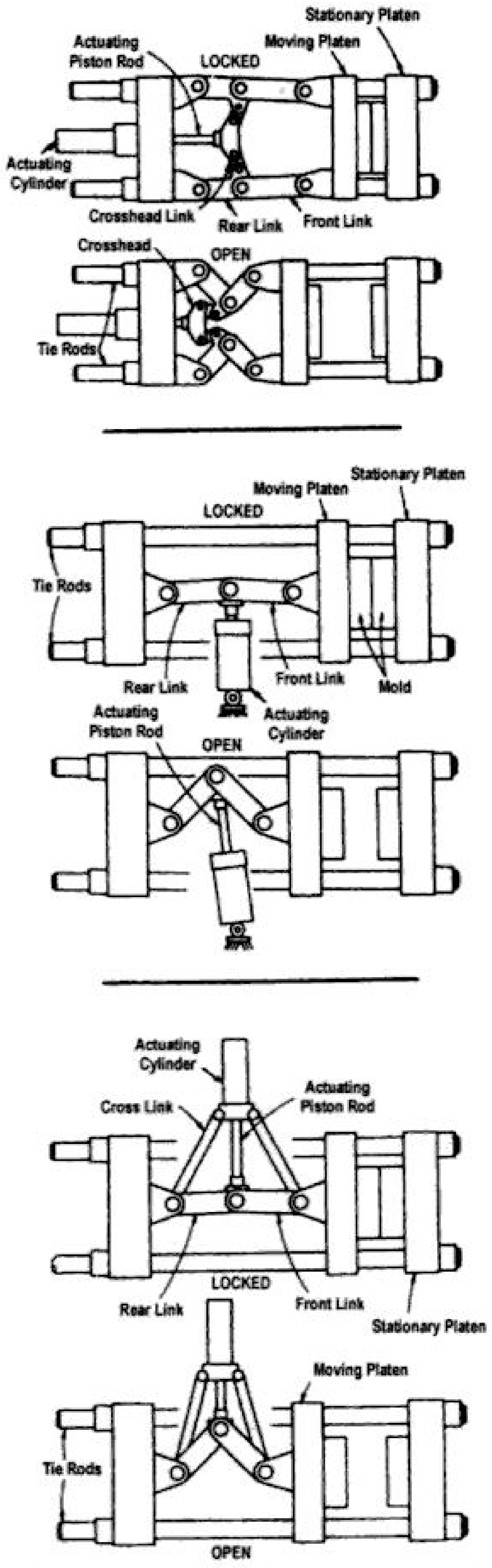


Fig. 2-39 Examples of different toggle mechanical clamp systems.

Comparison of Clamp Designs

Over the years many arguments have been presented showing each clamp design concept to be superior to the others. In reality each concept has its place, and the final deciding factor is usually cost.

The straight hydraulic design has proved over the years to provide long-term reliability, excellent low-pressure mold protection, and exact control of tonnage. It will not allow the clamp to be overstressed by high injection forces.

The toggle clamp has extremely fast closing and opening actions. It is usually lower in cost than the straight hydraulic. The energy required to hold the developed tonnage is less, but this energy is in any case small compared to the total energy usage of the machine. With good lubrication the toggle bushings and pins last a long time. However, they must be reworked after several years of service. The toggle design will also develop higher than lockup tonnage if the clamp is overpowered by the injection end, or there is temperature buildup in the mold.

The hydromechanical clamp tends to have the advantages of the straight hydraulic, whereas the toggle is more complex because of the block action required.

The debate over these clamp systems will continue for many years. There is now available much more useful information and data on these three basic concepts with their many variations. The result is that for a potential buyer of an IMM who has specific requirements for the machine, making comparisons has become easier. Table 2-2 provides a scheme for comparing the systems.

Tie-bars

The clamping tie-bars (rods) support the fixed and movable platens on which the mold is attached. They serve as equally loaded tension support members of the clamp when the mold is closed. The open distance between tie-rods through which the mold must fit determines the maximum outside dimensions of the mold that can be used.

There are retractable clamping tie-bar systems. Different designs are used to unlock one or all tiebars, mainly in order to permit installing molds that occupy the complete platen minus the tie rod circular areas. Thus the mold can have holes in it. A special

A = cross-sectional area of a tie-bar (mm^2)
ΔL = mean elongation of the tie-bars (mm)
L = length measured along the tie-bar(mm)
n = number of tie-bars (usually 4)

A simple device formerly used for measuring the clamping force for a four-tie-bar Negri Boosi toggle clamping machine is shown in Fig. 2-47. Two supports (1 and 3), rigidly fastened to the tie-bar at a distance L from each other, are the measurement base. Rod 2 is locked in support 1 but can slide inside support 3, where a micrometer dial gauge 4 is fitted. As the tie-bar stretches under load, rod 2 slides in support 3, moving the dial gauge tip, which is in contact with the rod's free end. Tie-bar elongation can thus be read from the gauge dial, allowing fractions of one hundredth of a millimeter to be accurately assessed. This measurement must be repeated on each tie-bar, and the mean elongation inserted in the above equation.

This mechanical method for assessing the tie-bar clamping force has since been supplemented by using electrical strain gauges. Fastened to the tie-bars and connected to

Fig. 2-46 HPM's compact locking mechanism.

a bridge-type measuring circuit, these strain gauges allow the IMM's tie-bar elongations and, in turn, the clamping force to be determined via an accurate electronic instrument. This output can also be used as another tool in process control (Chap. 7).

Tie-barless Systems

The clamping tie-barless system, available at least since the 1960s, is of a C-frame (also called U-frame, open-frame, etc.) construction designed to provide clamping pressure and proper parallelism as well as operating platens. Figure 2-48 shows an Engel tie-barless IMM with (a) stationary platen, (b) opening for the injection unit, (c) mold, (d) movable platen, (e) rotary joint, (f) clamping piston, (g) clamping cylinder, and (h) frame. Figure 2-49 is an example of an HPM 60- to 275-ton hydraulic-clamping tie-barless IMM using an open C-clamp design. As previously mentioned, without the tiebars

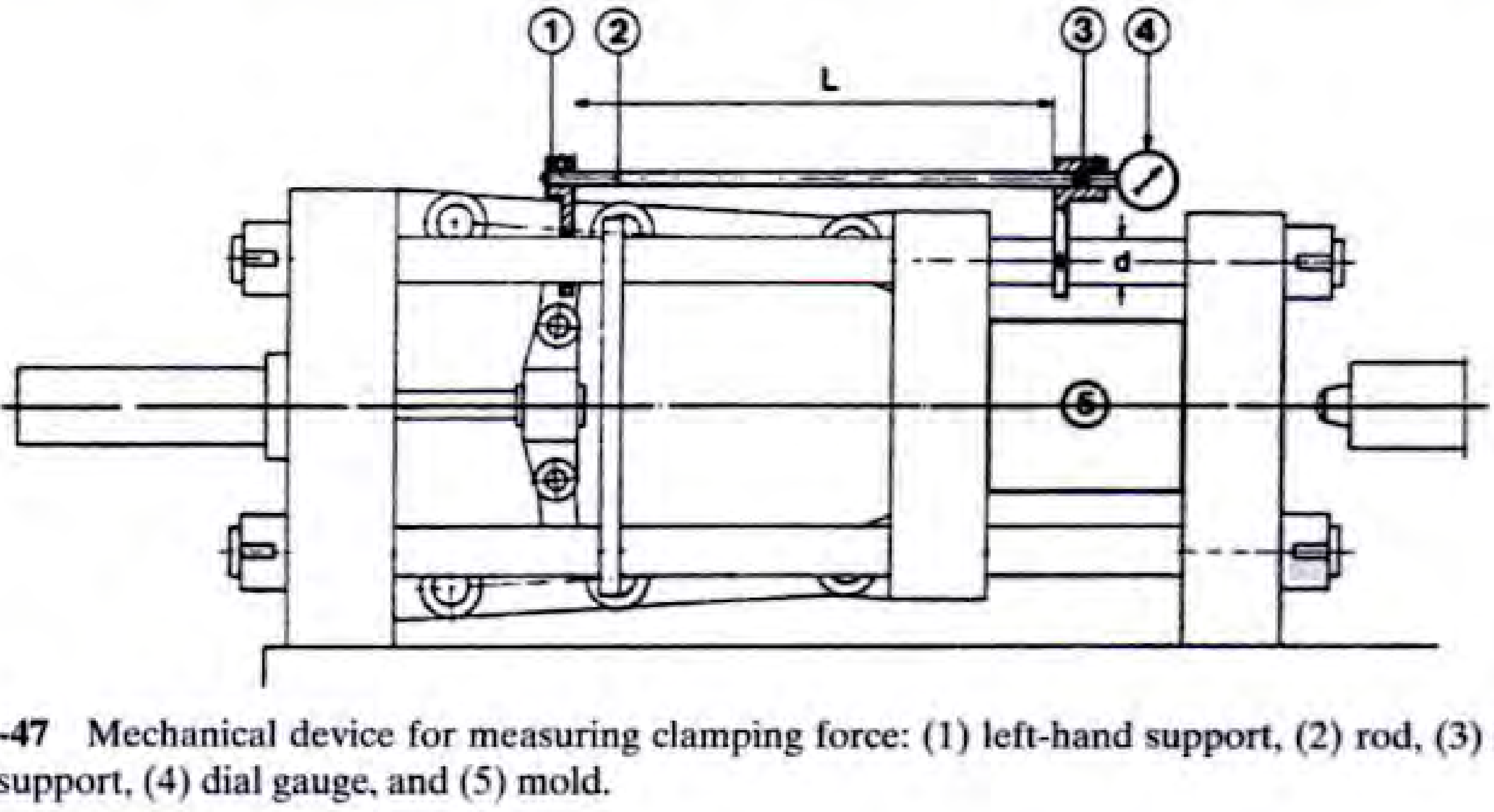


Fig. 2-47 Mechanical device for measuring clamping force: (1) left-hand support, (2) rod, (3) right-hand support, (4) dial gauge, and (5) mold.

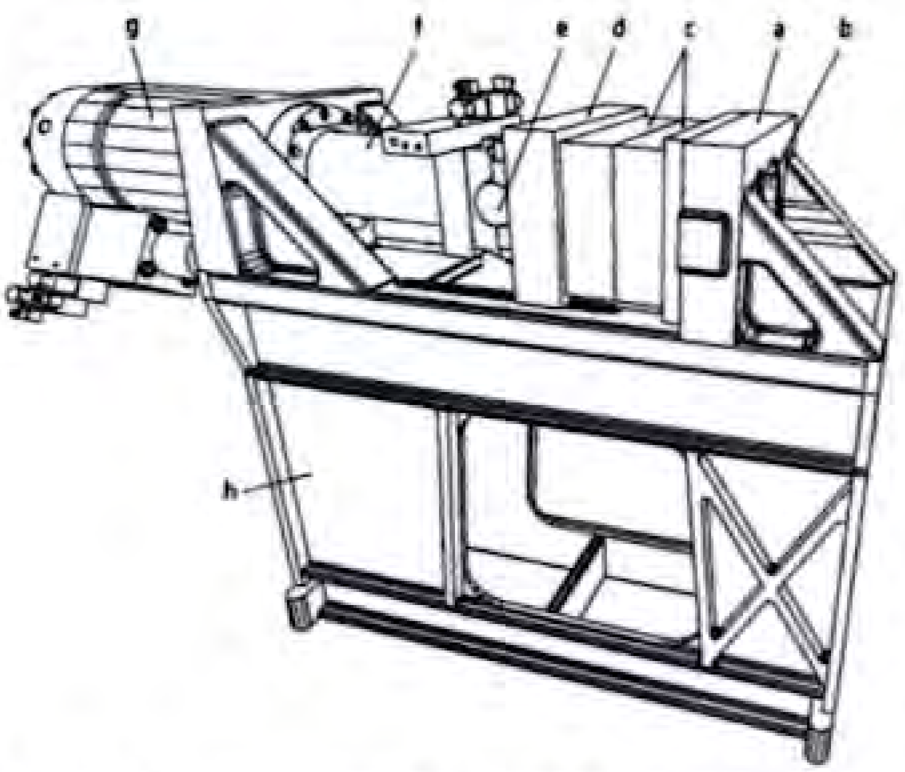


Fig. 2-48 Schematic of an Engel tiebarless IMM.

one can reduce the cost of an IMM by using larger molds, mount larger molds in a smaller IMM, mount molds more easily and quickly, automate part handling more simply, etc.

With the cost of injection molding going up, greater importance is being given to (1) improved efficiency through increased automation, (2) designing IMMs for greater utility, and (3) computer-aided process optimization to improve quality and reduce the number of rejects. Satisfying these requirements involves considering mold changing and product handling. The mold space should be optimally accessible from all sides if possible. In conventional machines with tie-bars, the tie-bars reduce the usable mold-mounting space and obstruct mold changing, especially when protruding core-pull cylinders or latches are used in the molds. The tie-barless IMM solves this problem (1, 7).

Improved controls are also required. The system must be easily understood by the operator and must have conventional graphics to display the increasingly large amount of data that it will output. If necessary the control system should also be capable of being expanded through additional software for process optimization and acquisition of quality-control data (Chaps. 7, 9, 12, and 13).

Platen Systems

Platens are the precision, very rigid plates on which a mold is fastened (Fig. 2-34) and where subsequent clamping takes place. Machines (hydraulic, electric, etc.) can have two or more platens. The basic injection molding machine in the past usually had three platens: two for closing and opening the mold and one to support a pressure clamping system applied to the mold. Since the 1960s, IMMs with only two platens have become popular.

Two-platen press In comparison with more conventional hydraulic presses, the two-platen press may provide improved technical performance, cost advantages, reduced floor space, reduced weight, significantly, reduced clamp speed resulting in shorter cycle time, and reduced tonnage. However, a three-platen system may still be required when stability is important to ensure molding accuracy, as in meeting repeatable tolerances on molded products. Different technical devices, usually located in the back of a platen and/or tie-bars, constitute the pressure clamping system as discussed above.

Clamping platens parallel and flat It is important for a molding press to maintain the platen surfaces parallel to each other and flat (no bellowing, etc.) when clamping pressure is applied. Bellowing is likely to occur with molds that have small cross-sectional area. Where this potential exists, one must use large support plates located between the molds and platens to distribute the load.

Floating clamping platens A *floating*, or *center*, platen is sometimes stacked between the main two platens in multidaylight press machines. There can be more than one floating platen. Each daylight opening between any two platens permits inserting a mold. The total clamping pressure of the IMM is applied uniformly via each platen on each mold. Thus, a multidaylight machine has two or more movable platens that can handle two or more molds simultaneously during one machine operating cycle.

Pivoted floating platens Milacron has a patented multishot (usually two-shot) overmolding process that uses a center platen that pivots (usually 180°, but also 90°) between shots. Makers of molds for such systems include Gram Technology (Birkerod, Denmark) and Ferromatik Milacron (Malterdingen, Germany) (430). The conventional two-shot process using conventional IMMs requires a larger-platen machine with higher clamp tonnage so that a shuttle or turntable action can be used. After shooting the first melt, the mold with this shot pivots and is positioned against a different mold half to accept the second shot, which is delivered from a second injection unit. This pivot design can also permit a four-sided, 90°-indexing center platen with up to four different injection units (see the section on Inmoldings in Chap. 15).

Shuttle clamping platens There are IMMs in which two (or more) platens are moved so that one mold is positioned to receive plastic material and then moves sideways (shuttle action), permitting the adjoining mold to receive the next shot, whereupon the shuttle cycle is repeated. The result is to permit insert molding, shorten the molding cycle, etc. Horizontal IMMs can be used, but more often vertical IMMs are used so that the shuttled molds are on a horizontal table (platen).

Book-opening clamping platens The conventional way for a press to open is for the two platens to remain parallel from open to close to open. Book-action presses (also called tilting presses) use instead a motion of the platens that resembles that of a cover of a book. They are used principally in compression molding, reaction injection molding and printing. They have been popular since the 1930s, when they were introduced in rubber compression molding (see the section on Reaction Injection Molding in Chap. 15).

Rotary clamping platens This system is also called a carousel system when the platens operated horizontally, or a Ferris wheel when they are operated vertically. It can be used to overmold two or more materials into a single part. For each plastic, a separate injection feed unit is then required. It is important to recognize that the stability of the rotary table system determines the quality.

Two or more mold halves are arranged in a circle on the moving platen with the matching mold halves attached to the fixed platen. The process starts with the first closed mold cavity receiving a shot of plastic. Upon opening, that cavity, with the plastic partially solidified, is rotated into the next position, where its matching mold cavity is recessed to receive the next shot. If there are three or more plastics, the procedure continues. Thus when the platens close after the initial startup, each cavity is simultaneously injected with the required plastic.

Railtrack clamping platens This installation resembles a railroad track system. It is reviewed in Chapter 15, in the subsection on Railtrack Moldings of the section on Continuous Injection Molding.

Barrels

The *barrel*, also called a cylinder or a plasticator barrel, is a cylinder that contains a screw or a plunger. Together with a screw, it provides the bearing surface where shear is imparted to the plastic materials. Heating media and sometimes cooling media are housed around it to keep the barrel (and thus the melt) at the desired temperature profile. The barrel's size is specified by its inside diameter (ID) and overall length.

Barrel Length-to-Diameter Ratio It is common practice to refer to the *L/D* ratio, that is, the ratio of barrel length to diameter. The *L/D* ratio is also often given for screws (Chap. 3); see Fig. 2-50.

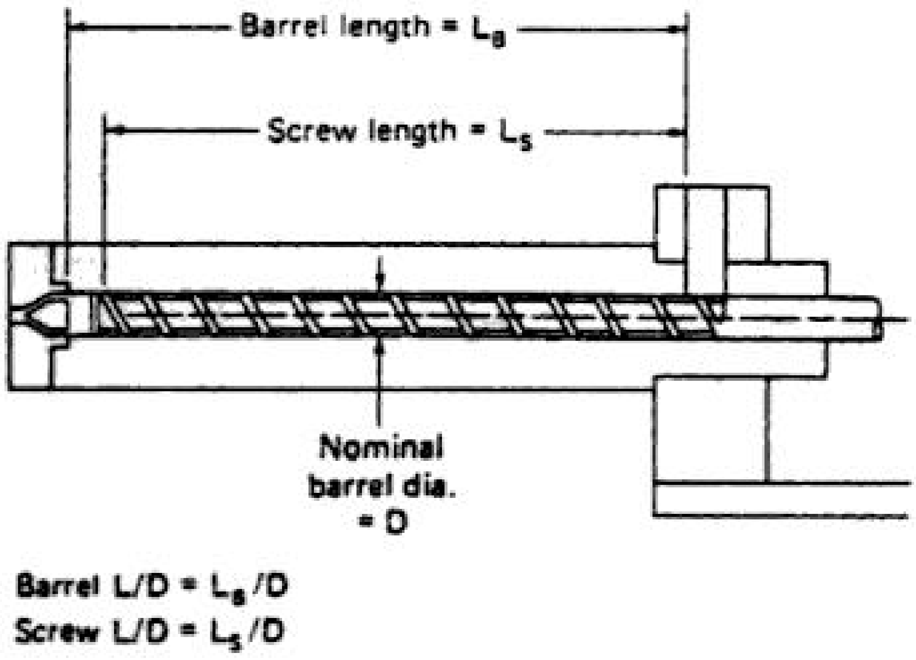


Fig. 2-50 *L/D* ratio.

In defining *L/D* for a barrel one may measure *L* either with or without the feed opening. Thus *L/D* is the distance from the forward edge or from the rear edge of the feed opening to the forward end of the barrel, divided by the barrel bore (ID).

Barrel Borescoping

Borescoping is the alignment of the barrel with the screw. Their clearance can range from 0.05 to 0.20 mm (for small- to large-diameter screws) on all sides of the screw. Borescoping alone is not a guarantee of perfect performance.

With an alignment scope one can tell what the internal shape of a barrel is at any point—whether it is a straight, curved, or even S-shaped as a result of machining or subsequent wear (see the Screw Wear Guide in Chap. 11). Other areas must also be examined. However, aligning with a scope will generally lead to producing better products with less downtime and less scrap, and extending the life of the barrel and screw. Most machines can be adjusted in a day at very little cost. The result will be at least a 25% extension of the machine's life.

Barrel and Feed Unit

There are materials, such as flakes and regrind, that present problems due to poor flow. The feed throat and feed hopper units are important in ensuring that such plastics are

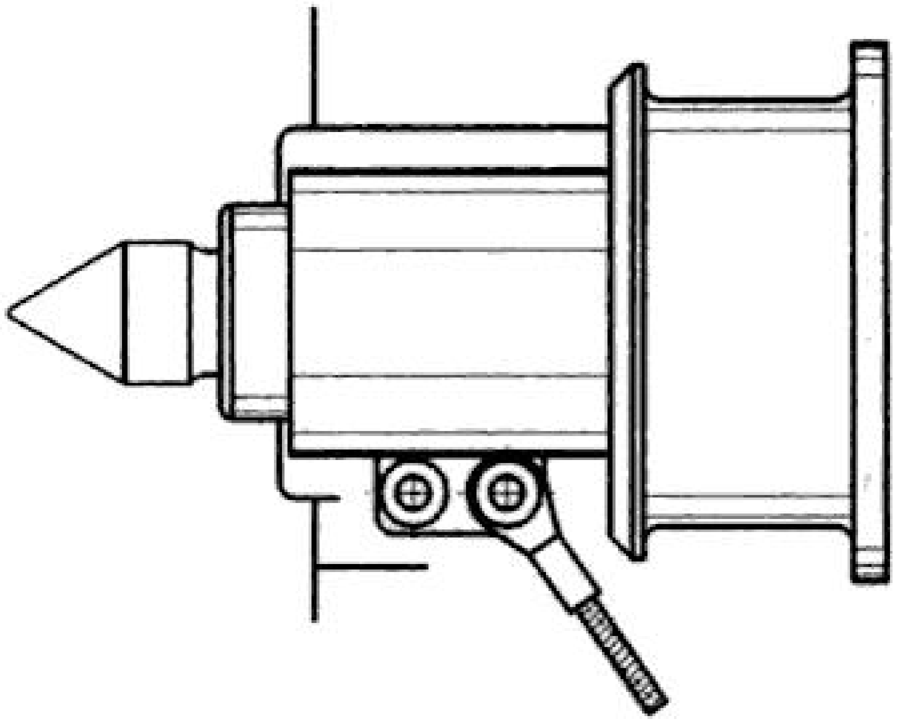


Fig. 2-52 Example of nozzle with a thermocouple attached to the nozzle heater band.

cooling channels or coils around the barrel and/or forced air around the barrel, which can be provided with fins to increase the cooling surface, as in cooling extruders (3).

Barrel Characteristics

For IMMs, the SPI's Machinery Component Manufacturers Division has guidelines for barrel dimensions and tolerances. Upon receiving or replacing machines with barrels, it is best to have them measured so that you can determine if any wear or damage occurs after they are put into operation.

Barrels contain pressure safety devices such as fail-safe rupture disks or bolts. If the barrel pressure exceeds its rated burst pressure, these devices rupture to relieve the pressure. These safety devices are to be handled carefully during maintenance of the barrels.

When using bimetallic liners in the barrels, any exposed edge of the liner can be easily damaged when inserting the screw. Protect it with a ring made to fit the end.

Different metal compositions are used to meet different requirements, principally based on the plastic being processed. Nitrided and bimetallic abrasion-resistant barrels are popular. Some barrels have insert sleeves requiring precision manufacture. These can extend the barrel's working life by improving their abrasion and/or corrosion resistance. They are alloys or blends containing boron, chromium, cobalt, manganese, nickel, silicon, or tungsten. Their actually chemistry may vary widely after final machining is complete. Also, the chemistry and hardness are not necessarily indicative of wear resistance. Other important factors are how these elements are combined and where they are located relative to the bore.

Screw Operations

A screw is basically a helically flighted hard steel shaft that rotates within a plasticizing barrel to mechanically process and advance the plastic being prepared. Its rotating drive system can be powered by a hydraulic or electric motor. The use of electric motors tends to increase the melt-processing efficiency and thus the production rate. They have a wide operating range to meet different performance requirements for all the different plastics processed. The objective is to obtain maximum throughput with nearly perfect melt quality. It is an endless task, due to the limits and variabilities of the plastics, machines, and controls (see the section on Plastic Material and Equipment Variables in Chap. 11). Since the first use of screw plasticators, improvements have been achieved in the resulting melt quality. This effort continues with advancement in screw design (Chap. 3) in response to the changing melting characteristics of plastic material (Chap. 6).

Machine Sizes and Design Variations

The clamping forces and maximum shot volumes of large injection molding machines have progressively increased during the course of their development. In the 1970s, "large" machines began at a clamping force of 1,100 tons; more recently, the clamping force (the definition is somewhat arbitrary) has moved to above 1,700 tons, as in the IMM shown in Fig. 2-53 from the past (1, 4, 44, 79, 82). The majority of IMMs of small and medium clamping force are delivered in standard forms. With increasing machine size, customers require greater departures from standard dimensions and designs. Even in the

Mold Closed

Mold Open

Fig. 2-53 The Billion IMM with 390-lb (177-kg) shot.

small and medium ranges, there are special forms of a machine for particular applications. The proportion of such machines grows with increasing clamping force. Table 2-3 provides some information on clamp forces of different manufactured machines, past and present.

The schematic (Fig. 2-53) of the Billion machine, with 390-lb (177-kg) shot and 10,000-ton clamping force, shows the principle of the mold-clamping system. It has eight locking columns and four closing cylinders: A, approach cylinders; B, clamp cylinders; C, locking columns; D, ejector; E, pivoting, cylinder (closing); F, return cylinder; G, pivoting plate; H, support plate; and J, pivoting cylinder (opening). This 92-ft (28-m) long machine's clamp system does not use tie-bars in the conventional sense. Instead, the stationary, rear, and moving platens are mounted within a series of eight extremely rigid steel frames, which serve as both a guide for the platens and a means of absorbing the clamping reaction forces in a most effective manner. This elimination of conventional tie-bars also means that a considerably greater platen area is made available for mold mounting than would otherwise be the case. Maximum opening and closing speeds are 1200 mm/sec (47 in./sec).

The machine was designed for coinjection. It can accommodate up to three injection units: one 200-mm ($7\frac{3}{4}$-in.) reciprocating screw with a calculated shot volume of 31,500 cu cm (1,920 cu in.) located centrally, flanked by two 180-mm diameter (7-in.) screw-transfer units with a calculated shot volume of 70,000 cu cm (4,270 cu in.).

Big machines often differ from catalogue items only in their dimensions. However, by using a method of construction based on the part that is to be produced and that departs quite markedly from the standard method, they can demonstrate totally new directions for injection molding technology. Decisions about the form a large machine will vary largely determined by the kind of product that will be made on it. Aspects such as secondary operations, handling of the parts, and mold changes, as well as others, have to be taken into consideration. These requirements determine whether or not a machine is built to catalogue specification.

A horizontal press is standard on large machines, and common on others. In principle, however, a vertical press offers advantages. For example, the effect of closing force on the melt during injection is smaller if the axis of the mold is vertical. Demolding is easier because when the press opens, the molding

Table 2-3 Examples of past and present injection molding clamping forces

Manufacturer	Country of origin	Clamp (tons) Toggle	Hydraulic	Hydromechanical	Vertical
Arburg	Germany	28–77	17–220		17–83
Autojectors	United States				5–250
Barwell	Taiwan				160–640
Battenfield of America	Austria, Germany	66–700	10–110	121–9,000	22–300
BMB SpA	Italy	110–3,000			
Boston Matthews	United Kingdom	10–50	10–50		10–22
Boy Machines	Germany		24–88		24
Bucher	Switzerland, Germany		100–770		500–1,000
Chen Hsong	Taiwan			25–2,000	
Cincinnati Milacron	United States	33–550	250–4,000		
DHC	Korea	27–1,000			
Engel	United States	500–4,000		1,500–4,000	500–1,500
Esgo	United Kingdom	35			35
Ferromatik	Germany		20–400		50–400
Fu Chun Shin	Taiwan	65–350		440–1,760	
Gluco	United States	20	40		5–200
GoldStar Cable	Korea		30–950		
Hettinga	United States	40–330	125–5,000		125–2,500
HPM	United States	75–500	35–4,000		125
Hull	United States		6–250		25–700
Husky	U.S., Can., Luxembourg			135–4,000	
Illinois Precision	United States				25
Itairy	Hong Kong	27–880	715–2,750		
Jaco	United States		50–75		40–80
Japan Steel Works	Japan	15–6,600			
Kawaguchi	Japan	50–650			
Krauss-Maffei	Germany		65–880	1,100–4,000	880–1,980
Kurto/John	Germany		25–35		
Main Group	Italy				40–250
Mannesmann Demag	Germany	44–4,400			
Meiki	Japan		40–3,300		500–1,800
Mir	Italy	50–5,000		105–2,590	105–745
Mitsubishi	Japan		90–6,600	15–50	
Multiplas	Hong Kong				16–1,100
Nan Rong Mechanical	Taiwan	50–880			
Negri Bossi	Italy	40–1,120			
Netstal	Switzerland	66–386			
Newbury	United States	35–700	35–700		30–200
Niigata	Japan	35–500			50–150
Nissei	Japan		11–1,500		33–5,000
PH Trueblood	United States				30–300
Presma	Italy	Up to 400			To 100
Presses KAP	France				10, 30, 40, 60
Remu	Italy			650–6,000	
REP	France		180		50–750
Rochester Plastic Machinery	United States	85–1,500			
Sadaplast	Switzerland				30–50
Sandretto	Italy, U.S.	60–1,430		1,430–5,000	

(Continued)

Table 2-3 (*Continued*)

Manufacturer	Country of origin	Clamp (tons) Toggle	Hydraulic	Hydromechanical	Vertical
Sharp Industries	Taiwan	85–1,400			
Shinwa Seiki	Japan		55–400		
Stork	Holland	65–1,400			
Sumitomo	Japan	27–385	8–82	110–606	27–82
Techmire	Canada		45		45
Technoplas	Japan		50–170		
TMC	Taiwan	66–1,000	7–80		
Toshiba	Japan		30–950	1,350–5,500	
Toyo	Japan	20–500			
Truematic	United States				15–250
Ube Industries	Japan	500–7,000			
Van Dom	United States	85–500	55–3,000		
Victor Plastic Machinery	Taiwan	50–275			
Vimm Machine	United States				60
Welltec	Hong Kong	55–1,760			
Windsor	Germany		400–4,000		400–1,000

remains at the center of the mold and can then be shed onto a retractable table.

In contrast, the great height of a vertical press is a disadvantage, particularly for mechanical monitoring and maintenance. In most cases, it is so serious that the decision is in favor of the conventional horizontal clamping unit.

Injection units on large machines are also normally horizontal. Vertical arrangements have two particular disadvantages: (1) the height of the injection unit required for heavy parts is usually substantial and (2) raw-material feed is less straightforward than with horizontal injection units, particularly with large screw diameters, where complete filling of the screw flights in the feed zone is not certain (Chap. 3).

Special processing injection molding machines have to be included in the evaluation when fixing the optimal machine configuration. These types of machines include coinjection or multicomponent, foam, gas injection (gas pressure), and others, as reviewed in Chap. 15. Each of these special types has potential advantages in fabricating molded parts. As an example, the gas injection process opens up special possibilities for large moldings. With such parts, the possibility of reducing the clamping force and reducing frozen-in stresses can assume great importance.

Knowledge about the secondary operations required on a molded part is an important factor in the selection of a machine. Sprue removal usually presents no problems and is normally carried out by a robot. However, additional operations like printing, inserts, conveying parts, and packing have to be considered when working on material flow. For determining the best machine configuration, experience shows that it is useful to analyze product flow in the reverse direction. The route of the part from packing back to production by the machine is studied. The use of this type of analysis can also provide new information about the optimum method.

Parts produced on large machines cannot be demolded simply by brute force. Product-handling technology becomes indispensable. They are often so heavy or their surfaces so sensitive that the risk of damaging them is great. And it is also usually the case that the moldings cannot be removed from below. For that, machines would have to be set up higher than would otherwise be necessary. This involves much more effort and considerable cost. With large machines, therefore, handling devices and/or robots are normally required for demolding (Chap. 10).

Handling devices can carry out simple sequences of movements. Final positions are determined by cams and limit switches.

Because the machines and handling devices are so large, operators would have to stand on ladders while setting them up, thus risking accidents. Also, there is no guarantee that the required level of precision would be attained by manual setting of movement limits. There are various devices that perform the required tasks with ease and safety. They include freely programmable industrial robots, cantilever-arm portals, vertical or horizontal removable gripping devices, etc.

Rebuilding and Repairs

Retrofit projects should be well planned and evaluated in comparison with buying a new machine, mold, or other equipment. Machine retrofits can be tailored to meet the customer's performance requirements at 40 to 70% of a new machine's cost. Even though the initial capital expenditure is thus lower than for a new machine, the long-term economic value of retrofitting can be questionable. In order to provide a good basis for a decision, a technical evaluation matrix system using weighted criteria and a time-related method for judging the economic value of an investment are required (111, 587)

Major rebuilding and repairs involve screws and barrels; molds are also involved. Screws and barrels are expensive and can cause downtime when damaged or worn. It may be practical (cost-efficient) to repair rather than replace. It is common practice to rebuild a worn screw with hard surfacing materials. Quite often the rebuilt screw will outlast the original screw in service. The larger the screw, the more economic screw repairing becomes. Usually it does not pay to rebuild screws of 2-in. (50-mm) diameter or smaller.

Stripping, Polishing, and Plating

After a period of service, most screws become scratched, carbonized, and/or discolored by the hot, high-pressure plastic. They are difficult to clean and tend to lose their original feeding characteristics. If they have been plated (usually with chrome), the chrome may be gone in some places or peeling in others. It is best to refurbish a screw in this condition by stripping off the old chrome, polishing, buffing, plating, and buffing again. The screw will look much better and will also perform better, at little cost and short time out of service. Most screws that are rebuilt are also stripped, etc.

Machine Downsizing and Upsizing

Machines are designed to process certain quantities of different plastics at certain rates. Very few of the installed IMMs run shot anywhere near the full shot capacity of the injection unit. Typical usage is from 25 to 60%, but in many cases it is even less. Most suppliers of IMMs offer several sizes for any given clamp tonnage. At the time of purchase, the thinking regarding the injection unit is to "make sure we have enough melting capacity." The problem with that is that having too much shot capacity can render some machines unusable for certain materials and applications. One reason is excessive residence time that causes degradation of the plastic; this situation can exist for most engineering plastics.

Another problem with very large injection units and small shot sizes is related to the plasticating-screw design. In order to properly plasticize the plastic, the screw should impart about 40% of the energy needed to melt the plastic via the drive motor. If the screw speed is too low and the screw's metering-zone flight depth is too deep relative to the throughput needed, very little energy will come from the screw drive, resulting in a poor melt mix and poor part quality control. One solution is to purchase a completely new, smaller injection unit. Another, usually less expensive, is to downsize the existing injection unit. Downsizing requires smaller screws, smaller heaters, modification of the barrel shroud, etc. Often it is possible to utilize greater injection pressures. Consideration should also be given to limiting the

- Supervision of the operator's actions and incentives may reduce the predictable human error that results in accidents.
- Employee vigilance, involving the individual who is closest to the machine and knows its characteristics, is essential. The presence or absence of a noise, changes in speed, or changes to the finished product may be signs of a developing hazard. These changes should be identified and corrective action taken if necessary.

Seeing that responsibility for safety covers the entire machine life, we need to analyze those areas that affect safety.

Identification of Hazards

Hazards are things that move, pinch, rotate, become hot, contain electricity, or merely exist and can cause hurt, injury, or loss. Some hazards on injection molding machines are obvious (e.g., the clamp closing). Others (e.g., a component failure due to contamination) may not be obvious or even predictable. It therefore becomes the responsibility of each person associated with the machine to be alert to potential hazards.

Hazards that are obvious must be evaluated as to their probability of occurrence and the danger they pose. This evaluation begins in the development of the initial concepts and continues throughout the product's life.

As an example of this evaluation process, consider the clamp motion of an IMM. The traditional IMM consists of a mold that is opened and closed under great force. This motion creates a hazard that cannot be eliminated. Historically, parts have been removed by human operators. This action, coupled with predictable human error, creates a high risk of serious injury.

Since we cannot eliminate this hazard and still have a usable tool, we must explore the second alternative in creating safety—that is, removing the human and his or her predictable errors from the hazard. This can be done by incorporating devices such as conveyors or robots for part removal. The use of automatic part-loading devices for setup, or the remote placement of operating devices, away from the hazard area, may also help in preventing a serious injury.

Some applications may require a person's presence at the hazard site. We must then turn to the third alternative, which is to guard against the hazard by placing a physical barrier between it and the person. Safety gates with interlocking devices are used for this purpose.

As a final alternative, when physical barriers cannot be used, warning signs notify the operator that a hazard exists. The necessity of part removal requires a part exit area. Reaching into this area might only be prevented by warning the operator against this hazard. Only after all other alternatives have been exhausted should the machine design rely on warning signs. The operator's reacting to situations before thinking of the consequences is one human error that is predictable.

The design of the machine reflects intended safety, but improper assembly, variations of critical part tolerances, loose belts, etc. can all destroy design integrity. Thorough testing and inspection of the IMM must be performed and documented to maintain this integrity.

The manufacturer's analysis procedure must also be used by the machine user. He or she has taken control of the machine and must also assume responsibility for maintaining its safety. The use of a checklist (as shown later in this chapter) may help in maintaining safety.

Auxiliary equipment, often added to improve productivity or safety, may create additional hazards. Pinch points, obstacles that cause tripping, or carelessly wired devices are examples of such hazards. The actions of personnel in the area may also create new hazards. One way to guard against new hazards is to establish and enforce safety rules for the molding department.

Safety Built into the Machines

This section discusses some of the IMM's inherent hazards along with appropriate preventive measures.

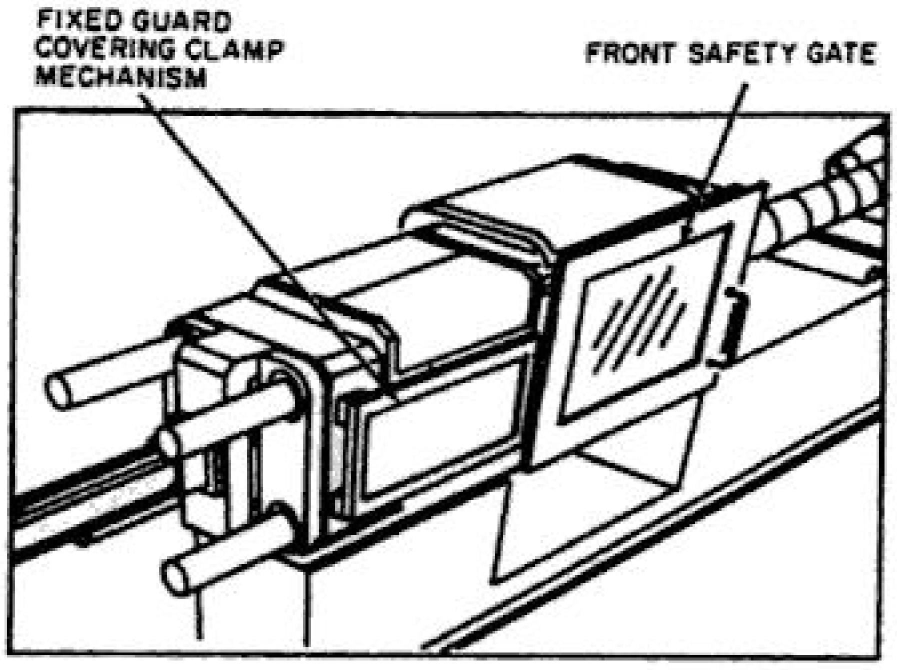


Fig. 2-56 Frontal area of a horizontal IMM, highlighting movable and fixed safety guards.

Clamp areas The closing and opening of most machines is accomplished through the use of either a hydraulic clamp or a toggle linkage. As the hydraulic clamp opens or the linkage operates, pinch areas can be created. Sheet metal or expanded-metal shields are typically used to guard the area behind the movable plate. Similar guards may be necessary across the top of smaller machines. Care must be taken to ensure that the guards do not themselves create pinch hazards. These guards should be electrically interlocked to prevent machine operation if they are not in place (Figs. 2-56 and 2-57).

Front safety gates The front safety gate is used to deter entry into the mold parting line during the closing and injection portion of the machine cycle. Gates include a window for viewing the clamp motion. The window should conform to the American National Standard Safety Performance Specifications and Methods of Test for Safety Glazing Material Used in Buildings, Z97.1-1975. Gates are designed so that they must be fully closed before the clamp can be closed.

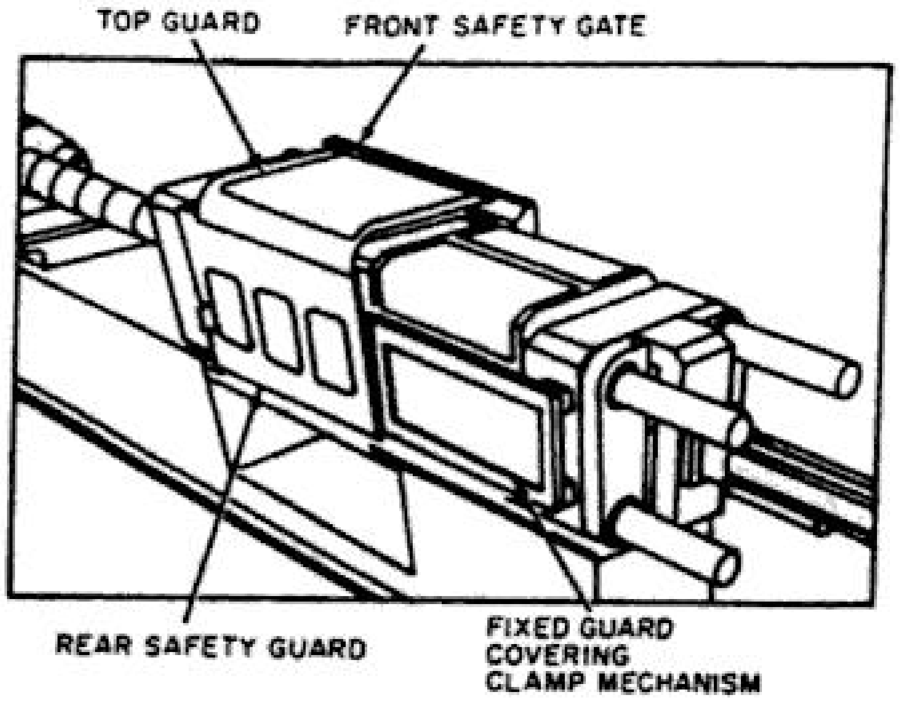


Fig. 2-57 Top and rear area of a horizontal IMM, highlighting movable and fixed safety guards.

Power safety gates On larger machines, safety gates are often closed and opened with hydraulic or pneumatic power. The pressure and speed used in these systems should be kept metered down so that the gate itself does not create a pinch or strike hazard.

The leading edge of the powered gate should be constructed with some form of resilient padding. If the closing force or inertia of the gate creates a pinch or strike hazard greater than can be cushioned with padding, a leading-edge safety strip such as the type used on elevator doors should be provided.

During opening of the power gate, the rear edge could strike anyone in its line of travel. The gate should be designed so there is no pinch point. The rear edge of the powered gate should be padded with a resilient material. Safety strips along the rear edge are not normally considered necessary.

Interlocking the safety gates Because of predictable human error that normally causes an accident, the safety gate should be interlocked to prevent the operator from entering the hazard area created by the clamp.

The primary interlock used on the safety gate is an electrical device such as a normally open limit switch, held closed when the gate is fully closed (Fig. 2-58). The device should be positioned so that it cannot be operated inadvertently. The limit switch is wired into the circuit in such a way that the clamp will

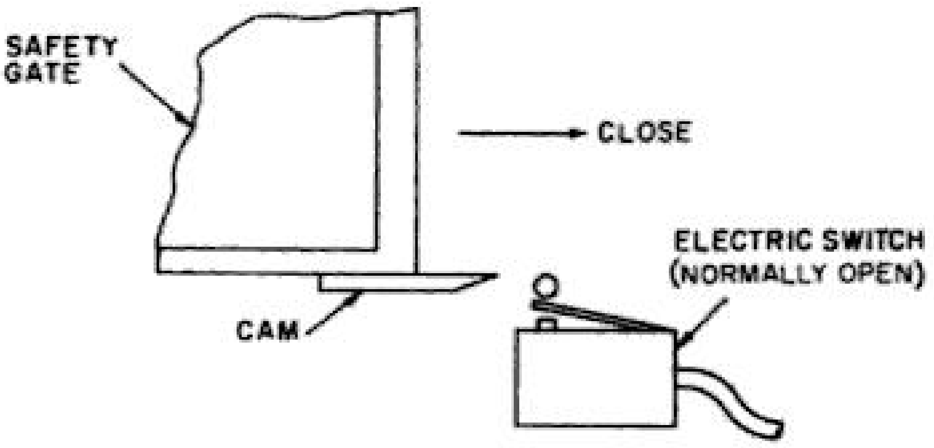


Fig. 2-58 Example of an electrical interlock.

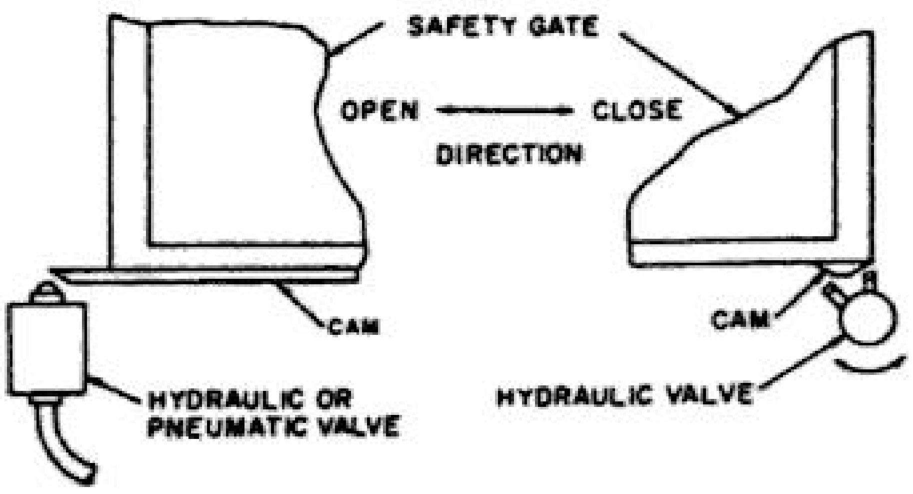


Fig. 2-59 Example of a hydraulic interlock

stop its motion or reverse to an open position when the device is released. The reaction of the clamp is determined by the portion of the cycle the machine is in. The clamp should not be allowed to open during the injection portion of the cycle, because the molten plastic being forced into the mold could escape from the mold cavity, creating additional hazards to the operator or damage to the mold. The limit switch is also positioned so that it will be released before the gate is opened 1 in. Allowing the gate to open a greater distance might allow an operator to reach into the hazard zone before it is safe. The machine operator will depend on the position of the gate to tell him or her when it is safe to reach into the mold area.

As a backup to the electrical interlock, a hydraulic or pneumatic interlock is used (Fig. 2-59). This device provides redundancy, should there be a failure of the electrical interlock. The hydraulic or pneumatic device has been incorporated into circuits in different ways, the most common being to interrupt the flow of pilot oil to the main clamp's four-way valve, preventing the valve from shifting to a closing position. Some circuits block the pilot flow, whereas others divert it away from the valve. Another method is to provide a blocking piston on one end of the spool that physically prevents the valve spool from shifting to the clamp close position. A less desirable method is to dump the entire volume of oil through the hydraulic interlock valve to the tank. This method is normally not practical because of the large volume of oil present.

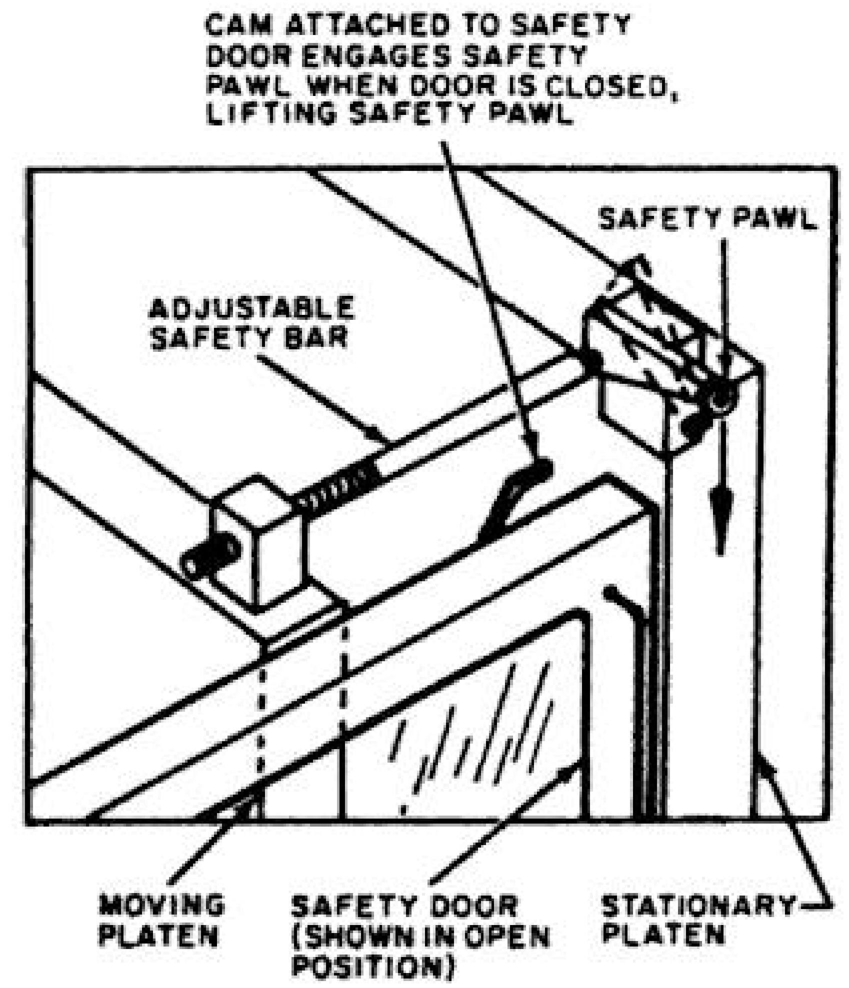


Fig. 2-60 Example of an interference-type mechanical safety bar.

Mechanical safety devices A mechanical safety device is a bar used to physically prevent the clamp from closing when the safety gate is open (Figs. 2-60 to 2-62). Initially, mechanical safety devices were used on toggle machines to guard against inadvertent closure of the mold due to a mechanical failure of the traversing cylinder. Later, hydraulic presses, which did not have this mechanical failure problem, began appearing with mechanical safety devices. This

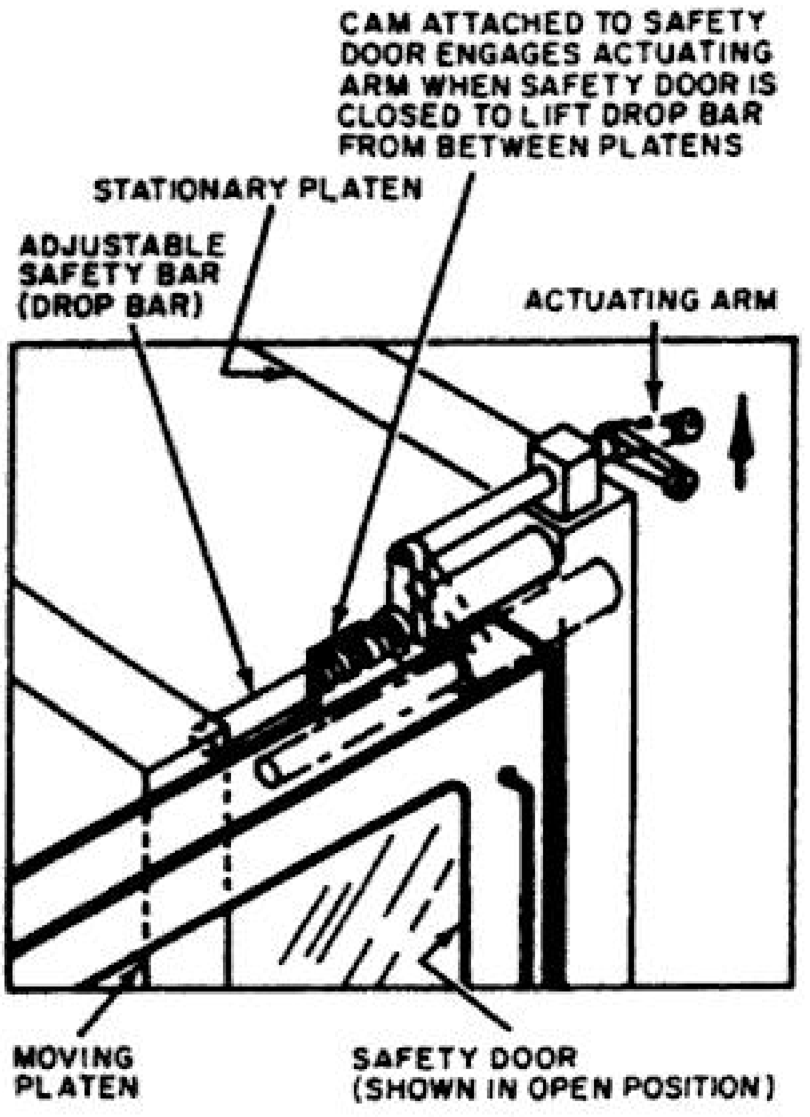


Fig. 2-61 Example of a drop-bar-type mechanical safety.

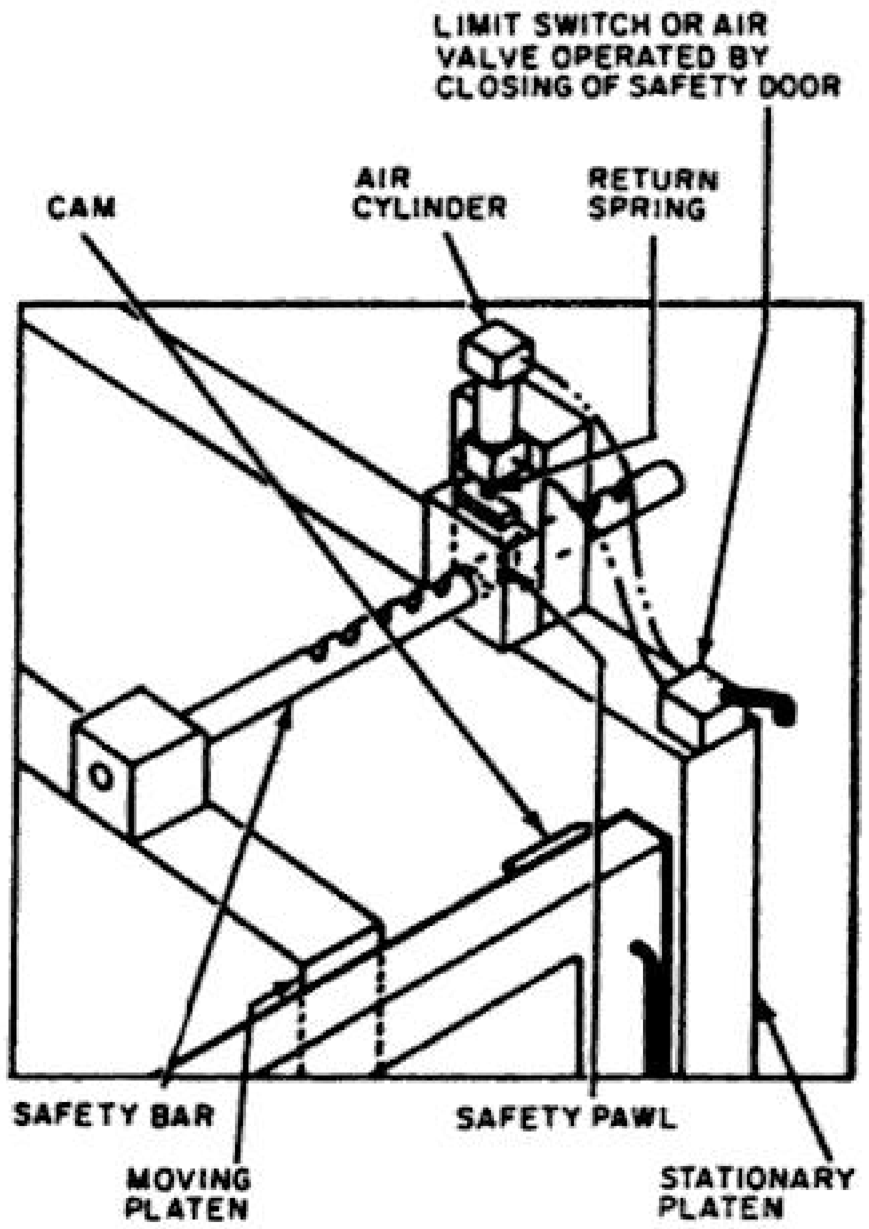


Fig. 2-62 Example of a rack–pawl-type mechanical safety.

device became a third interlock for the safety gate.

Three basic design types of mechanical safeties are commonly used in the industry: an interference type, a drop-bar type, and a rack–pawl type. The type is usually determined by both the design and the size of the machine. The interference type consists of an adjustable safety bar attached to the moving platen. A safety pawl is attached to the stationary platen and engaged by a camming device on the safety gate. As the gate is closed, the pawl is lifted, removing the mechanical interference and allowing the mold to close. The drop-bar type consists of an adjustable safety bar attached to the stationary platen. This bar pivots into and out of the die space. A cam attached to the safety gate engages an actuating arm on the bar to lift it from between the platens when the safety door is closed. This type of bar is normally limited to the smaller machines. The mass of the bar required on larger machines makes it difficult to lift.

One drawback of these two types of safety bars is that they must be properly adjusted as the mold height changes. Improper adjustment could make the safety device inoperative. Therefore, it is recommended that some type of interlock device be added to prevent operation should the bar be out of adjustment. Mechanical or electrical interlocks are commonly used for this purpose.

The rack–pawl mechanical safety bar is a third alternative. This consists of a ratcheted (notched) bar attached to the moving platen. A safety pawl attached to the stationary platen is lifted by an air cylinder when the safety gate is closed. If the gate is opened during the clamp opening stroke, the pawl ratchets back on the bar. This type of safety bar has the advantage that it will prevent clamp closure along the opening stroke and not merely in the full-open position. This feature is particularly beneficial in toggle-type machines where the breaking of a small traversing cylinder could cause a repeat stroke during the clamp opening cycle. The disadvantage of this type of device is that a safe condition exists only when the safety pawl is positioned in a notch. On small, short-stroke machines, a condition might exist in which the safety pawl is never positioned in a notch.

Each of these safety devices places a mechanical obstruction between the stationary and moving platens. This obstruction in itself can create a new pinch point that may need guarding.

Rear guards The clamp area opposite the machine operator must be guarded to prevent access to the closing hazard. This area is normally used only for maintenance or during mold setup. It is often visually blocked from the operator, who might close the clamp, believing the rear of the machine to be clear. It is therefore recommended that the rear guard be electrically interlocked to shut off the motors when it is opened.

The rear guard is typically constructed with a metal frame supporting an expanded-metal screen. It should be so placed on the machine as to leave an opening between the guard and the platens or machine frame. This allows clearance for water lines and other necessary items that are connected to the molds.

Top guards The top of the machine, or the area directly above the die space, can allow exposure to the clamp-closing hazard. The need for a guard in this area depends on predictable human error. On machines where it would be possible for the operator, standing on the floor, to reach over the top of the front or rear guard down into the hazard zone, a guard should be provided. If this guard is portable or movable for purposes other than maintenance, then it must be interlocked.

If, on the other hand, the top access area to the hazard zone is remote from the operator standing on the floor, a top guard may not be required. This might be the case on large machines or those where the front and rear guards are high enough to prevent the operator from reaching over the top. It must be assumed that if the operator or another person makes a conscious effort to climb onto the machine or another object, he or she is also conscious of the hazard now faced. This conscious effort will generally eliminate predictable human error.

Bottom or drop-through guards The bottom of the machine, or the area where completed parts drop out, can allow exposure to the clamp-closing hazard. A normal operating practice today is for the operator to sit on a stool and inspect or remove and pack-age parts. These parts are ejected from the mold and drop onto a conveyor or chute that brings them to the operator. The predictable human error is that the operator will reach up into the hazard area, should a part become hung up. To guard against this, the machine should be constructed so that the distance the operator must reach is greater than the normal reaching distance. This meets the design objective of removing the operator from the hazard. If this is not possible, guards should be provided to prevent access. The guard design is critical because part removal is essential to the molding operation. If the guards restrict part removal, they themselves become targets for removal.

Maintenance of guards The guards for the clamp, when properly designed and maintained, will normally protect the operator. The users of the IMM must keep these guards in good repair, reconstruct them when necessary, and keep them installed on the machine.

Feed openings Material for IMMs is loaded through hoppers into the plasticating barrel. The rotating and reciprocating screw, within the barrel, creates a hazard for anyone inserting a hand into the opening. This hazard must be guarded against. If guarding is not possible, then warning signs should be used. Bridging of the plastic in the feed opening or trapped foreign matter may necessitate work in this area. In that case, the power to the machine should be shut off and a soft metal rod used to remove unwanted parts. Hands should never be inserted into the opening.

Injection cylinders Rotating rams and reciprocating cylinders create hazards at the injection end of the machine. Access to this part of the machine is necessary only for maintenance, so fixed permanent guards should be used. Interlocking of these guards is not considered necessary.

Purging protection During a material change or shutdown, material should be purged from the barrel. This should be done with a purging compound compatible with the material being used. Improperly mixed materials can cause violent reactions.

During normal purging, a shield must be provided to protect the front, top, and rear of the purging area behind the stationary platen (Fig. 2-63). The material being shot into the air may splatter onto the operator if the purge

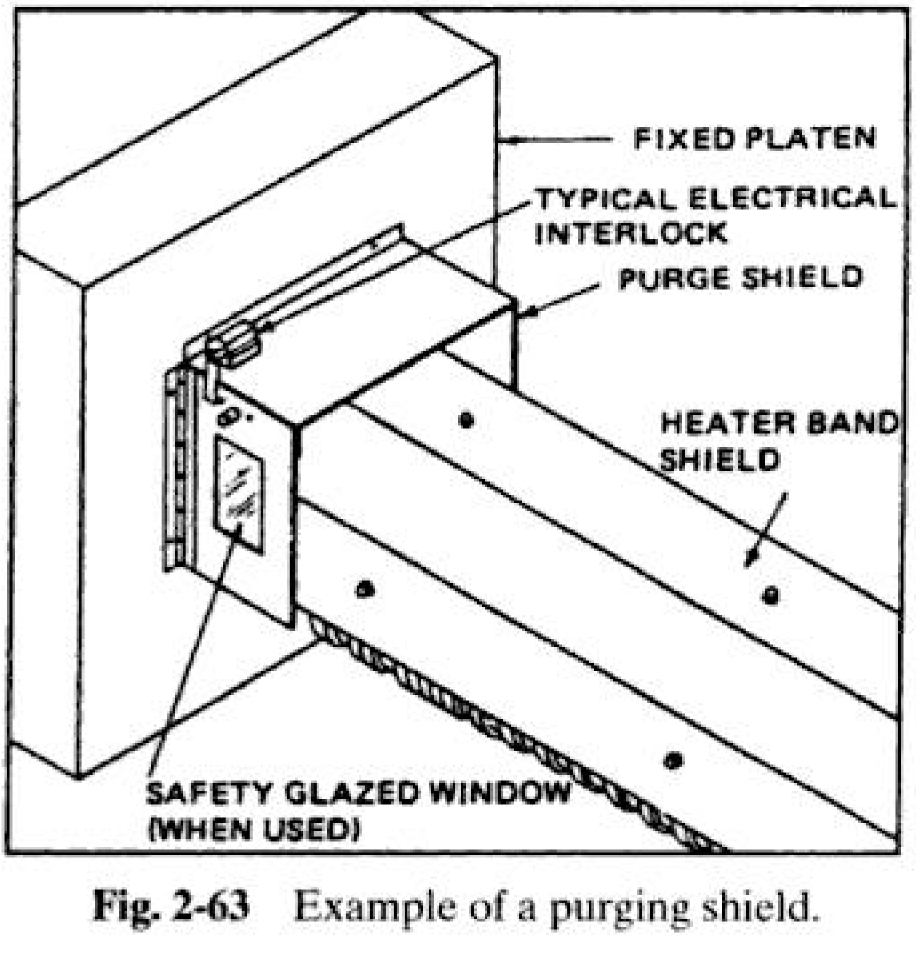


Fig. 2-63 Example of a purging shield.

Table 2-4 Safety checklist

	O.K.	NEEDS REPAIR
CLAMP:		
1. Hydraulic Cylinders:		
a. Are packing glands tight?	____	____
b. Are bolts tight?	____	____
c. Is the packing leaking?	____	____
d. Are tie-rods tight?	____	____
e. Are tie-bar nuts tight?	____	____
2. Toggle Machine Linkage:		
a. Are all bolts tight?	____	____
b. Are retainer washers on properly?	____	____
c. General condition (pins and links).	____	____
3. Plates:		
a. Are mold clamps tight?	____	____
b. Are cylinder mounting bolts tight?	____	____
c. Are there any loose parts lying on plates?	____	____
4. Safety Bar:		
a. Are anchor blocks anchored securely to plates?	____	____
b. Is the bar properly guarded?	____	____
c. Is the bar adequately guided?	____	____
d. Does the safety pawl move freely?	____	____
e. Does the safety pawl camming work?	____	____
f. Is the proper air pressure used if necessary?	____	____
INJECTION:		
1. Hydraulic Cylinders:		
a. Are packing glands tight?	____	____
b. Are bolts tight?	____	____
c. Is the packing leaking?	____	____
d. Are the tie-rods tight?	____	____
e. Are the tie-bar nuts tight?	____	____
2. Screw Drive:		
a. Are mounting studs/bolts tight?	____	____
b. Is screw secure to drive device?	____	____
3. Barrel and Front End:		
a. Is barrel securely mounted to feed device?	____	____
b. Are front end parts securely mounted to barrel?	____	____
c. Does nozzle tip properly align with die?	____	____
d. Are heating bands properly secured and functioning?	____	____
e. Are thermocouples properly secured and functioning?	____	____
HYDRAULICS:		
1. Hoses:		
a. Are hoses properly used and installed?	____	____
b. Is the proper hose being used?	____	____
c. Do hoses show any sign of wear?	____	____
d. Are connectors tight?	____	____
2. Piping:		
a. Are pipes and tubing properly supported?	____	____
b. Are weld repairs made properly?	____	____
c. Are flange bolts tight?	____	____
d. Are tubing connections tight?	____	____

(*Continued*)

Table 2-4 (*Continued*)

	O.K.	NEEDS REPAIR
3. Hydraulic Leaks:		
a. Welds.	____	____
b. Hoses and/or fittings.	____	____
c. Pipes and/or connections.	____	____
d. Ball joints.	____	____
e. Packing.	____	____
f. Are leaks cleaned up?	____	____
SAFETY GATES AND GUARDS		
1. Safety Gate:		
a. Are the rail support brackets tight?	____	____
b. Are the rails secure to the brackets?	____	____
c. Are the roller/trolley, etc., tight?	____	____
d. Are the gates secure to the trolley?	____	____
e. Are the gates/windows in good condition?	____	____
f. Is the door edge safety working properly?	____	____
g. Does the hydraulic/pneumatic interlock work properly?	____	____
h. Does the electrical interlock work properly?	____	____
i. Does the gate prevent access to pinch points?	____	____
2. Rear Guard:		
a. Are the mounting brackets secure and tight?	____	____
b. Are guards secure to the brackets?	____	____
c. Are the guards in good condition?	____	____
d. Does the electrical interlock work properly?	____	____
e. Does the rear guard prevent access to pinch points?	____	____
3. Fixed Guards:		
a. Are the guards securely mounted to the machine?	____	____
b. Do the guards prevent access to pinch points?	____	____
c. If guards are removed for reasons other than maintenance, are they interlocked to prevent machine operation?	____	____
4. Top Guards:		
a. Is the top of the machine adequately protected by either a guard or height to prevent someone standing on the floor from reaching over the top of the safety gate?	____	____
b. Is the top guard, if needed, properly interlocked?	____	____
5. Purge Guard:		
a. Is purging prevented by machine circuitry when the safety gate is open?	____	____
b. Is the purge guard securely mounted to the machine?	____	____
c. Is the purge guard in good condition?	____	____
d. Does the purge guard contain a safety-glazed window in good condition?	____	____
e. Does the purge guard protect the front, rear, and top of the purging area?	____	____
6. Pump Coupling Guards:		
a. Are guards in place?	____	____
b. Do guards adequately cover rotating shaft?	____	____
7. Feed Openings:		
a. Are feed openings guarded against accidental insertion of hands?	____	____

Table 2-4 (*Continued*)

	O.K.	NEEDS REPAIR
SAFETY TAGS:		
1. Are tags properly located?	______	______
2. Are tags legible and understandable?	______	______
ELECTRICAL:		
1. Controls and Operator's Panel:		
a. Is the inside clean and neat?	______	______
b. Is the disconnect working properly?	______	______
c. Is the panel door kept closed?	______	______
d. Are there any uncovered openings?	______	______
e. Are all tags legible?	______	______
f. Are all buttons and switches working properly?	______	______
g. Do all components work freely?	______	______
2. Wire Ways and Junction Boxes:		
a. Are all covers on boxes and connectors?	______	______
b. Is any sealtite broken, or are connectors loose?	______	______
3. Switches:		
a. Are all covers in place?	______	______
b. Are switches free of oil and water?	______	______
c. Are all switches working freely?	______	______
4. Electrical Circuit:		
a. Are circuit drawings legible?	______	______
b. Are the circuit drawings up-to-date for the machine?	______	______
c. Have any circuit changes been made, and have they been approved by the machine builder?	______	______
d. Does the circuit conform to the latest state of the art?	______	______
5. Machine and Auxiliary Equipment:		
a. Is electrical interface wiring done safely?	______	______
b. Is there duplication or confusion of terms on various pieces of equipment?	______	______
c. Is the overall electrical circuit safe?	______	______
d. Has the interface created any electrical, hydraulic, or mechanical safety hazards?	______	______
OPERATOR SAFETY:		
1. Has the operator been trained?	______	______
2. Can the operator read all tags?	______	______
3. Can the operator understand the tags?	______	______
4. Has the operator had time to become familiar with the machine?	______	______
5. Is the operator's manual easily accessible to the operator?	______	______

12. When lifting, keep your back straight and lift with your legs. If the load is too heavy, get help or notify your supervisor.

13. Report all injuries to your supervisor immediately.

14. Wear safety shoes and safety glasses at all times.

15. Follow directions for mold setup as posted on the setup sheet. No unauthorized deviations are to be made.

16. Be sure barrel and mold temperatures are maintained. Report deviations to your supervisor.

17. Maintain correct hydraulic-oil temperature and level.

18. Check to see that the nozzle tip is properly seated in the mold before starting.

19. Check pressure gauges for proper settings.

20. When in doubt, ask your supervisor.

21. Never climb on the machine while it is running.

22. Whenever you leave your machine, be sure it is turned off.

23. At the start of each shift, be sure the machine is operating properly and that molding parameters are set properly.

24. If the machine must be shut down, plastic materials should not be left in a plasticizing cylinder heated to operating temperatures.

25. Material should never be left in the mold. Remove the molded parts and sprue before shutting down the machine.

26. Before working on the machine or between plates, be sure proper lockout procedures have been followed.

27. When purging material from the plasticizing cylinder or changing materials, be sure of the compatibility of materials being used. Check with your supervisor for this information.

28. Follow all posted danger and caution signs.

American National Standard

The standard ANSI B151.1 is periodically revised by the American National Standard Institute (ANSI) pursuant to its safety requirements for the "Construction, Care, and Use of Horizontal Injection Molding Machines." This project on safety requirements was initiated under the auspices of the Injection Molding Section of the Machinery Division (D. V. Rosato was a member and prepared the original draft) and the Safety Committee of the Molders Management Division of the Society of the Plastics Industry, Inc. (SPI).

Both divisions of the SPI have long been concerned with operator safety on plastics processing equipment. Accordingly, each section of the divisions has established a safety committee charged with the task of establishing necessary standards.

A standard treating the construction, care, and use of horizontal injection molding machines is complicated by the wide variety and sizes of machines manufactured and in use, and by the virtually infinite combinations of parts being produced, production methods used, and operating conditions existing in industry today.

The primary objective of this standard is to eliminate injuries to personnel associated with machine activity by establishing requirements for the construction, care, and use of these machines.

To accomplish this objective, the SPI committee decided to approach the problem of machine safety from two directions:

1. Eliminating by design certain recognized construction hazards and establishing standard approaches to design so that machines available from competitive manufacturers will have similar operational characteristics
2. Safeguarding the point of operation to protect the operator from recognized hazards

To aid in the interpretation of these requirements, responsibilities have been assigned to the builder, rebuilder, modifier, and employer.

Recognizing the impossibility of updating equipment and changing operation methods allied with existing machines immediately after the approval date of this standard, a three-year period has been provided to employers for modifying machines.

Safety Standards

Contemporary U.S. safety standards have embraced an array of relatively new machine-guarding safety concepts and requirements. Among these are: (1) positive-opening contacts, (2) positive-guided relays, (3) tamper-resistant and difficult-to-defeat safety systems, (4) fail-to-safe components and safety systems, (5) single-component failure control reliability, and (6) positive-mode vs. negative-mode interlock installation (344).

These requirements can be found in different standards, such as OSHA 29 CFR 1910.212 General Machine Guarding Requirements for all Machines, UL 491 Power Operated Machine Controls and Systems, EMD 89/392/eec European Machinery Safety Directive, ISO 14000 Processes, ANSI/RIA 15.06 Safety Requirements for Industrial Robots and Robot Systems, and ANSI B11.19 Safeguarding Reference for B11 Machine Tool Safety Standards.

Plasticator Safety

If you pack plastic into a steel pipe with no included air, plug both ends of the pipe, and heat it, you have made a bomb. The damage it can cause depends on the amount of heat applied that produces internal pressure until the pipe or plugs let go. This situation relates to a plasticator, even though it is extremely rare that an explosion occurs, because safety devices/plugs are located in the barrel wall. To eliminate any potential problem, proper startup procedures are used.

If all the plastic between the screw and barrel is not melted, a frozen plastic plug could form. Precautions used include one or more release plugs in the barrel wall and/or the bolts used to attach components to the barrel. These devices are designed to be released when pressures reach specified amounts where different processing equipment operates under different pressures (see the subsection on Barrel-Venting Safety in Chap. 3).

Barrel-Cover Safety

To avoid electrical shock from the heater barrel, keep the barrel guard in place. Consider using integral armored leads or ceramic terminal covers on all adapter-zone and nozzle heater bands. In addition to being important to operator safety, barrel covering can yield important bonuses in melt quality and energy savings.

Plant Safety

All processing equipment should have procedures to operate and to meet safety requirements; they are available from equipment suppliers, who can also help to understand how to handle plastics (otherwise do not buy the equipment). Topics include safe startups, location of safety devices, etc. Processing plastics usually generates a lot of force and heat; machines for that purpose are built to run safely, but they must be treated with understanding and respect (465).

Safety Information

Various sources provide valuable information. If an equipment manufacturer does not provide safety information, consider not buying its equipment. The SPI and ANSI are major providers of safety information, pertaining to equipment and to many different aspects in the plant, such as material handling, material storage, and the different upstream and downstream equipment.

Designing Facilities

Upgrading

When plastic fabricators consider replacing an inefficient facility with a state-of-the-art operation, two initial pitfalls must be avoided: they can overestimate difficulties or underestimate them, with results ranging from expensive too disastrous. These problems can be avoided by assembling a qualified team that includes an architect, a contractor, and if needed a consulting engineer who have experience with plastics manufacturing plants (288, 341).

Choosing the correct site is often the most critical decision in the process. This decision depends on various criteria such as adequate access to power and water. Consider what combination of highway and rail access will work best for receiving raw materials and shipping products. Check local zoning laws with regard to the permissibility of silos or

In addition, the injection mold has to be designed in such a way that it meets the extremely high cleanliness requirements. Normally required greasing of dowel pins, ejection mechanisms, and core pulls is not possible, since the contamination and wear generated would neutralize the clean-room conditions. However, if special materials and dedicated know-how are used, the molds can be run dry, that is, without external lubrication.

If parts have to be packed without handling next to the machine, removal by robot (Chap. 10) is essential. Robots are normally installed above the mold. Any abraded particles will therefore fall directly into the mold and lead to contamination. This means that robots also have to meet stringent cleanliness and minimal abrasion requirements.

Raw materials (virgin or recycled) that are to be used for injection molding under clean-room conditions must themselves be produced under these cleanliness conditions. Only a few material suppliers offer such materials. Special testing and careful packing in vacuum-tight containers are essential if processing under clean-room conditions is to be problem-free.

All auxiliary equipment (Chap. 10) required for production that affects clean-room conditions must come up to the same high standards. This applies especially to cooling and heating equipment; conveying devices; and all pipe, tube, and other couplings. Products must be protected by reliable special packaging. As soon as possible after molding, the parts must be packed in containers so as to exclude subsequent contamination.

Release agents should never be used during clean-room processing. Every molding should be fully documented with information about particle level during production, temperature of feedstock materials, purity of batch (determined on batch samples), and injection molding conditions during production. The customer should receive these data in the form of an enclosed quality certificate (Chaps. 12 and 13).

As demands for parts molded in a clean-room environment increase, more molders are becoming interested in clean-room production and particularly in how IMM features influence cleanliness. As an example, particles can be monitored and filtered, but the oil and grease thrown into the air by IMMs can become a problem. Hydraulic-oil mist from the oil storage tank, hydraulic cylinder, or toggle mechanism is the machine's biggest potential polluter. Oil and grease are needed for machine operation, but cannot be allowed on molded parts. Oil mist can be reduced by sealing the oil storage tank and venting excess mist outside the room. The entire toggle mechanism can be enclosed to eliminate drippage that ordinarily would fall from the toggle joints to a machine's base. Full-drip trays can be placed under all manifold and hydraulic components to catch any oil that is lost during maintenance.

Other special features can be incorporated in the machine to minimize the throwing off of particulates. Greaseless nylon bushings and shoes for the movable platen can be used to cut down on grease contamination without sacrificing performance. Totally enclosed fan-cooled motors can help minimize dust in the area of the molding machine. The coils of a standard electric motor are open to the air and collect dirt that can be blown into the room when the motor is started. An enclosed motor will collect less dirt.

Because the maintenance of a clean atmosphere is so expensive, clean rooms have to be as small as efficient operation will allow. Machines are placed close together, which generates annoying levels of heat and noise, if not actual part contamination. Heat should be reduced both for comfort and to maintain the balance of cooling, filtering, and humidity in the room. The machine's barrel is the major contributor of heat, although the press's motor and hydraulic system contribute to the problem. A thermal blanket around the barrel will help contain the heat, or a heat shield can be used and incorporated into a system to vent the heat outside the room. The major source of noise is vibration from motors and pumps resonating in the machine base. This vibration can be reduced by securing motors on rubber mounts and connecting pumps to the base with a rubber hose instead of metal pipe.

Advances in microprocessor technology, along with mechanical design modifications, have improved clean-room molding productivity. Programmable microprocessor controls can continuously monitor the temperatures, pressures, and timing under which a piece was molded. Molders of pharmaceutical pieces and food packaging are required to provide government agencies with documentation of molding conditions, and other molders may be required to do so in the future. Machine controls equipped with linear potentiometers to monitor distances, pressures, and flows can give a molder hard-copy documentation of injection and clamp settings. This printed record can fulfill the FDA's GMP (good manufacturing practices) obligations and allow the fast and accurate setup of repeat runs of delicate precision parts.

IMMs designed for clean-room use are usually identifiable by their stainless-steel gates and white paint. These cosmetic additions make the machine easier to clean, an advantage whether or not the machine is in a clean room. Molders of electronic parts and food packaging often choose to use machines with clean-room features to keep their molding shops clean even if they do not maintain any areas that have clean-room certification. For these molders, the decision to operate a clean-room shop is based on the expectation of profitability.

The complete package of clean-room options described above can add surprisingly little to the cost of an injection molding machine—usually less than 10%. The number of clean machines will continue to grow as more molders are able to make these design features work for them.

Noise Generation

It is better to prevent noise generation in machinery during the design stage than to try to reduce it later. There are injection molding and auxiliary equipment machines built with exceptionally low noise levels. However, at times noise reduction by external means is preferred. Design changes to reduce noise sometimes decrease efficiency. Although this is relatively unimportant in small, fractional-horsepower equipment, it becomes costly and wasteful in large, high-power machinery that has been designed for maximum performance and efficiency.

One of the best ways to reduce machinery noise by external means is to place it in an acoustic enclosure. Such enclosures provide more dB reduction per dollar than any other form of industrial noise control. For this reason many are in use today, and they are very efficient when designed and installed correctly. A good acoustic enclosure can easily reduce noise by 20 to 30 dB and more; a very simple design, by 10 dB.

The performance of an acoustic material can be described in terms of its transmission coefficient T, which is defined as the fraction of incident sound power transmitted through the material. Materials with low transmission coefficients isolate noise better than materials with higher coefficients. If the material has, say, a transmission coefficient of 0.01, when airborne sound strikes one side of a wall, only 1% of the sound comes out the other side. Of course, the sound does not "go through" the wall; it makes the wall vibrate, and this radiates the sound again. Sound coefficients vary with frequency.

The sound transmission loss TL of a wall or barrier measures its sound-isolating ability. It is the ratio of the airborne sound transmitted by the wall to the airborne sound striking the wall. It is expressed in decibels (dB).

TL is related to the transmission coefficient by the equation

$$TL = 10\ \log(1/T)$$

For example, a wall having a TL of 30 dB transmits only 1/1,000 of the energy incident on it. The transmission loss, like the transmission coefficient, varies with frequency. To make a correct design, it is necessary to know the frequency, or frequency band, of the noise to be isolated. Approximate TL values for several different materials, at 1,000 Hz, are given in Table 2.6.

Table 2-6 Sound transmission loss *TL*

Material	*TL* Thickness[a]: $\frac{1}{16}$ in.	$\frac{1}{8}$ in.	$\frac{1}{4}$ in.	4 in.	6 in.	8 in.
Steel	33	38	39			
Aluminum	23	25	26			
Sheet lead	37	43	49			
Glass		25	26			
Dense poured concrete				42	46	50
Hollow-core concrete				37	39	41

[a] 1 in. = 2.54 cm.

Startup and Shutdown Operations

To obtain the best processing melts for any plastic, one starts with the plastic manufacturer's recommended heat profile and/or one's own experience (see the section on Processing Different Plastics in Chap. 6). There are different starting points for the various types of plastics, which have to be interfaced with the different capabilities of IMMs to be used. The time and effort expended on startup make it possible to achieve maximum efficiency of performance vs. cost for the processed plastics. By the application of common sense with available control systems, the information gained can be stored and applied to future setups (Chap. 7). As explained above (see the sub-subsection on the Hunkar test in the subsection "Injection Molding: A Technology in Transition to Electrical Power"), electric IMMs can provide higher process capabilities with quick startup and setup without the oil heating required in hydraulic IMMs. Specialty IMMs have their own procedures, as reviewed in the subsection on Structural Foam Molding the section on Startup for Molding in Chap. 15.

Molding Operation Training Program

The basic instructions presented in this section are intended to develop a training program in steps conducive to easy learning, which over time will result in full knowledge of the molding operation. The program provides instruction that can be made to fit any time span, in order to suit individual abilities to absorb information while actively engaged in learning by doing.

Suggestions are included for the substitution of calculated values for those obtained by the trial and error method, in the interest of conserving time of personnel and minimizing the loss of material. The main object of the instructions is to give each worker in the injection molding operation a good understanding of every element that goes into the operation; the worker, in turn, having gained the needed knowledge, should take full advantage of such information by putting it to constructive and productive use.

Under practical operating conditions, learning the injection molding process takes place in stages:

- The first stage covers the running of an injection molding machine.
- The second stage involves setting molding conditions on a prescribed set of parameters for a specific plastic material and a specific mold that will produce acceptable parts.
- The final stage is devoted to problem solving and fine-tuning of the operation, which will lead to high productivity and part quality.

Table 2-7 provides general information and is a guide for injection molding settings.

Specific information on all machine settings and plastic properties is acquired initially from the plastic supplier's data sheet on the material to be used. Initial setting information can also be obtained from workers in the molding plant who have experience in processing the same material.

Packing In general, once the mold is filled initially, additional material is added to the mold by the injection pressure to compensate for thermal shrinkage as the material cools. This process is called *packing*. Too much packing will result in highly stressed parts and may cause ejection problems. Insufficient packing causes short shots, poor surface, sink marks, welds, and other defects. The proper amount of packing is determined by trial and error or with the assistance of computerized process simulation. The material will continue to flow into the mold as long as there is injection pressure, provided that the gate is not sealed. When no more material enters the mold, contraction of the cooling material results in a rapid decrease in the pressure in the mold. The residual pressure caused by the original deformation of the steel of the mold and the adhesion of the plastic to the steel must be overcome by the knockout system to eject the parts.

First Stage: Running an IMM

In the injection molding operation, a granular plastic material is softened by heat so that it will flow under pressure and can be delivered to a tightly closed mold, where it is held for a specified time. The mold is maintained at a temperature that will permit the injected material to become solid in a short time. After a prescribed time interval, the mold is opened and the injected material released as a finished product.

If we can clearly understand and picture the basic process, the more involved actual operations will be easy to understand and remember. The general description just given applies to thermoplastic as well as thermoset materials (see Chap. 6 for details on materials).

Now let us describe the operation of a machine in greater detail, starting with an *injection screw machine* for thermoplastics arranged for semiautomatic operation. Hard plastic granules are delivered to a hopper, from which they are fed through a throat onto a rotating screw. The screw moves and compresses the material through a heated chamber, where the granules soften to such a degree that they become fluid and can be delivered to a section of the heating chamber known as the measuring chamber. In addition to turning, the screw will on proper signal stop its rotation and move in a forward or reverse direction as a plunger.

When enough material for the mold cavity is supplied to the measuring chamber, as determined by the controlled distance of the backward-moving screw, an electrical command is given to it to act as a plunger and inject the fluid material into the tightly closed mold. The mold is maintained at a relatively low temperature that will cause the plastic to become rigid after a set length of *curing* time. Then the mold opens, and at the same time, the operator causes the gate to open, the parts are ejected from the mold (sometimes into the hands of the operator), the mold is checked to see that it is fully clear of plastic, the gate is closed again, and a new cycle is started.

The molded parts are briefly checked for quality and consistency in appearance and disposed of either for storage or for other operations, such as gauging, auxiliary operations (hot stamping, etc.), or packaging. Normally, the work at the press is planned so that the attendant is kept occupied during the cycle; in this way, consistent results in part quality, cycle time, and safety of operation can be anticipated. The operation of cycles becomes repetitive, and the attendant should exert every effort to have the motions organized and coordinated so that variables will not be introduced that could influence the consistency of quality and uniformity in the cycle. The best results are obtained when all elements in a cycle are repeated consistently from shot to shot.

In spite of all precautions taken by the operator and setup person with respect to

Table 2-7 Guide to injection molding (and extrusion) machine settings[a]

Resin and process	Specific gravity (g/cu cm)	Density (lb/sq ft)	Specific volume (cu in./lb)	Specific volume (cu cm/g)	Injection temperature (°F)	Linear mold shrinkage (in./in.)	Specific heat (btu/lb · °F)	Water absorption (% in 24 h)	Maximum Water content allowable for molding (%)
ABS extrusion	1.02	64.0	27.0	0.980		0.005	0.34	0.25	
ABS injection	1.05	65.0	26.0	0.952	500	0.005	0.40	0.40	0.20
Acetal injection	1.41	88.0	19.7	0.709	390	0.020	0.35	0.25	
Acrylic extrusion	1.19	74.3	23.3	0.839		0.004	0.35	0.30	
Acrylic injection	1.16	72.0	24.1	0.868	450	0.005	0.35	0.20	0.08
CAB	1.20	74.6	23.1	0.833	440	0.004	0.35	1.50	0.15
Cellulose acetate extrusion	1.28	80.2	21.6	0.781		0.005	0.40	2.50	
Cellulose acetate injection	1.26	79.0	21.9	0.794	450	0.005	0.36	2.40	0.20
Cellulose proprionate extrusion	1.22	76.1	22.7	0.821		0.004	0.40	1.70	
Cellulose proprionate injection	1.22	75.5	22.9	0.828	425	0.004	0.40	2.00	0.25
CTFE	2.11	134.0	13.1	0.473	550	0.008	0.22	0.01	
FEP	2.11	134.0	12.9	0.465	600	0.010	0.28	<0.01	
Ionomer extrusion	0.95	59.6	29.0	1.050		0.007	0.54	0.07	
Ionomer injection	0.95	59.1	29.2	1.060	420	0.007	0.54	0.20	
Nylon 6	1.13	70.5	24.5	0.886	550	0.013	0.40	1.60	0.15
Nylon 6/6	1.14	71.2	24.3	0.878	510	0.015	0.40	1.50	0.15
Nylon 6/10	1.08	67.4	25.6	0.927	450	0.011	0.40	0.40	0.15
Nylon 6/12	1.07	66.8	25.9	0.935	500	0.011	0.40	0.40	0.20

timer," which for several seconds maintains pressure on the material in the cavity.

5. When the injection overall timer times out, the melt *decompression timer* starts. When melt decompression times out, the nozzle valve (if used) closes, the extruder starts turning, preparing the plastic for the following shot, and the clamp high pressure drops to *low hold*.

6. While turning and feeding the plastic into the shot chamber, the extruder moves backward (to provide space for the shot) until it contacts a limit switch that causes it to stop.

7. The *overall timer* or *clamp timer* times out, bringing about slow opening of the clamp.

8. The opening clamp activates a limit switch that causes its rapid reverse movement until another limit switch is contacted that slows down the clamp travel to the point at which the final limit switch contact provides the stop for the open position.

9. A *clamp-open timer* is provided that either sets a time for removal of parts from the mold or, in the case of automatic (continuous) molding, can be energized by the reverse stop limit switch to perform the same electrical function as performed by manual gate closing and the activation of the limit switch by the gate.

All the limit switches and timers carry out their commands in an orderly manner, and any interference with this systematic arrangement by pushing a control button will throw the plan out of order. There are certain steps required to restore the orderly working of the machine, but unfortunately, these steps vary from machine to machine. When we recognize that each timer alone can have three modes of operation, upon timing out, for resetting to zero for the following restart, we realize that extreme care must be exercised in restarting a machine after interruption. Close attention to the details of machine operation is very much in order here.

Repeating the cycle in a consistent manner is obviously the major responsibility of the machine operator. Also, certain observations must be made that will lead to a better understanding of the process and will aid the worker's advancement in the field.

Certain details require attention:

1. A machine in good working order should produce no unusual noises. It should close the mold by rapid movement of the ram, slow down as the mold faces come within $\frac{1}{16}$ in. of each other, and finally shut the mold by squeezing action under high pressure (no banging). During mold opening, about the first half inch should be done slowly, followed by rapid movement up to the distance at which ejection begins and then slowing down to a stop at the open position.

2. The tie-rods of the machine and leader pins of the mold should be adequately lubricated to prevent excessive wear and associated problems.

3. The temperature of the hydraulic oil should be within the limits on the gauge mounted on the machine; overheated oil will bring about higher leakage in hydraulic pumps and valves, thereby making it difficult to maintain the required pressure for injection and clamping cylinders. Maintenance of constant pressure on the components is an important factor in producing acceptable parts.

4. The extruder screw travel distance, forward and reverse, should be repeatable ensuring reproducible shot volume in mold filling. If screw travel is not in the normal forward position, not all the required volume of material is injected into the mold, with the result that parts are not dense, excessive shrinkage takes place, and the surface is not smooth. An increase in the backtravel of the screw may cause an excess of material to be delivered and may overpack and flash the parts, causing enlarged dimensions, waste material, and possibly the need for a deflashing operation. Adequacy of the supply of material in the hopper should be checked when it is expected to reach a low level.

5. The injection high pressure, which can be read by depressing a button (at the hydraulic panel for injection pressure) during the injection time, should be checked for deviation from the required setup reading.

Uniform pressure on the plastic in the mold is a very important determinant of product quality.

6. Temperature settings for the injection cylinder at each zone should be recorded and checked at intervals of about 4 h to see that unexpected variations are not introduced. A plastic material is not a pure chemical of certain description, but encompasses all kinds of additives (colorants, plasticizers for flow, flame retardants, ultraviolet stabilizers, antioxidants, etc.), so the heating temperature must be confined within limits, not just for the sake of the basic plastic, but also in the interests of protecting the additives. Excessive temperature and/or prolonged exposure to that of the normal melt heat can cause gassing, degradation of the material, and change in flow properties, all of which can have a most undesirable effect on parts.

Automatic operation of the thermoplastic injection screw machine is in every respect the same as that for the semiautomatic method, except that the stop limit switch for the clamp ram will initiate the clamp-open timer, which in turn will restart the cycle while the gate stays closed.

Molds that have been designed and tested for automatic operation require only intermittent observation to ensure that everything is working in an approved manner. The details requiring attention in the semiautomatic operation also apply to this mode, but the operator in this case will be concerned with checking product quality, ensuring an adequate supply of granular plastic material, and removing the molded parts to a designated station, in addition to these details. The duties of an operator can be to perform auxiliary operations, if necessary, at a single press or to attend to a number of cavities and required checking for quality. An operator can attend 4 to 16 presses.

A slight modification in the way a mold functions can enable automatic operation and thus improve productivity. Automatically operated molds usually result in better and more consistent quality and fewer rejects of parts. In most cases, mold life is also enhanced.

The thermoset injection machine is, from the operator's point of view, very similar to a thermoplastic machine. There are, however, some additional points of concern:

1. The material content in the hopper should not fall below the half-point, so that there is always a sufficient weight of material to exert a pressure that will ensure good flow to the throat.

2. The temperature in the cylinder is critical. It must be observed that no increase in the setting occurs that could cause hardening of the plastic in the chamber, since this could cause the operation to be interrupted.

3. The nozzle of the cylinder must be maintained at a low temperature to prevent hardening of the material in it. This is usually accomplished by retracting the nozzle from the sprue bushing of the mold. (The mold is usually at temperatures of 300°F and up, depending on the material.) The nozzle can also be maintained at a low temperature by incorporating a circulating coolant in it. Whatever the method employed, it must be seen that the material in the nozzle is maintained in soft condition to ensure free flow for each shot.

Handling plastic materials A machine attendant may be involved in occasionally supplying plastic material to the hopper. However, in most cases, he or she will deal with defective parts, runners, and sprues to be reground for future use. It must be recognized that plastic materials can be easily contaminated, unless proper precautions are taken to assure chemical cleanliness. The following is an explanation of how to keep plastic materials protected from contamination.

In addition to machine variables, there is one major source of problems in controlling quality plastic parts—namely, the cleanliness and conditioning of the material as it is placed in the hopper. If we keep the material free of contamination—that is, free of foreign matter as well as other plastic—our chances of making good products are enhanced. It takes only a few parts per million of contamination to affect the properties of some materials. The way contamination will influence properties is not known without extensive research. Even when materials are intentionally combined, the component ingredients lose some of their original characteristics while gaining some new ones. Take, for example, ABS, an alloy of acrylonitrile, butadiene, and styrene. Although ABS itself has desirable properties, the styrene part of it has lost its rigidity and clarity, the butadiene has lost chemical resistance, and the acrylonitrile has lost resistance to ultraviolet rays and weathering. The combination, however, has toughness, impact resistance, and good moldability, entitling it to a vital place in the plastic family.

It must be remembered that the ABS combination is achieved under predetermined favorable conditions. Accidentally contaminated materials may not look objectionable, but properties may be adversely affected. Think for a minute of one cubic foot of material as containing about two million cubes of the material; it only takes 10 to 20 similar cubes of another material to cause contamination. To make matters still worse, these small cubes in many instances cannot be distinguished from each other, nor can they be seen in the molded part if it happens to be opaque.

A greater variety of materials will be used in the future, and the products that they will be applied to will be more intricate and functionally more important. Thus, it behooves us to seek immediately a foolproof manner for handling the materials so that all dangers of contamination are eliminated, and the chances of weakened parts are avoided. Above all, care, and more care, will be needed. (See Chap. 10 on material handling and size reduction/granulating.)

Second Stage: Parameter Setting and Starting a Job

Principles of machine operation During the process of converting a plastic raw material into a finished molded product, three basic elements in modeling—time, temperature, and pressure—must be correlated in a way that will produce a part with anticipated properties. Most deviations in product quality can be traced to variations from established values in time, temperature, or pressure. Changes in any of these individually or in combination spell problems in product properties and performance characteristics.

Time involves these elements: time beginning with material entering the heating cylinder until injected into the mold (also called residence time in the cylinder); time of injection into the mold; time of maintaining pressure in the mold cavity; time of solidification, or *cure time*; press open time; press opening and closing time; time of part ejection in relation to mold opening time.

Temperature is affected by the temperature of material entering the hopper; throat temperature; heat contributed by screw compression and rotation; heat absorbed from the cylinder and the setting arrangement of pyrometers in the heat zones; averaging of heat by continuous mixing and homogenizing up to injection time; mold temperatures; flow control of coolant in mold passages for desired temperatures; and temperature of the environment.

Pressures that require consideration are the injection high pressure (the pressure needed to fill cavities to proper part density); the hold pressure (the pressure that is maintained on material during solidification and prevents backflow into the nozzle area); the back pressure, which influences mixing and feeding of material into the measuring chamber; and the clamp pressure, which achieves mold closing.

Principles of the molding operation The molding machine has the function of injecting molten plastic material into a tightly closed mold where the shape of a product is formed. The mold is kept closed for a specified time, the cure time, during which the fluid material becomes solid and rigid. A coolant circulates through passages in the mold, so that heat from the fluid plastic is transferred to the mold and from there to the circulating fluid, a process that accelerates the curing (solidification) of the part. At the end of cure time, the mold is opened, and the parts are ejected, ready for packaging or other operations if

Fig. 2-65 Schematic of an IMM.

required. At this point, a new cycle begins. Now, let us see in detail how the machine carries out its job. (See Fig. 2-65.)

The cavity half of the mold is attached to the stationary platen (7), where it is centered by means of the locating ring. The core half of the mold is mounted on the moving platen (8). When the press gate in front of the mold is closed, a hydraulic circuit is activated that causes the main ram (9) to move forward at a fast rate. This movement is brought about by supplying a large volume of oil from pumps directly into the booster ram (10). This oil exerts a pressure on the body of the main ram (9), causing it to slide over the booster ram (10) and move forward until at a designated position the moving main ram actuates a limit switch that sends a signal to the hydraulic circuit ordering the high-volume pump to dump its oil at low pressure into the prefill tank (11), while at the same time, the low-volume pump keeps supplying its oil to the booster ram (10), thus causing slow main ram movement.

The pressure at which this slow movement takes place is controlled by a mold protection valve. The pressure of this valve is set at a low figure (around 200 psi), so that the pressure exerted on mold halves, if something is caught between them, will be low and not cause damage to the mold. The space vacated in the clamp cylinder housing (12) is filled with oil by gravity from the prefill tank (11) through the opening of the prefill piston (13) in its retracted position. The mold halves make contact at the low speed of the ram movement, and at this point, another limit switch closes the prefill piston (13) and activates a high-pressure pump (2,000 to 3,000 psi), which will apply its full pressure over the main ram (9), holding the mold halves tight and resisting opening when plastic material is injected into the mold at pressures up to 20,000 psi. This second limit switch also initiates the movement of the injection ram (14), which injects the plastic into the mold.

Injection is carried out by the front of the screw (2), which contains a shutoff valve (15) that prevents any possible backflow of the fluid plastic. The screw is firmly attached to the injecting ram (14), whose movement takes place at a fast rate (usually in about 1 to 2 sec for the full shot capacity).

The injection time is controlled by a timer (the injection high timer), and the ability to respond to the timer setting is determined by the pressure of injection and fluidity of the material.

The speed of injection can be varied by means of a flow control valve that can bypass a desired amount of the pump oil and thereby reduce the speed. This valve usually has 10 bypassing positions, thus providing a considerable degree of injection-speed variation.

Once the shot is completed, the high-volume oil injection pump is ordered by a signal from the timer to dump its oil into the prefill tank (11) at low pressure; at the same time, a low-volume pump (hold pump) maintains pressure on the material in the cavity until the gate through which the material was fed freezes and prevents back flow to the cylinder. (Back flow can be caused by the pressure within the cavity if the feed gate is open.) The hold-pump duration is set by the injection hold timer. At the expiration of this timer, the screw starts rotating, picks up material from the throat in the cooled chamber (16), and moves, compresses, and shears it in the extruder chamber (3), where it absorbs heat and liquefies before entering the measuring portion of the injection chamber.

The extruder barrel is heated by strip heater bands (18). A group of heaters is divided into zones, with each zone having a pyrometer for controlling the temperature. There are usually three or four zones on the extruder chamber. The extruder work—represented by feeding, compressing, and shearing of the material—partly shows up as heat induced in the plastic. The heat needed to fluidize the plastic is derived partly from the work of the screw, the balance coming from the strip heaters of the extruder chamber.

As the material comes off the extruder screw (2), it creates pressure on the front face of the screw, causing it to retract so that a space is created for the incoming material required for the shot. This backward movement of the screw makes it necessary to push oil out from behind the injecting ram (14).

The displaced oil passes through a controlled valve, which can be adjusted to provide varying degrees of resistance for the screw's backward travel. This resistance, known as the back pressure, is utilized to provide good mixing and homogenizing of the material in the injection chamber. When a slight temperature adjustment is needed for the material that is to be injected, a small increase in the back pressure will accomplish this requirement. The duration of screw rotation is determined by a limit switch, which is activated by the backward-moving screw at a position where the necessary volume of material required for the shot has been reached. The screw limit switch may also start a melt decompress timer, which will cause continued limited backward movement of the screw. This additional screw movement creates a space in front of the screw that permits the built-up pressure to decrease enough that, when the mold opens, no drooling of plastic takes place.

The final stop of the screw movement usually coincides with the expiration of the cure time as determined by the corresponding cure timer. On a signal from the cure timer, the press starts opening the mold. This is accomplished by feeding oil from a small-volume pump into the space behind the ram bushing (17). This causes the press to start opening slowly; then another limit switch is actuated by the ram movement, which orders a large volume of oil to be fed into the space so as to shorten the press opening time. Since the

Some specified physical conditions for processing are worth noting.

Melt temperature A range of temperatures is given within which adjustments can be made in order to obtain favorable fluidity of a material.

Mold temperature A range of values is again given, within which adjustments may be made if pyrometer readings indicate that such a step will improve quality and productivity.

Injection pressure More accurately, this means the pressure needed in the cavity to produce consistent quality of parts. It is a very important processing datum. The reading on the "injection pressure" gauge is a pressure that is composed of several incremental pressure drops—within the heating cylinder, through the nozzle, through the sprue bushing and runners, through the gate, and then through the cavity—together with the pressure required at the end of flow to produce a dense part with a smooth surface. The pressure at the end of the flow in the cavity need only be 2,000 psi for many materials, and this value may only be $\frac{1}{5}$ to $\frac{1}{10}$ of the gauge pressure reading, depending on the size of pressure drops that were listed. The most important reading is the one that determines the quality of the part, which is made at the end of the material flow and is in many cases about 2,000 psi.

Process control devices are made that limit the cavity pressure to a specified predetermined value, and they have proved very successful in minimizing rejects. The consistency of injection pressure in the cavity is an essential element in producing uniform parts. The values shown on processing sheets refer to gauge readings and are intended to indicate whether or not the material flows easily and is readily compressible.

Back pressure on material The back pressure is the resistance to backward movement of the screw during preparation for a subsequent shot. This pressure is exerted by the material on the screw while it is being fed into the shot chamber. During rotation of the screw and the material under pressure, thorough mixing of the polymer is achieved, and some temperature increase also results. In dealing with heat-sensitive and shear-rate-insensitive materials, care must be taken to keep this value within prescribed limits.

Screw torque There are two basic torque settings available on the machine. In practice, it has been found that the high torque setting is rarely adjusted and the low torque setting would be adjusted only if a highly liquid melt material is being molded, requiring high speeds of screw rotation.

Screw rotation speed This is related to the work input into a material; higher speeds are applied only when insufficient heat is absorbed from the cylinder for a particular shot. Heat-sensitive and shear-rate-insensitive materials do not tolerate the highest speeds.

Vents There is a maximum vent depth beyond which the flow of material will not take place. However, this depth will be located away from the gate (by at least 90 to 180°).

Types of nozzle Two types of nozzles are available: the general-purpose and nylon types. With the advent of screw-type injection machines and effective utilization of the melt decompress feature, the drooling present with a general-purpose nozzle while molding nylons can be effectively controlled. This is because the check-ring shutoff system fits the barrel properly to produce effective suction at the point of the nozzle outlet.

Drying temperature Materials that are moisture-sensitive and those that may pick up moisture for some other reason will have to be dried before molding. A drying temperature is used that will permit the removal of moisture without causing the granules to adhere to each other, behavior that could cause bridging over the throat where the screw picks up the material. It is also useful to set the water valve for cooling the throat so that its temperature will not be too low, causing condensation on the plastic, or too high,

Table 2-9 Examples of mold forces

Bolt size (in.)	Engagement in platen (in.)	Slot in clamp (in.)	Holding power in clamp (lb)	Torque wrench (in./lb)
$\frac{1}{2}$	0.75–1.0	$2\frac{13}{16}$	32	210
$\frac{5}{8}$	$1\frac{5}{16}$–$1\frac{1}{8}$	$3\frac{3}{8}$	45	340
$\frac{5}{8}$	$1\frac{5}{16}$–$1\frac{1}{8}$	5	35	340
$\frac{3}{4}$	$1\frac{1}{8}$–$1\frac{5}{16}$	$3\frac{1}{8}$	50	450
$\frac{3}{4}$	$1\frac{1}{8}$–$1\frac{5}{16}$	5	40	450
1	1.5–1.75	$5\frac{5}{16}$	80	900

causing bridging. Attention to the correct setting of the water valve can yield savings in water and heat of plastication in the chamber. The preferred method of drying is the dehumidifying process, whereby the humidity is removed and dry air supplied at the specified conditions for each material. Also available are so-called vented injection machines that are capable of removing moisture during the processing of the material. A simple test for moisture content has been developed by General Electric and is known as the T.V.I. test.

Mold shrinkage These data can be used in checking dimensions of parts, thus giving indirect verification that the setting of all parameters has been properly executed.

Specific gravity This value is used for such purposes as evaluating machine capacity in relation to polystyrene, screw travel, rate of injection, etc.

Purging information and precautionary notes If a purging procedure or shutdown steps or any other precautionary move is indicated for a specific material, that should be suitably indicated under a similar heading.

Clamping and moving the mold Attaching of molds to platens should be done in a manner that will ensure retention of the mold in position without danger of shifting or loosening. Any change of position of a mold half will place an excessive burden on the leader pins and bushings that keep the halves aligned, thus causing wear on the pins and bushings and in time affecting the quality of the parts being molded.

The conventional method of holding mold halves in place is by employing mold clamps. The platens are tapped for bolts ranging from $\frac{1}{2}$ to 1 in. in diameter, and the holes are laid out to an SPE standard design.

The forces holding a mold in the press have been analyzed, and the result is in Table 2-9. Only forged bolts with a yield strength of 120,000 psi (827 MPa) should be used. In order for each clamp to hold with equal force, a torque wrench is indicated.

When the calculations are made for an actual clamping system, the number of clamps should be divisible by four, since there are four clamping faces. For example, mounting a 300-lb (136-kg) mold with $\frac{1}{2}$-in. bolts would give $\frac{300}{32}$, or 9.37 bolts. To be divisible by 4, 12 clamps, or 3 on each side, are required. In all cases, the clamp surface should be parallel to the clamping slot and platen. The closer the holding bolt is placed to the flange of a mold, the higher is its holding power.

Moving a mold to the press and removing it to storage are normally done by means of chains or wire-rope slings. These auxiliary means for hoisting a weight are treated in technical handbooks under such headings as "Crane Chain and Hooks" and "Strength and Properties of Wire Rope." Additionally, the Federal Government's OSHA prescribes certain regulations for weight handling and makes the user liable to stiff penalties if they are not followed.

Under average conditions of a molding shop, the task of frequent inspection of the hoisting means, during as well as at the approaching end of their useful life, should be assigned to one responsible person. This person should obtain literature from the suppliers of these devices and become familiar with such information and use it to instruct others in the safe handling of molds. Improperly lifted molds can be a hazard to workers and damage presses in the event they fall. They can also be damaged and rendered unusable.

Note: At this point in the instructions it is desirable to become familiar with the previously reviewed hydraulic system of the machine so that the following descriptions will be easier to comprehend.

Guidelines for molding parameters The literature on processing of plastics usually suggest limits within which the controlling instruments should operate, but seldom do we find explanations for the prescriptions.

The setup sheet, which is expected to contain all the needed information for starting a job and getting ready for a production run, is in itself a very useful explanatory tool.

The implementation of this information will be good if one has an understanding of all the items on the list and their variables, as well as the factors surrounding them. It will be the aim of this sub-subsection not only to list every item considered vital to successful operation, but also to provide information that will aid in the proper interpretation of such items. The systematic arrangement and listing of the items is the setup record (Table 2-10).

Description of setup record The setup record is made in order to establish the most favorable operating conditions for each mold in a particular press. These favorable conditions pertain to good product quality, minimal rejects, and shortest possible cycles. Once these favorable operating conditions are established and approved by management, they should be faithfully executed. Should any modifications become necessary during some future run, they must be implemented only with the approval of the authorized individual in charge of plant management. In such an event, the setup record should be suitably revised, or an additional one made that indicates the reason for modification and the elements affected.

The setup record is a most important document in starting a job. If properly interpreted and precisely carried out, this record should result in the same quality, consistent cycles, and low quantity of rejects every time the job is in operation. For these reasons, it is desirable to describe each column of the record and point out what factors enter into the determination of a particular setting. Thus, those filling out the record and those applying it to the setup will have the same understanding of the information at hand. The goal is to acquaint those involved with the setup and the running of the operation with this description so that the job is carried out in a standardized manner leading to good performance.

If we consider that 1 sec of machine time alone is worth between $\frac{3}{4}$ and $1\frac{1}{2}$ cents (depending on machine size), and each machine produces at least two shots per minute, or 720,000 shots a year, we can see that a single second wasted during one shot can amount to about $7,200 per year. With these kinds of values in mind, the exact reproduction of the settings indicated on the setup record becomes imperative.

Discussion of injection molding parameters The most productive setup sheet will implement the basic principles of molding: time, temperature, and pressure (see earlier discussion). Only if these elements are fully explored in relation to machine specifications and material processing characteristics can we be assured that the molding operation has been optimized. For example, if the mold temperature is kept at the low end of the range because the part thickness is 0.065 in. (0.165 cm) or less, the material temperature must be in the medium to upper rage, so it can be injected at the full speed of the machine. And the pressure will be just high enough to do the filling of the cavity without opening the mold.

Let us look at some of the details connected to the setup sheet specifications.

Table 2-10 Example of a setup record for injection molding

Item	Part No.	Mold No.	Mold Type	Pcs./Mold	Mold Drwg. No.
Material	Pc. Wt.	Shot Wt.	Overall Cycle Pcs/Hr.	Clamp & Shot Size	Make & No. of Press

SET	Clamp Fwd. slow LS-2 Mold Protection		TIMERS IN SEC.	Injection High or Total Injection		MOLD MOUNTING DATA	Eye Bolts Size & No.			Water Hose Size & No.	
CLAMP CYCLE	Pressure Buildup LS-3 Prefill Closed			Injection Low			Mold Shot Height-In.		WATER DATA		
	LS-5 Clamp Fast Reverse			Cooling—Cure			Horizontal-In. (Eye Bolt Side)			Water Temp.—Cavity	
	LS-6 Clamp Slow down			Melt—Decompress			Vertical-In.			Water Temp.—Core	
	LS-7 Clamp Reverse stop			Clamp—Open			Spacer size		TEMP. CAVITY POSITION	1	
	LS-8 Clamp Overstroke			Air Ejection—on/off			Pull backs or K.O. Rods size & no.			2	
	LS-20 Hyd. Eject		TEMP. CYLINDER, NOZZLE & NOZZLE VALVE	Front, Zone #1			Mold Weight			3	
CLAMP DATA	Press Daylight			Middle, Zone #2			Time to place Mold			4	
	Clamp High—Clamp Low			Rear, Zone #3		MOLD PLACEMENT	Sling Type Size & No.		TEMP. CORE POSITION	1	
	Clamp Open—Slow/Fast			Rear, Zone #4			Lift Size			2	
PRESSURES, FEED & SPEEDS	Injection High			Time to reach settings			Type of Hold Down Clamps			3	
	Injection High-Squeeze			Melt Temp.			Heels			4	
	Injection Hold			Nozzle Temp.			No. of Hold Down Clamps		MISC. COLUMNS AS NEEDED		
	LS-25 Setting			Nozzle Valve Temp.			Hold Down Clamp Spacing—Cavity				
	Back Pressure			Nozzle V. actuated			Hold Down Clamp Spacing—Core				
	Injection Feed			Throat Temp.			"Screw Jacks" Bottom Supports				
	Cushion		FIRST SHOT	First shot feed for runnerless mold			Torque on Clamp Bolts				
						REMOVAL	Core & Cavity Temp.				
	Injection Speed Setting			Mold warm-up time			Cover with Moldsaver				
	Screw RPM			Hot runner warm-up time			Time to Remove Mold				

Factors to Consider

In the past, many parameters for mold setup were determined by the trial-and-error method, thus wasting considerable time and losing expensive material. We now have inexpensive and easy-to-manipulate process controllers that enable us to figure out many of the parameter settings correctly in a few seconds so that only minor adjustments are necessary. To go this route, we shall provide certain formulas that will enable the setup person to calculate in a few seconds what would take quite a few minutes and a considerable amount of material to accomplish by the trial-and-error method.

The machine data along with material data must be compiled for the available molding machines and materials in use at the plant, so that the needed factors will be at hand when formulas are applied to a specific problem. Some data for which formulas will be given are available from a few of the machinery manufacturers; on the other hand, many machines on the market lack detailed data that their manufacturers think the customers will not use.

The following formulas will be useful in establishing the time of material injection, rate of injection, and related information.

Determination of cubic-inch machine capacity The equipment manufacturer's designed machine shot capacity in ounces is normally expressed in terms of a standard grade of crystal polystyrene which has a specific gravity of 1.06. Machine capacity in cubic inches can be calculated from machine capacity in ounces by the formula

$$\text{capacity (cu in.)} = \frac{1.734 \times \text{capacity (oz)}}{1.06}$$

Thus, for polystyrene (specific gravity 1.06), a 32-oz, 250-ton press will have a capacity in cubic inches of

$$\frac{1.734 \times 32}{1.06} = 52.35 \text{ cu in. (859 cu cm)}$$

This is the theoretical required capacity.

Screw travel Suppose that in the above 32-oz (0.91-kg) machine, the plasticating screw has a diameter of 2.75 in. and an area of 5.94 sq in. (38 sq cm). Dividing 52.35 cu in. by the area of the cylinder, 5.94 sq in., we obtain 8.81 in. (22.4 cm) of screw travel. The usual way of measuring screw travel is by mounting an inch scale in front of the screw travel pointer. In the interest of simplification, the scale is usually in whole inches, and machine cubic inches are correspondingly rounded off to the nearest whole number. In this case, the travel distance was selected as 10 in. (25.4 cm), which made the cubic content 5.94 × 10 or, rounded off, 59 cu in. (968 cu cm). The 10-in. selection was dictated by the need for melt decompress travel, which normally is 1 in. or more above the shot travel requirement. The shot travel requirement for the 32 oz is 8.81 in.; by providing a 10-in. travel, we have a 1.19-in. (3-cm) allowance for melt decompress action.

It should be noted that the ounces of machine capacity indicated on the specification sheet are nominal, but the actual travel distance for a specific weight of shot can be figured as indicated above. These calculations show the theoretical cubic inches that correspond to shot capacity, as well as the practical values, derived by multiplying the area of the screw by its actual travel distance as shown on the scale ($5.94 \times 10 = 59$), thus giving a volume of 59 cu in.

If the shot size is given in grams, the conversion is

$$\begin{aligned}\text{cu in.} &= \frac{0.0611 \times \text{grams}}{\text{specific gravity (of GPPS)}} \\ &= \frac{0.0611 \times 28.35 \times 32}{1.06} \\ &= 52.29 \text{ cu in. (858 cu cm)}\end{aligned}$$

(*Note:* 1 oz = 28.35 g.) This value for all practical purposes is the same as the one obtained in the ounce calculations.

Let us take a practical example and apply the above information.

Example. A shot of polypropylene with a specific gravity of 0.905 weighs 14 oz (396.7 g). How many cubic inches will that be, and what screw travel will it involve?

$$\begin{aligned}\frac{1.734 \times \text{ounces}}{\text{specific gravity}} &= \frac{1.734 \times 14}{0.905} \\ &= 26.78 \text{ cu in. (439 cu cm)}\end{aligned}$$

To establish the travel distance, we take the 10-in. travel for a 59-cu in. volume and set up a proportion as follows:

$$\frac{\text{example cubic inches}}{\text{actual cubic inches}} = \frac{x}{10}$$

or

$$x = 10 \times \frac{\text{example cubic inches}}{\text{actual cubic inches}}$$

so that

$$10 \times \frac{26.78}{59} = 4.5 \text{ in. (11.4 cm)}$$

of screw travel will be needed to fill the shot of polypropylene for 14 oz of material. If the job requires a melt decompress action of 1 in., the total screw travel will be $4.5 + 1.0 = 5.5$ in.

Injection rate This rate is measured in cubic inches per second. Many machine suppliers show this information as part of their specification sheet. In the case of 250 tons and 32 oz, the rate is shown as 22.5 cu in./sec, so that the time required to fill the complete shot of 59 cu in. is

$$\frac{59}{22.5} = 2.62 \text{ sec}$$

The number of cubic inches of a plastic material injected per second, if not given in the machine specification, can be established by determining how many gallons per minute (gpm) are fed into the injection cylinder by the pump or pumps, and the diameter of the shooting piston. These quantities are, as a rule, shown on the hydraulic diagram of the machine. Since the injecting piston and screw

1. Converting machine shot capacity into cubic inches

2. Finding the screw diameter and its area, to give the theoretical travel distance of the feed screw (melt decompress *not* included)

3. Speed of screw travel

4. Flow rate in cubic inches per second

5. Converting the weight of a shot for a job into cubic inches

With the above information applied to the job at hand, we can determine the distance that screw travel is increased by the distance of melt decompress, the time needed to inject material, the timer setting for injection high pressure, and adjustments in pressure or speed of injection if necessary.

For materials that are known to be shear-rate-insensitive and/or heat-sensitive, the setting of the back pressure is important. It is also significant for other materials, but to a lesser degree. For a better understanding of this problem, let us first explain how the injection pump pressure is reflected in the material pressure in front of the screw plunger and in the mold cavity.

The force that causes the piston in the injection cylinder to move forward is the same force that moves the plasticating screw, since they are connected to each other. The force that moves the cylinder piston is the area of the piston in square inches multiplied by the pounds per square inch of pump pressure. The above force is also equal to the area of the plasticating screw multiplied by the injection pounds per square inch on the material. Putting this information in equation form, we have

$$\text{area of piston} \times \text{pump pressure} = \text{area of screw} \times \text{pressure on material}$$

If we use the 250 ton, 32 oz. press as an example, where the screw diameter is 2.75 in. (7 cm), the piston diameter $8\frac{3}{4}$ in. (22.2 cm), and the pump pressure 2,100 psi (14.5 MPa), we obtain, substituting the values in the above formula,

$$60.132 \times 2{,}100 = 5.9396 \times \text{pressure on material}$$

$$\text{pressure on material} = \frac{60.132 \times 2{,}100}{5.9396} = 21{,}260 \text{ psi (146.5 MPa)}$$

Since the force on the piston has to overcome its own friction and that of the screw, the actual pressure on the material will be reduced from 21,260 to about 21,000 psi. We can say that the multiplier of pump pressure against the cavity to obtain the material pressure is about 10 for a machine with the above specifications.

The setting of the back pressure as read on the injection-pressure gauge is on the order of 50 to 100 psi (0.34 to 0.68 MPa). If we use the multiplier of 10, the pressure on the material in front of the screw plunger will be 500 to 1,000 psi. With the material in a highly fluid condition, these pressures are adequate for mixing the material thoroughly, driving out the gases, and measuring a reasonably accurate volume for a shot. The pressures on the material can climb as high as 5,000 psi (34 MPa) (500-psi gauge reading), but pressures higher than necessary can cause excessive drooling at the nozzle, overheating the material in the measuring chamber with resultant byproducts, and consequent molding problems. Such pressure settings should be used with care, especially when we consider that the readings are made on the dial portion of the gauge, which may not be very accurate.

It was mentioned that the injection high timer setting should correspond to the maximum rate of injection of the machine. In the case of the 250-ton press, according to press specification, the time of injection would be equal to the volume of the injection chamber divided by the injection rate:

$$\frac{59 \text{ cu in.}}{22.5 \text{ cu in./sec}} = 2.62 \text{ sec}$$

If the material is injected within this period, it will be quite fluid throughout the cavity, and for practical purposes the solidification and cooling should occur in a uniform manner throughout the part. Pressure will also be applied uniformly over the molding surfaces. Both these conditions will result in good flow welds, minimal stresses in the part, and favorable appearance. On the other hand, when filling of the cavity takes 3 sec or more, the portion around the gate starts solidifying before the forward-moving material has filled the cavity, and this causes a decrease in the opening for material flow, as well as a differential rate of cooling of part surfaces. In practical terms, higher injection pressures are needed, which cause stresses in the part and unfavorable conditions for self-welding of the flow, thereby creating poor and visible welds and a finished product whose appearance does not reflect the finish of the mold.

If the injection speed is such that the material is fluid throughout the cavity, even for a very short time, that may tend to cause mold opening and flashing. This indicates that the practical values of clamping pressure for the mold projected area do not hold—for example, the 2 tons/sq in. of cavity projected area for polyethylene. Since fast injection offers many advantages in product properties, we must beware of such undesirable side effects as flashing, poor dimensional control, and waste of materials. All these occur because the pressure generated in the cavity exceeds that of the clamp.

Mold clamping pressure Let us take as an example a part molded in a 250-ton press; the material used is polyethylene. The clamping pressure that is available for keeping the mold closed, in actual terms, is not 250 tons, but on the average 10% less, or about 225 tons. The reason for this is that molding conditions are never perfect; for example, the press platens are not perfectly parallel, the mold thicknesses from front to back are not exactly the same at all points, the guide pins and bushings may not be perfectly aligned. Such deviations from ideality use up a certain part of the clamping force to get the mold tightly closed, so that both mold halves make intimate contact to prevent material leakage. Observations under actual operating conditions indicate that 10% of clamp capacity may be considered a reasonable estimate of the force used to straighten mold faces and bring them to the close condition. In the case of polyethylene, the usual requirement of clamp force is 2 tons/sq in. of projected mold area. In the selected example, the projected mold area should be $225/2 = 112.5$ or, in round figures, 110 sq in. The force that can develop in the cavity should be around 220 tons maximum in order to prevent leakage from the cavity (flashing). This means that 220 tons or 440,000 lb $= P \times 110$, or

$$\begin{aligned} P &= \frac{440{,}000}{110} = 4{,}000 \text{ psi (28 MPa)} \\ &= \text{pressure in cavity} \end{aligned}$$

Gate size The parts we are molding will be 0.090 in. (0.23 cm) thick in the shape of a box, and the material content will be 25 cu in. (410 cu cm). The recommended gate depth size is two-thirds the part thickness, and 2 gate widths is twice this depth. The gate area will be 0.060 × 0.120 sq in. (0.15 × 0.30 sq cm). What should the injection pressure gauge setting be? The pressure that is indicated on the injection gauge is that in front of the screw when the material is being injected from the measuring chamber into the mold. This pressure on the average molded product is about 50% *higher* than the average pressure in the cavity, because of the pressure drop in the nozzle, sprue bushing, runner, and gate. This would make the injection pressure gauge reading 6,000 psi (41 MPa). The injection time would be

$$\frac{\text{25 cu in. (size of our shot)}}{\text{22.5 cu in./sec (from machine data)}} = 1.1 \text{ sec}$$

Let us now assume that the prescribed pressure and time of filling did not produce complete parts. This would indicate that the gates could not accommodate so much material in 1.1 sec.

We shall apply the Newtonian flow formula, which reads as follows:

$$Q = \begin{cases} \frac{\pi P R^4}{8\mu L} & \text{(for cylindrical shapes)} \\ \frac{P h^4}{9\mu L} & \\ \text{(for rectangular shapes with width} & \\ w = 2h) & \end{cases}$$

where Q = material flow, cu in./sec

R = radius of cylinder (gate) through which flow takes place, in.

L = length of cylinder (gate), in.
μ = viscosity, lb · sec/in.
h = height of rectangular duct (gate), in.
w = width of rectangular duct (gate) (usually $2h$), in.
P = pressure, psi

The flow formula applies to viscoelastic materials such as thermoplastics when under one set of conditions (pressure and viscosity). In the molding conditions that we have set up, the pressure and viscosity will be the same as on the first trial run, and we shall change gate dimensions to improve the gate's ability to accommodate twice the amount of material in the same time span. Since the volume per second increases as the fourth power of the gate depth, raising this dimension 19% will double the capacity of flow in the same time period. All other factors will remain the same. Thus, the gate will now be 0.071 × 0.143 sq in. (0.18 × 0.36 sq cm). This small change in size should have no effect on degating or any other aspect of the molding parameters.

This modification should result in filled-out cavities; if a small cushion is available and the hold pressure is set at about 1,000 psi higher than the injection high pressure, our parts should be of the desired quality.

This example points out that an analysis of machine specifications and moldability features of the mold can lead to an arrangement that will produce quality products, saving on power as well as wear and tear on machines, by using lower injection pressure.

Applying pressure transducers in strategic mold locations can lead to a more accurate determination of prevailing molding conditions. (See Chap. 7 on process control technology.)

Force on mold faces In the discussion of clamp size vs. counteracting pressure generated in the cavity during injection molding, it was remarked that the average force used to straighten out mold faces amounts to about 10% of clamp capacity. The question arises, how do we determine the actual force for full contact of mold faces if the suspicion exists that the case under investigation wastes a higher percentage of clamp force than the 10% cited? The following steps will provide a reasonably close answer.

In order to maintain the integrity of the land area outside the cavity, a pressure of $3\frac{1}{2}$ tons/sq in. is allowed for steels, Bhn 300 and 5 tons/sq in. for H13 heat-treated steel (or similar tool steels). These values not only lead to long tool life, but also provide enough concentrated pressure to give the mold effective closing force. To test the size of the force needed to obtain good contact between faces of the mold halves, we first see that the land area is so dimensioned as to give approximately $3\frac{1}{2}$ or 5 tons/sq in. (depending on the steel).

Having verified this, we take a piece of paper whose area is the same as the mold base, of 0.003- to 0.005-in. thickness, cut out the shape of the cavity, and place it between the mold halves. Applying a force of $\frac{1}{3}$ ton/sq in. by reducing the clamp pressure, we close the press, and upon opening it, we check to see if the impression is uniform all over the contact area of the paper. If contact is lacking in any part of the land circumference, the test should be repeated at increased pressure. The increase should be made in increments of 5 tons of clamp size until complete contact is established. The tonnage read when the impression on the paper covers the full circumference of the cavity is the tonnage wasted straightening the mold. The difference between it and rated capacity is the amount left to keep the mold from opening during injection of the fluid plastic.

Let us continue with the example in which we decided that the clamp would keep a mold closed with 110 sq in. (710 sq cm) of projected area. The rectangular 110-sq in. part will have dimensions of 10 in. × 11 in. and a perimeter of 2 × 11 in. + 2 × 10 in., or 42 in. (107 cm). We are working with a mold of 300-Bhn hardness. The square inches are calculated as follows:

$$\text{tonnage} = \text{area} \times 3.5$$

or

$$250 = A \times 3.5$$

and

$$A = \frac{250}{3.5} = 71.4 \text{ sq in. (461 sq cm)}$$

A is expressed as perimeter times width of land, from which the width is calculated:

$$71.4 = 42 \times W$$

$$W = \frac{71.4}{42} = 1.7 \text{ in. (4.3 cm)}$$

When contact of the 1.7 in. × 42 in. land area is uniform after being compressed with $\frac{1}{3}$ ton/sq in. on 71.4 sq in., or 23.8 tons of clamping force, we have obtained the tonnage needed to straighten out the mold halves. Otherwise, the clamp size must be increased in steps of 5 tons until good contact is observed, and a reading taken. If, for example, this reading were 33.8 tons, then about 216 tons would be available to prevent the mold from opening and the 110-sq-in. (710-sq-cm) cavity from flashing—a pressure that under normal conditions would be expected to keep the mold closed.

Residence time A time element that deserves more consideration than it normally receives is residence time in the heating chamber to which a material is exposed during molding.

The average chamber with an L/D (length-to-diameter) ratio of 20/1 has a volume twice its rated capacity. Thus, a 32-oz (0.9-kg) nominal machine with about 59-cu in. (968-cu cm) actual chamber volume would have about 118-cu in. capacity with the screw in the full forward position. If the full shot (32 oz) had a cycle time of 60 sec (1 min), the material on the screw would be exposed to the full heat for 2 min. If the shot were only 16 oz and the cycle half a minute, the exposure would still be only 2 min because of the reduced cycle time. With a shot of 8 oz (0.2 kg) and the cycle again half a minute, the exposure would be double the 2 min, or a total of 4 min. This length of time may be excessive for some materials and can cause degradation of properties. Whenever the residence time is on the high side and the danger of polymer damage exists, corrective measures must be taken.

The most important corrective step is to keep the heat derived from the work of plastication to a minimum. This means that the screw rotation speed should be at the low end, the back pressure should be as low as practical, and pressure drops (from such sources as small nozzle diameter, small sprue, small runners, small gates, rough finish in runners, sharp corners at bends, and rough surfaces of cavity and core) should be minimized, so that the mechanical energy converted into heat will be at the lowest possible level. In addition, cylinder temperatures should be arranged to be as low as possible in the lead section area, with a gradual increase toward the metering portion to the level required for adequate melt temperature.

If all these measures do not remedy the problem, then the only relief can come from a machine with a cylinder of lower shot capacity.

Mold placement and job starting Procedures for placing the mold in the press and the sequence of other moves necessary to start a job should be based on the general operating manual of the machine manufacturer. Any information contained here is intended only to act as a supplement to:

1. Machine instructional manuals
2. Local plant and shop safety rules and codes
3. Federal and other government safety laws and regulations

Whenever there may appear to be a contradiction between the three instructional sources, one should clarify and reconcile the points in question before proceeding with the setup. If one knows the machine functions, safety features, and operating procedures and observes them with concentration and attention to detail, successful and safe molding operation will result.

All warning signs on the machine are for the benefit of persons at or near the machine and should be faithfully adhered to. The standard requirements for dress and appearance around running machinery should be strictly observed. These requirements have been established over a period of many years and found to be most effective in eliminating accidents. Plant safety regulations provide for the wearing of protective devices applicable to specific operations and the maintenance of a safe and orderly workplace.

Whatever the work performed, the guidelines should include safety and caution. Extenuating circumstances may dictate deviation in procedures for any operation in an individual shop. Individual plants may have particular preferences regarding setup. Generally speaking, one must be sure that nothing is done to jeopardize manufacturers' warranties while at the same time satisfying governmental regulations.

From the instant a mold is picked up from a storage shelf up to the time production is initiated, the setup personnel should have as their main concern the safety of people working around the press and protection of the mold and press against damage. One should not actuate electrical buttons or selector switches without assuring that the deck is clear for the contemplated action. When work is performed between platens and one's arms are extended into the area between mold halves, it is important to have the main power disconnect-switch open, to be sure that no accidental pressing of a pushbutton can initiate any press movement.

All safety gates are to be in place before any machine movement is initiated.

1. Daylight When daylight adjustment requires removal or addition of spacer blocks between the moving platen and ram piston, the clamp should be in the extreme open position (i.e., maximum daylight) before removing any bolts from joints. If the clamp piston is being moved while disconnected, one should be on the lookout for a tendency to slight rotation of the piston. Such rotation, if not controlled, could cause damage to limit switches or the limit-switch bar. A simple jig can be made to prevent such rotation, and can be applicable to a variety of clamp sizes at the plant.

The minimum mold size should be one-half the distance between strain rod centers. On the 250-ton press that distance is 24 in. × 24 in. (61 × 61 cm), and the smallest mold size should therefore be 12 in. × 12 in. (30.5 × 30.5 cm). A smaller mold would cause excessive platen deflection; if full clamp pressure of 250 tons were applied, this could endanger the integrity of the platen. A reduction in the pressure on the clamp would permit the use of smaller molds, provided the number of tons per square inch of mold area were reduced accordingly. For example, for a 10 in. × 10 in. mold one should reduce the clamp force in the same proportion:

$$\frac{250}{12 \times 12} = \frac{x}{10 \times 10}$$

or

$$x = \frac{250 \times 10 \times 10}{12 \times 12}$$

which yields a mold clamp setting of 173.6 tons.

2. Mold protection The usual setting for pressure in connection with mold protection is 200 psi (1.4 MPa). This value will generate a pressure and force on the mold that can be calculated as follows.

First, we have to determine the area of the booster opening in order to obtain the force that is active during mold protection.

From machine specifications, we know that the clamp ram speed at fast close is 2,000 in./min (5,080 cm/min). According to the hydraulic sequence, in this operation we have a 60-gpm (0.23-cu m/min) pump plus 17 gpm (0.06 cu m/min) plus 6 gpm (0.2 cu m/min) active on the booster area, which brings about the high-speed movement of the ram. Expressing this mathematically, we have

$$\begin{aligned} &\text{cubic inches of oil per minute} \\ &\quad = \text{area} \times \text{inches per minute} \\ 231(60+17+6) &= \text{area} \times 2{,}000\ \text{in./min} \\ \text{area} &= \frac{231 \times 83}{2{,}000} \\ &= 9.5865\ \text{sq in. } (61.85\ \text{sq cm}) \end{aligned}$$

The factor 231 is the number of cubic inches per gallon.

The force exerted on the platen is

$$9.5865 \times 200\ \text{psi} = 1,917\ \text{lb}\ (870\ \text{kg})$$

Part of this force, estimated to be about 350 lb (159 kg), is used to move the platen, thus giving a net force of $1,917 - 350 = 1,567$ lb (711 kg) for mold protection.

The force needed to move the platen can be figured by obtaining the weight of platen

Table 2-11 Example of injection molding data record

JOB	MOLD DESCRIPTION	MACHINE SETUP INSTRUCTIONS	SPECIAL INSTRUMENTATION
OPERATORS	SCREW USED		SAFETY CHECK
ENGINEERS	PRESS NO.	NOZZLE #	

DATE TIME	Run Number	Resin	Lot Number	TEMPERATURES (°F) (°C)								PRESSURES (PSI) (kp/cm²)				CYCLE TIMES (SEC)									WEIGHTS (GMS)		REMARKS
									MOLD																		
				Rear	Center		Front	Nozzle	Fixed	Movable	Melt	Injection 1st Stage	Injection 2nd Stage	Clamp (Tons)	Back	Injection	Hold	Open	Overall	Booster	Ram in Motion	Screw Retraction	Pad (Inches)	RPM	Full Shot	Part Only	

COMMENTS ON MOLDING OPERATION, START-UP, ETC.

Before any mode is selected, power has to be available in the control circuit so that the individual control settings can be operative. This power is applied by turning the control off–on selector switch to the "on" position. The "control" light indicates power availability. The next move is to energize all the electric motors, so that pumps driven by these motors can supply oil that will actuate the appropriate hydraulic circuit and bring about desired action. The motors are energized by pushing the motor start button, and a light indicates that motors are running. Should it be necessary to stop the motors, as could happen with a severe oil leak, pushing the motor stop button will accomplish this. For the Cincinnati Milacron 250-ton machine, the following moves are necessary (the cycle reset pushbutton must be depressed to activate any of the modes listed below).

With the electric motors running, the operator selects the setup mode by turning the mold-set selector switch to the "on" position. This switch position brings about a slow movement of the clamp, and the pressure that the pump will generate (about 200 psi) is determined by the mold protection pilot seat. A pushbutton has to be depressed in order to initiate any machine action.

The clamp open–close selector switch, if held in position, will bring about ram opening or closing, depending on the switch position. One should open and close the clamp three or four times to gain confidence in performing these actions.

Now the operator is ready to start placing the mold in position. However, because of the preceding run, certain actions are necessary to prevent possible interference with the mold location. (1) The positive stripping bars should be adjusted to zero ejection action by screwing the bars to a position in which the stripping plate cannot be actuated. (2) The plasticizing chamber should be in the retracted position. This is accomplished by operating a manual detent lever of a valve that admits oil to the cylinder that carries the injection assembly. The detent lever in the extreme left position causes the flow of oil in the cap end, which causes the injection assembly to be retracted. The opposite position of the detent lever will cause a forward movement of the chamber until the nozzle contacts the sprue bushing seat of the mold. The speed of movement can be controlled with the aid of a needle valve, also hand-operated. This needle valve changes the flow rate of oil to the activating cylinder and thereby its speed. During operation, the injection assembly must be in the forward position and make good contact with the sprue bushing seat. For this reason, constant pressure must be maintained at the forward position of the cylinder, so the restricting needle valve must be open at least one turn in order to ensure that there is an opening for the pressurized oil during the entire operating period. The limit switch that causes a buildup of high pressure to close the mold should be moved out of the way (in the direction of the stationary platen) so that there is no high pressure generated before the full operation is started.

The operator should move the injection assembly back and forth several times to acquire a proper feel for it, leaving it in the retracted position.

With the potential interferences out of the way, it is time to heat the injection cylinder so it will be ready for manipulation of the screw when the mold is clamped in position. The heat off–on selector switch, turned to "on," will supply power to all heater zone pyrometers. Each pyrometer should be set to suit the material and conditions of the contemplated job as outlined in the setup record. The pyrometers are located in the main electrical enclosure.

The operator is now ready to handle the mold. Eyebolts screwed into appropriate tapped holes are used for lifting the mold out of storage and placing it in the press. Only forged steel eyebolts should be used for the purpose. Before use, they should be checked to see that their threads are in good condition and the threaded portion is not bent, to be sure the bolt has not been unduly stressed.

The standard sizes and capacities of eyebolts are as follows:

- $\frac{1}{2}$ in. will support 2,600 lb (1,180 kg), has a thread engagement of $\frac{3}{4}$ in. (1.9 cm)

- $\frac{3}{4}$ in. will support 6,000 lb (2,724 kg), has a thread engagement of $1\frac{1}{4}$ in. (3.2 cm)
- 1 in. will support 11,000 lb (4,994 kg), has a thread engagement of $1\frac{1}{2}$ in. (3.8 cm)

The eyebolts are hooked by means of rope or chain slings onto a lifting device of sufficient capacity, such as a hoist, lift, or crane. (See directions for slings, and be sure to follow practices of hoisting outlined therein.)

The safe handling procedure for the mold is now established, and the steps for placing the mold can be as follows (not necessarily in the same sequence):

1. Set the clamp opening to the required daylight. The approximate daylight opening is mold thickness plus two times core height. Setting the limit switch for "clamp open stop" will establish the extreme backward movement of the platen.

2. Lower the mold between platens while lining up the locating ring of the mold with the corresponding opening in the stationary platen. The clamp is moved slowly (set up) forward to hold the mold firmly in position. The size and number of clamps have been determined by the mold weight, and they are placed in position and tightened with a torque wrench. The clamp attachment is for the stationary half of the mold only. The moving half of the platen may have to be backed away from the mold in order to attach stripping rods to the stripper plate. If this operation is not needed, or when it is completed, the platen is moved forward to contact the mold; clamping for the moving half is completed in the same way as for the stationary half. *Caution:* It is safest to have the main power supply disconnected while fastening the clamps to the mold.

3. Ejection rods should be adjusted in a uniform manner for effective operation of the ejection system.

4. Limit switches and other settings should be made in accordance with the setup copies of the operator's manual to ensure opening and closing of the press in the desired manner.

5. Change the selector switches from "mold set" to "off" and from "auto-hand" to "hand." With the press in the hand mode, open and close the mold to see that everything is functioning properly. The closing of the mold must be free of banging and hammering; the parting line edges of the mold halves must be protected against peening if flash-free parts are to be molded. The clamp should start "fast forward," followed by "slow down" at low pressure as the mold halves approach closing, and finally "slow" at high pressure. The opening of the clamp should start slowly until mold halves are separated about 0.5 in. (1.27 cm), continue fast, and change to slow when stripping starts so that the chance of marking or punching of the plastic is prevented. With these settings, the approximate limit-switch settings can be checked.

6. The *extruder reverse stop* should be set to a position that can be calculated as shown in setup.

7. The extruder *speed, torque*, and *back pressure* are indicated on the material processing sheet and should be set according to the setup record.

8. Check cylinder temperatures to determine whether settings have been reached. Also check the nozzle temperature. With the extruder unit in the retracted position and the extruder selector switch in "run off–on" turned to the "on" position, depress the extruder "run" button until the extruder reverse stop limit switch is actuated, indicating that the shot zone is filled with material.

9. Depress the "injection forward" button to purge material into a suitable container, making sure it does not splatter. Repeat this operation until all new clean material is coming through.

10. The needle valve that controls the movement of the heating cylinder by means of the *pull-in* cylinder is opened, and the *seal valve* is moved so that it will cause the pull-in cylinder to seat the nozzle against the sprue bushing. Depressing the "clamp forward" button will apply the full pump pressure to the pull-in cylinder and thus bring about a good seat between the nozzle and the bushing.

11. Set *injection high pressure, speed of injection*, and *low-pressure injection* as indicated on the setup record.

12. Set the "full-semi-auto" switch to "semi," set the extruder switch to "on," and change "hand" to "auto." The press is now ready for normal operation.

13. After a final check of pyrometers to see that they are up to the setting, the press may be operated by opening and closing the gate.

Note: There may be slight variations in designations of switches or preferred sequences on presses of different manufacturers; however, the general procedure is the same.

The press is now ready for the semiautomatic mode of operation, except that final adjustments for settings, when needed, must be made.

Operating the Machine

The job can now be run, and the result should be a smooth cycle along these lines:

1. The safety gate is open, and its limit switch is not activated.

2. Closing the safety gate activates its limit switch, and the clamp closes fast.

3. As the clamp approaches mold closing, the mold protection limit switch is activated and causes slow movement of the ram.

4. When mold halves make contact, the high-pressure limit switch is activated and brings about high-pressure buildup in the main ram area.

5. The clamp pressure switch is operated. The nozzle valve (if present) opens, and injection forward at high speed takes place.

6. The injection high-pressure timer times out, and the injection low-pressure timer takes over to control the duration of the injection hold pressure.

7. The injection low-pressure timer times out, and the extruder starts running. The clamp goes to a low-pressure hold.

8. The extruder reverse limit switch is operated, and the extruder stops. It may run an additional distance for melt decompression if desired.

9. The curing timer times out, and the clamp opens slowly.

10. The clamp fast reverse limit switch is operated, and the clamp opens fast.

11. The clamp reverse slowdown limit switch is operated, and the clamp slows down for stripping action.

12. The clamp reverse stop limit switch is operated, and the clamp stops in its open position.

13. If the clamp open timer is used and it times out, the press is ready for the next cycle.

Example: Startup for molding polyethylene lids

1. Inspect the mold and compare it with the engineering drawings. Particularly check the vents to be sure they are correct.

2. Mount the mold in the molding machine, set the mold temperature at 40 to 50°F (4.4 to 10°C), and operate on a dry cycle for a few minutes to see if all the mold parts are operating properly.

3. Adjust the machine to the clamp force required and continue the dry cycle.

4. Set the temperature controllers to obtain the desired melt temperature. A graduated temperature profile is suggested along the barrel of the extruder, increasing by 25°F (14°C) increments from the throat to the injection portion of the machine. This will permit a good steady feed rate and uniform melting of the polymer. Melt temperature conditions depend considerably on the type of mold and machine being used.

5. Adjust the injection pressure to 12,000 to 15,000 psi (83 to 103 MPa) on the plastic. This should be the maximum pressure that can be used without causing flashing and overpacking of the mold.

6. Set the injection speed fairly high. This is usually 0.4 to 0.6 oz/sec (0.011 to 0.017 kg/sec) for each lid cavity; thus, a four-cavity mold would require an injection speed of 1.6 to 2.4 oz/sec (0.045 to 0.069 kg/sec).

7. With the machine still cycling, start plastic feeding into the screw with the nozzle away from the mold. After about 10 cycles, the injection unit can be brought up against the mold.

8. Interrupt the automatic cycle and operate shot into the cavities on the first cycle. Note this could cause the gates to freeze while the shot is being removed manually. Return the machine to automatic cycling.

9. Adjust the plunger-forward timer so that the dead time is approximately 0.1 to 0.3 sec.

10. Reduce the shot size until short shots appear; then slowly increase it until the mold cavities are just filled, without packing.

11. Reduce the clamp time until the snap rings begin to tear when the lid is ejected; then increase the clamp time slightly (by 0.1 to 0.3 sec) to give each lid time to solidify. After molding has proceeded long enough for all molding conditions to become stable, reduce the gate timer setting as much as possible while still permitting the lids to clear the mold during ejection before the mold closes again.

12. Increase the injection pressure and injection speed while decreasing the plunger-forward time. This may necessitate increasing the cooling time slightly, but it should make possible a shorter total cycle.

13. If warpage, flash, or short shots are occurring erratically, shot-size control is probably not adequate, and a small cushion will have to be maintained to produce uniform lids.

14. If a cushion is used, it will probably be necessary to reduce the injection pressure and injection speed and to control the amount of packing with the plunger-forward time.

15. If molding problems still occur, contact a technical service representative of the material supplier.

Keep the machine operating manually until the runner system and all the cavities can be filled with plastic in a single shot, if possible. If the machine cannot fill the runner system and cavities with one shot, adjust the shot size so that all the cavities will be filled uniformly with the same material from a given or successive shot.

Final Stage: Optimizing Molding Production

Anyone involved in this part of training should have a detailed knowledge of machine operation, be familiar with all molding parameter settings and their tolerable variations, have an understanding of mold components, and, finally, have the knowledge of processing data for materials that may be under review in some specific analysis of a molding problem.

One of the major concerns to a person in this program is to ensure that the products of molding match or exceed the expectation of the designer, not only in appearance, but also, and mainly, in performance characteristics. This means that all parameter settings must be accurately carried out, but in addition, one must be on the lookout for external causes of variation in properties. For example, a change in ambient temperature can affect the heating chamber, and since the reaction to heat is relatively slow, we will then find a considerable number of parts being molded to a substandard quality. The worst aspect of this occurrence is that there are no external signs of the malfunction taking place. Similarly, a voltage fluctuation will affect most electrical parts, but the results are not, in most cases, detectable on the surfaces of the product. When a product is made by an operator attending a machine, a variation in the operator's behavior from cycle to cycle can cause property inconsistencies that are also not visible to the naked eye. Another source of considerable property and appearance variation is the pumps used to actuate parts of the injection machine.

It has been demonstrated that when a process control keeps the cavity pressure of each cycle at a consistent value, then not only are the properties of parts the same, but the reject rates are practically negligible. This, in turn, means that if the fluctuation of the pump pressure is kept to a very minimum, a similar result can be obtained on a press of standard design. Uniformity of cavity pressure is one of the most important prerequisites for reproducibility in a molded product.

Here are two major measures that can protect the pump from the usual fluctuations and

Screw decompression
Hopper magnet
Precision-leveling mounts
Other

Specification Information, Details

The machine in which the mold is running is an important factor. For parts requiring critical parallel dimensions, not only are molds with thick, well-supported plates necessary, but also thick platens on the machine to minimize deflection. Moving platens should have backup support over a large area to distribute clamp tonnage evenly. The moving platens usually ride on hardened tie-bars supported on the machine's base to minimize deflection. There are also designs in which the platen just moves on the machine base (1, 7).

Machine designs contribute to long mold life and efficient machine operation. However, the machine must be correctly specified in order to take full advantage of features offering high productivity. Important specifications are:

Injection specifications

Screw diameter (mm). Outside diameter of the screw that plasticizes and injects the material into the mold

Screw L/D ratio. The ratio of the screw's length to its outside diameter

Maximum injection pressure. The highest specific pressure applied to the thermoplastic material as it is injected into the mold

Nominal shot volume (cu cm). The volume generated by the screw as it travels throughout the injection phase

Actual shot volume (cu cm). The actual amount of thermoplastic material the machine can inject into the mold.

Actual shot weight (g). The amount of material the machine can inject into the mold. It varies with the material's specific gravity and can be determined by multiplying the actual shot volume by the specific gravity.

Injection rate (cu cm/sec). The volume of material the machine can transfer into the mold in a second at maximum injection speed. Used to determine the time required by the machine to inject a predetermined volume of material into the mold.

Plasticizing capacity (kg/h or g/sec). The amount of material (by weight) the machine can plasticize per unit time at maximum rotational speed. It varies as a function of the kind of the thermoplastic material being plasticized.

Maximum screw rotational speed (rpm). The highest rotation speed the screw can attain during the plasticizing phase

Plasticizing barrel-heating input (kW). The maximum power rating of heaters used to heat the plasticizing barrel

Power rating of the hydraulic or electric motor driving the screw (kW). The power available to drive the screw in the plasticizing phase.

Maximum screw torque (N·m). The peak torque applied to the screw during rotation in the plasticizing phase

Contact force between nozzle and mold (kN). The force applied to the nozzle to push it against the sprue bushing during the injection phase

Barrel heating zones. The number of plasticizing barrel zones with individual temperature control

Table 2.12 provides a guide to IMM specification.

Mold-clamping specifications

Mold clamping force (kN). The maximum force applicable to clamp the mold

Moving platen stroke (mm). The maximum moving-platen stroke. Identical to the mold-opening stroke.

Distance between tie-bars (mm). The widest clearance between tie-bars over which the moving platen slides. Used to

Table 2-12 Guide to specifying an injection molding machine

INJECTION MOLDING MACHINE — SPECIFICATION FORM

Sheet 1 of 2
Date Prepared: ____________
Supersedes Issue Dated: ____________
Manufacturer: ____________
Address: ____________

INJECTION MOLDING MACHINE — SPECIFICATION FORM

Sheet 2 of 2
Date Prepared: ____________
Supersedes Issue Dated: ____________
Manufacturer: ____________
Address: ____________

determine maximum permissible mold width.

Platen dimensions (mm). Maximum overall dimensions of the mold platens. Used to determine maximum permissible mold length.

Minimum and maximum mold heights (mm). Minimum and maximum heights (thicknesses) of mold admitted between platens.

General specifications

Electric motor rating (kW). The power rating of the electric motor driving the hydraulic system

Peak combined power rating (kW). The power rating of the electric motor plus the plasticizing barrel heaters' total peak power input. If an electric motor is installed to drive the plasticizing screw, this motor's rating must be included in the peak combined power rating. In actual practice, the power input varies between 25 and 60% of peak combined power rating, depending on running rates.

Dry cycling rate. The number of cycles the machine can perform in 1 min, with mold installed, but ignoring injection and plasticizing. The following phases are performed by the machine during dry-cycling-rate measurements:

- Mold closing and clamping
- Nozzle-to-mold approach
- Nozzle retraction from mold
- Mold opening

Dry cycle time also includes dwell time.

The machine must have an injection rate capable of completely filling the part (mold cavity) after overcoming losses through the machine nozzle and runner system. Faster fill can lower part stresses, reduce overpacking, and provide a wider operating window. In many cases, the reduced packing requirements can lower the part weight by 2 to 5% while dimensional and quality requirements are still met.

Injection pressure requirements vary according to application. Some require 20,000 psi (138 MPa) to adequately inject the part, whereas others, such as thin walls, require pressures of 40,000 psi (276 MPa) just to fill the part. The following example of a container shows the importance of proper machine specifications whereby the result is a faster cycle, lower part weight, and less core shift:

Screw *L/D*	20:1	25:1
Pressure, psi	20,000	29,000
Injection time, sec	1.0	0.5
Cycle time, sec	8.0	6.5
Part weight, g	22.0	21.4
Core shift, in.	0.005	0.003
Barrel temperature, °F	500	450

For certain applications, two-stage injection can offer significant advantages over machines equipped with a reciprocating screw extruder. Because the extruder screw and shooting pot on a two-stage machine are independent (Fig. 2-6), the screw can be sized to minimize residence time and the shooting pot to provide maximum shot control. With a reciprocating screw extruder (Fig. 2-2), a very large screw diameter may be necessary to provide the required recovery. The stroke will then be only a small fraction of the screw diameter, making shot control very difficult. As a general rule, a properly sized screw should be between 1 and 3 diameters long for maximum control, and never less than $\frac{1}{2}$ diameter.

To obtain the widest processing latitude and optimum physical properties of plastics, an appropriate match of shot size (volume of cavities plus runners and sprue that solidify) to barrel capacity is very desirable. A shot weight of 70 to 80% of barrel capacity is recommended. This minimizes melt residence time in the barrel, enabling processing at higher melt temperatures with optimum melt flow while avoiding degradation (Chaps. 3 and 4).

Since the optimum match of barrel capacity is not always practical due to clamp requirements or machine availability, shot sizes as low as 30 to 35% may be used with the understanding that the processing latitude of many plastics may be significantly reduced. As a result, the ultimate physical properties of the plastic material will not be fully developed. When utilizing the lesser barrel capacities, lower melt temperatures are normally required to prevent thermal degradation due to longer residence time in the barrel. Lower melt temperatures mean higher melt viscosity and more resistance to flow. Greater injection pressures will be needed to fill the part, and molded-in stresses may result that could adversely affect dimensional stability and other properties of the finished molded part. Higher utilization of barrel capacity is recommended to reduce residence time (Chap. 3).

When calculating optimum barrel usage, always consider the specific gravity of the actual plastic vs. the specific gravity of the material for which the machine was rated. Most machines are normally rated in kilograms (ounces) of general-purpose polystyrene (GPPS). As an example, given that the specific gravities of PVC and GPPS are 1.35 and 1.05, respectively, a 1.7-kg (60-oz) barrel rated for GPPS will deliver 2.2 kg (77 oz) of PVC, since

$$1.7\text{ kg} \times \frac{1.35}{1.05} = 2.2\text{ kg}$$

and

$$60\text{ oz} \times \frac{1.35}{1.05} = 77\text{ oz}$$

A recommended PVC shot weight, including sprue, runner(s), and part(s), would then be 1.8 kg (62 oz) on this machine (2.2 kg × 80% of capacity = 1.8 kg; 77 oz × 80% of capacity = 62 oz). The shot size should not fall below 35% of capacity, or 0.77 kg (27 oz). The clamp capacity is based on the PVC required (for the specific PVC molding material). The injection molding machine is to have a minimum clamp force of 300 to 400 kg/sq cm (2 to 3 tons/sq in.) of projected part area, including runner(s) when they solidify in a cold runner system (Chap. 4).

The clamping and injection ends (plasticizers) of a molding machine are described and rated separately. Clamp ends are rated by the maximum number of tons (or MPa) of locking force exerted. In a fully hydraulic machine, the relationship is

$$F = \frac{P \times A}{2,000}$$

where F = force (tons or MPa)
P = hydraulic pressure (psi or Pa)
A = area of clamp ram (sq in. or sq cm)

As a general rule of thumb, for typical commodity plastic materials, $2\frac{1}{2}$ tons of force may be required for each square inch of projected area of whatever is molded. The projected area is the maximum area parallel to the clamping force (the platens). A part behind another similar part, as in a stacked mold, does not require extra clamping force (Chap. 4). For example, a center-gated PS box 10 × 14 in. (140 sq in.) would require a 350-ton press (140 sq in. × 2.5 tons/sq in. = 350 tons). The depth of the box is not relevant in determining the clamping-force requirements, because the sides are not perpendicular to the clamping force.

Productivity and People

Instructions for operating machines can be simply stated by issuing the usual guidelines, such as these startup procedures (details of which are reviewed in a preceding section of this chapter):

- Preset the heat controllers on the barrel and nozzle.
- Start the machine motor and screw motor when the heat controllers indicate that the proper temperature has been reached.
- While the equipment is in manual operation, close the safety gate and the press to lock.
- Check to see that the resin feed hopper gate is closed, and adjust the flow control valve down to zero.
- Turn the plunger switch to the out position. Adjust the flow control valve until the screw rotates. (If it will not rotate, the heat has not been on long enough, so shut down the machine and try again in 10 or 15 min.)
- As the screw rotates, open the feed (off and on) to allow small amounts of resin to feed

Table 2-13 Causes and solutions of common startup problems

Problem	Possible Cause	Solution
Nonfills	1. Improper seal.	Check for uniform compression (feeler gauge).
	2. Gel time too short.	Adjust resin mix to lengthen gel time.
	3. Air entrapment.	Additional air vents required.
Thickness variation	1. Improper clamping.	Stiffen backup member.
	2. Excessive pumping pressure.	Reduce pressure. Reduce viscosity of resin mix.
Blistering	1. Demolded too soon.	Extend molding cycle time.
	2. Improper catalyzation.	Check resin mix and pumping equipment for accurate catalyst content and disperson.
Extended curing cycle	1. Improper catalyzation.	If using catalyst injection techniques, check equipment for proper catalyst metering. Remix resin and contents if two-pot technique is being used (agitate resin drum to disperse inhibitor evenly).
Cracking and crazing	1. Improper reinforcement content and loading.	Increase glass content. Make sure reinforcement is not displaced during mold closing.
	2. Undercure.	Extend molding cycle time.
	3. Resin richness.	Increase filler loading.

into the screw. Watch the screw load, and if it exceeds 100%, reduce the screw rotation rate.

- Continue opening and closing the feed hopper until the machine is pumping well and the load is holding fairly even.
- Open the feed to the screw, and let it purge until the melt appears to be consistent (adjust the back-pressure valve to hold the screw in the forward position).
- Etc.

However, there is more to productivity than guidelines and checklists (see Table 2-13). Trained operators are needed. This section is a summary of the entire subject.

Today's emphasis on latest-generation machinery and space-age controls often makes the individual seem less important than he or she used to be. However, the men and women on the machine lines now have a more important role than ever. They add a critical capability to a line: they give it versatility.

The more one visits plants of all types, the more one finds that totally dedicated lines are not as common as might be expected. In fact, they are the exception rather than the rule—in the context of the full range of lines running today. The obvious reason for the growing emphasis on versatility is that market fragmentation, product proliferation, and all that they imply are bringing shorter runs and more variations to most lines in the typical types of plants making molded products.

Assuming that you do have a well-rounded, ongoing training program and genuine, continuing, two-way communication with plant personnel, ask yourself this question: Have you taken time to think of all possible ways to team the people with whatever machines you have, to add versatility? For instance, if you are not sure whether a commitment to a fully automatic operation will pay off, why not train or retrain a group of people to team up with a semiautomatic loading sequence? For another, do you make the most of varying the numbers of people, to speed up or slow down a given line? Assume you have a powered belt and two tables where crew members assemble combinations, complete packages, or otherwise complement the machinery running ahead of them on the line. Assume you can vary the

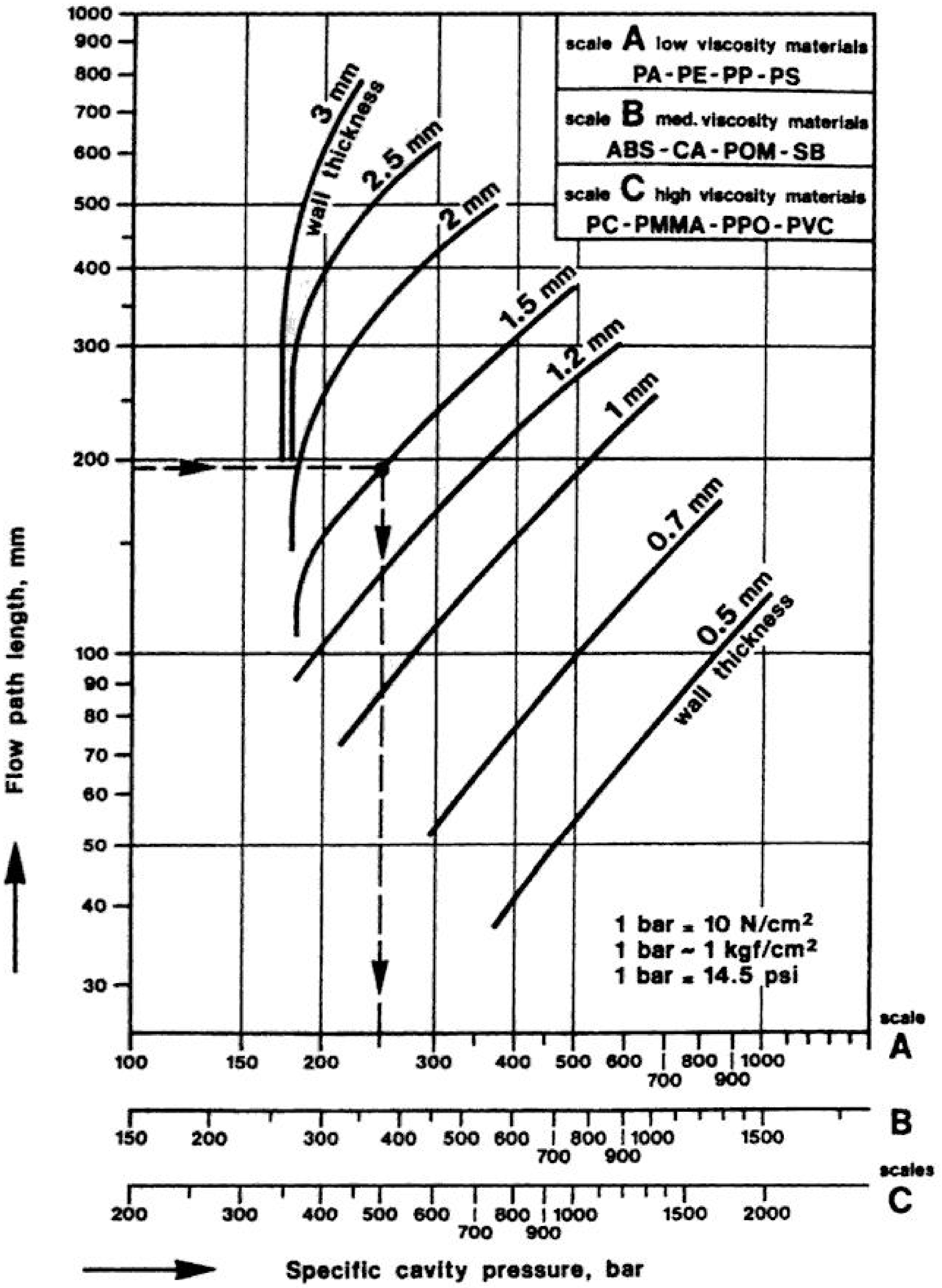


Fig. 2-67 Diagram for calculating the pressure in a mold from the part thickness, melt flow path, and melt viscosity.

length" means the longest distance covered by the material during mold filling, starting from the injection gate. The projected area means the area that the part projects on the vertical plane. The container has a thickness of 0.65 mm and a flow length of approximately 150 mm. In the diagram shown in Fig. 2-68, scale A must be consulted, since PE is a low-viscosity material. From this diagram, it is easy to see that on the basis of the

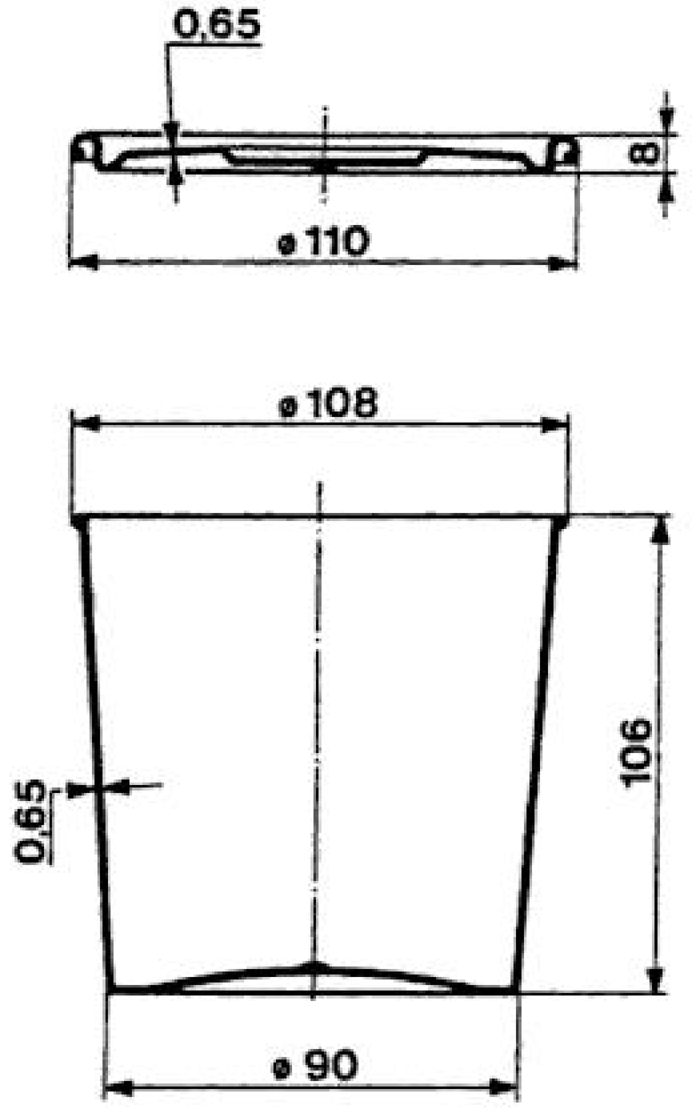


Fig. 2-68 Example of a food container and its lid molded in polyethylene.

geometrical data for the container, 850 bar of pressure are required in the mold in order to fill the mold cavity.

The container has a diameter of 108 mm, corresponding to a projected surface of 92 sq cm. By multiplying that area by the pressure (820 bar), we obtain a hydrostatic thrust in the mold of 75 tons, which increased by 15% gives us a clamping force of 86 tons. The lid has a thickness of 0.65 mm and a flow length of 60 mm, which corresponds, again according to the diagram in Fig. 2-68, to a required pressure in the mold of 370 bar. With a projected area of 95 sq cm and hydrostatic thrust of 35 tons, a clamping force of 40 tons will be necessary. Table 2-14 shows a summary of the data used to calculate the clamping force for the two moldings in question.

This experimental method of estimating the specific pressure in a mold has been confirmed and proved during a great number of molding tests using plastics and molds of all types.

We must point out that such choices, which until just a few years ago were based only on the experience of expert designers, can now be made with greater certainty with the help of electronic processors and special computer programs (Chap. 9). These mold flow programs make it possible (much more accurately) to simulate mold-filling operations and thus calculate various quantities such as the dimensions of runners and cooling systems, as well as the necessary clamping force. The most efficient and quickest way to determine factors such as clamp tonnage required is via CAD programs. The time-consuming hand–diagram approach has been presented here as an aid to understanding the basics.

Probably one of the most difficult aspects of purchasing an IMM, particularly if it is not for a specific product, is ensuring that that the quotes solicited from different machine manufacturers are comparable. With the specification of complete details, particularly when unusual requirements exist, the quotes will be more compatible.

Terminology

Adapter A device for connecting nonmating parts. Adapters may be used, for

Table 2-14 Guide to determining an IMM suitable to produce the food container and lid

	Container	Lid
Flow path	150 mm	60 mm
Part thickness	0.65 mm	0.65 mm
Material	PE (scale A)	
Average pressure in mold, P	820 bars	370 bars
Base circle diameter	108 mm	110 mm
Projected area S	92 sq cm	95 sq cm
Hydrostatic thrust in the mold ($P \times S$)	75 tons	35 tons
Mold clamping force (hydrostatic thrust increased by 15%)	86 tons	40 tons

example, to attach a plasticator barrel to a nozzle, and a thermal insulator to the nozzle and the barrel for temperature control.

Air shot (Also called air purge.) Expelling the contents of a plasticator shot into the air to study the characteristics of the melt; usually performed on startup with the mold in the open position.

Air entrapment Air can be entrapped and form voids in the melt during processing. This can happen when plastic (pellets, flakes, etc.) is melted in a normal air environment (as in a plasticator) and the air cannot escape. Generally, the melt is subjected to a compression load, or even a vacuum, which causes release of air through the hopper, but in some cases the air is trapped. If air entrapment is acceptable, no further action is required. However, it is usually unacceptable for reasons of performance and/or aesthetics.

Changing the initial melt temperature in either direction may solve the problem. Another approach is to increase the pressure. Particle size, melt shape, and melt delivery system may have to be changed or better controlled. A vacuum hopper feed system may be useful. Changes in screw design may be helpful. Usually a vented barrel will solve the problem.

The presence of bubbles can be due to air alone, moisture, plastic surface agents, volatiles, plastic degradation, or the use of contaminated regrind. With molds, air or moisture in the mold cavity is usually the problem. So the first step to solving a bubble, void, or air problem is to be sure what the case is. A logical troubleshooting approach can be used.

Air flotation or felting process Forming of a fibrous-felted sheet or board from an air suspension of damp or dry fibers.

Barrel, injection molding, compared with extruder An extruder barrel differs from injection molding barrels in several ways. It is usually longer, with minimum L/D of 24 and a maximum of 36 or more. The L/D for the barrel of an injection molder is usually 18 or 20, though occasionally as high as 24. (Some vented barrels have $L/D = 32$, but the trend is toward shorter lengths.) The barrel of an extruder is usually designed to withstand lower melt pressures, usually 500 psi (35 MPa) to possibly 10,000 psi (69 MPa); that of an IMM is designed for 20,000 psi (138 MPa) as the usual standard and can go up to 30,000 psi (207 MPa). This means a thinner wall and eliminates the high-pressure sleeve or bell end. The extruder barrel, like the IMM barrel, connects to the die adapter, but the seal is slightly different. It has a female counterbore, just as in the IMM, but the die adapter has a recess for a rapidly removable breaker plate.

Barrel inventory The amount of plastic contained in the plasticator barrel.

Barrel jacket A jacket surrounding the outside of a barrel for circulation of a heat transfer medium.

Barrel liner, grooved A liner whose bore is provided with longitudinal grooves to enhance plastic melt flow.

Barrel liner sleeve A cylindrical housing in which the screw rotates that permits replacement when wear occurs.

Capacity (volume) thermoset Due to the lack of a nonreturn valve on thermoset plastic screws, the swept volume cannot be used as a measure of the true shot size, since some material flows back over the screw during injection. The amount of back flow is dependent on variables in both the machine and the molding material.

Cavity insert, magnetic A means of direct mounting of cavity inserts in pockets in the platens. Platens are brought together with clamping force achieved by mutual magnetic attraction.

Clamping tonnage (force) The maximum force holding the mold closed between the press platens. The tonnage required during molding is essentially the pressure the plastic melt requires in the mold cavity times the projected area of melt. The total area at the mold parting line is based on the area of the part(s) projected onto a plane at right angles to the direction of the mold cavity. It includes runners, sprues, vents, or culls in the mold that solidify during molding.

Computer-integrated injection molding (CIIM), in software packages, translates the results of computer simulation of the molding of a specific part into machine settings for specific microprocessor-controlled machines. CIIM automates the entry of a large number of set points in microprocessor-controlled machines and maximizes their efficiency.

Core-pulling sequence Different core-pulling sequences used by industry contribute directly to improved performance, flexibility through the interchangeability of cores, speedier and more efficient machine design, and lower costs for both the machinery and molding companies. Examples of such sequences are as follows:

Sequence A	Sequence B
Reset ejector	Clamp close
Core-in	Cores-in
Clamp close	Inject
Inject	Cores-out
Clamp open (to adjustable stop position)	Clamp open
Cores-out	Eject
Clamp open (continue)	
Eject	

Sequence C	Sequence D
Clamp close	Clamp close during cores-in
Inject	Inject
Clamp open	Clamp open during cores-out
Cores-out	Eject
Eject	
Cores in	

In sequence A, clamp pre-positioning is required only with mechanical ejectors. Sequence C can only be used with hydraulic ejection. Sequence D requires interlock to ensure cores are in proper position prior to injection or ejection.

Cycle The complete, repeating sequence of operations in a process or part of a process. As an example in molding, the cycle time (period), is the elapsed time between a certain point in one molding cycle and the same point in the next.

Hydraulic gradient The loss of hydraulic head per unit distance of flow.

Hydraulic line pressure In injection molding machines, a design compromise between the highest pressure that can be efficiently generated and used and the highest pressure that can be safely and surely contained with a minimum likelihood of system leaks. It is generally agreed that 2,000 to 3,000 psi is most desirable.

Hydraulic press A press in which the molding force is created by the pressure exerted by a fluid.

Injection pressure, actual The maximum pressure based on reading a pressure transducer recording the melt pressure in the forward end of the plasticator while the IMM is operating.

Injection pressure, theoretical The maximum theoretical pressure (psi or MPa) of the screw against the plastic melt, assuming no loss of pressure due to frictional drag of the screw.

Injection rate The maximum rate of displacement of the injection screw (cu in./sec or cu cm/sec) when the IMM is operating at maximum injection pressure.

Injection rate, adjusted An injection rate adjusted in stepless control between the maximum and minimum injection pressure rates. The purpose is to provide proper filling of the cavity or cavities. Such schemes are usually classified as fast–slow–fast fill, slow–fast fill, etc.

Inlay or overlay molding The application during or after molding.

In-mold decorating Decorating the plastic part while it is being molded. Decoration includes printed film or foil that may be thermoformed; it may be inserted in the mold manually or automatically (Chap. 15).

In-mold operation Performing operations such as decorating, assembly, painting, labeling, and/or lamination in the mold usually can result in cost savings compared to postmold operations. Some part designs require materials that do not share any adhesive properties. In these cases, in-mold assembly not only allows use of such incompatible materials but also facilitates molding parts with movable joints in a single fabricating step. With plastic labeling that includes thermoformed film, there is a possibility of adding strength to the product so that a thinner wall can be molded.

Insert molding Also called molded insert. A process by which components such as pins, studs, terminals, and fasteners may be molded in a part to eliminate the cost of postmolding. Considerable stresses can be set up in such thermoplastic parts. To relieve those stresses, allow parts to cool slowly during molding and/or provide for oven cooling or annealing after molding.

Insert, open-hole An insert with a hole completely through it.

Insert, threaded mechanical A self-threading metal insert with an exterior locking device for anchorage in the part to be joined. The threaded interior of the insert allows for repeated assembly and disassembly. Threaded mechanical inserts provide high-strength joining of plastic parts with low stresses.

Intensification ratio The ratio of the injection pressure to the pressure of the hydraulic fluid (line pressure). It is numerically equal to the cross-sectional area of the hydraulic cylinder that actuates the screw or plunger divided by that of the screw or plunger itself.

Intrusion For the molding of heavy sections or when the shooting capacity of the machine is not adequate, intrusion molding is used, in which the screw runs continuously, filling the cavity directly. When the cavity is filled, a cushion is extruded in front of the plunger (screw), which then comes forward to supply the needed injection pressure.

Jet method A processing technique in which most of the heat is applied to the plastic as it passes through the nozzle, rather than in a heating cylinder as in conventional injection molding.

Jetting The turbulent flow of plastic from an undersized gate or thin section into a thicker mold cavity, as opposed to the usually desired laminar flow of plastic progressing radially from a gate to the extremities of the cavity. Melt spurts without wetting the walls near gate into the large unrestricted area of the cavity at high injection speeds. Results include ripples on surfaces, nonuniform density, unwanted stresses, etc. Corrective action usually requires reducing the injection rate by enlarging the gate or relocating it away from the open area.

Line downstream That portion of a fabricating line where the molded product leaves the IMM.

Line upstream That portion of a fabricating line that has not yet entered the hopper of the IMM.

Machine locating ring A ring on the platen that serves to align the nozzle of the plasticator cylinder with the entrance of the sprue bushing in the mold.

Machine melting capacity The amount of a plastic that can be melted per hour by the machine under specified operating conditions.

Mold, cold slug The first thermoplastic melt to enter an injection cold runner mold, so called because in passing through the sprue orifice it is cooled below the effective molding temperature.

Mold, cold slug well Space provided directly opposite the sprue opening in an injection mold to trap the cold slug.

Mold, combination A mold that has both positive portions (ridges) and cavity portions, such as a refrigerator door liner.

Mold, cored A mold incorporating passages for electrical heating elements, water, steam, etc.

Mold core pin (1) A pin used to produce a hole in a mold. (2) In injection blow molding, the internal rod used to hold the inside of the preform. This rod also retains the plastic melt during the injection molding steps as it is transferred through the cycle. Also, the blowing pin where air or other blowing medium blows through the channels cut in the center of the core rod to expand the preform in the blowing mold.

Mold core-pulling sequence The SPI recommended core-pulling sequences as follows: (1) Sequence A (clamp pre-position only required with mechanical ejector): reset ejector, core-in, clamp close, inject, clamp open (to adjustable stop position), cores-out, clamp open (continue), and eject. (2) Sequence B: clamp close, cores-in, inject, cores-out, clamp open, and eject. (3) Sequence C (can only be used in hydraulic ejection): clamp close, inject, clamp open, cores-out, eject, and cores-in. (4) Sequence D (requires interlock to ensure cores are in proper position prior to injection or ejection): clamp close during cores-in, inject, clamp open during cores-out, and eject.

Mold, double-cavity A mold possessing two cavities for the simultaneous fabrication of two parts.

Motionless mixer See *Static mixer*.

Nozzle The orifice-containing end of the heating barrel that connects the injection unit to the mold through a platen.

Nozzle, conventional A nozzle with a straight hole leading to the screw bushing.

Nozzle dispersion disk mixers Melt-distributive and -dispersive mixing devices of various shapes and sizes, installed between the endcap–nozzle adapter and the nozzle tip. They can be actual circular disks and can have holes through which the melt can pass. Due to the resulting increase in shear, they tend to be used with low-viscosity plastics. Color change usually requires changing the mixer to ensure that there will be no contamination.

Nozzle drooling Leakage from the nozzle or from the nozzle area, during the injection step, into the mold: an undesirable situation to be corrected. May be due to plastic becoming trapped between the nozzle tip and mold bushing.

Nozzle, extended A nozzle with an extension that penetrates into the mold and shortens, or eliminates the need for, a sprue bushing.

Nozzle freezeoff The solidification of melt in the nozzle orifice (opening), preventing the transfer of melt from the plasticator to the mold. Solutions to the problem include removing contaminated material from the nozzle, raising the gate mold temperature if a controller is used, increasing the manifold temperature, increasing the melt temperature, reducing the cycle time, and opening the nozzle orifice.

Nozzle gate A valve incorporated in a nozzle to prevent leakage from it.

Nozzle plates, dispersion plug Two perforated plates held together with a connecting rod, which are placed in the nozzle to aid in the dispersing a colorant or other additive in a plastic as it flows through orifices in the plates. Their use is a remedy when proper mixing does not occur during conventional injection molding.

Nozzle pressure control During the initial mold filling of the cycle, high injection pressures may be needed in order to maintain the desired mold filling speed. Once the mold is filled, this high pressure may not be necessary, or even desired. If a second-stage holding pressure is required, then a signal which initiates the changeover must be generated. Changeover at the velocity pressure transfer (VPT) point may be set, or triggered in various ways. The device for doing so is called a nozzle pressure control (NPC) or melt pressure control (MPC).

Nozzle, shutoff A nozzle whose tip is part of the mold cavity, thus feeding material directly into the cavity, eliminating the need for sprue and runner system. The nozzle becomes the mold gate.

Nozzle, retraction stroke The maximum stroke of a mechanism (usually a hydraulic cylinder), used to separate the injection unit from the bushing of the mold for cleaning and/or purging purposes.

Nozzle temperature control To provide improved melt flow control with certain machines (such as those using long nozzles) and plastics (such as heat-sensitive types), temperature control of the nozzle is used.

Offset method A specialized adaptation of injection molding that permits the use of incompletely cured thermoset plastics by heating only one small charge at a time, heating it just enough to make the plastic melt, using very high pressures for injection, utilizing the heat of compression and friction heat developed during injection, and finally adding heat only as the plastic passes through the nozzle.

Operation, automatic A machine operating automatically will perform a complete cycle of programmed molding functions repetitively and stop only in the event of a malfunction on the part of the machine or mold, or when it is manually interrupted.

Operation, semiautomatic A machine operating semiautomatically will perform a complete cycle of programmed molding functions automatically and then stop. It will then require an operator to manually start another cycle.

Packing time The amount of time that packing pressure in the mold cavity(s) is maintained by the screw until the gate freezes off.

Plasticating The melting or plasticizing of the plastics in the injection barrel prior to injection in the mold.

Plasticating performance test The SPI Injection Molding Division guideline bulletin on plasticating performance recommends a performance test procedure for screw IMMs. The purpose of this test is to define a uniform comparative method of rating the plasticizing (plasticating) rate of a screw IMM. It not intended to provide an absolute rating of the capacity of the device in any given situation or material, but rather provides a means of comparing the performance of one machine with another under certain specified situations and materials.

Plasticating vs. shot size Selection of the machine screw size usually depends only on the maximum shot size, but the plasticating ability can also be important. It is usually incorrect to assume that the screw's plasticating ability remains the same regardless of the shot size being used. As an example, when the screw reciprocates in preparing the melt, that may be 25 or 90% of shot capacity; thus, a portion of the screw feed section loses its ability to influence plastication.

Plasticizing capacity The amount of plastic that can be melted, homogenized, and heated to processing temperature in the barrel, per unit of time (pounds or kilograms per hour). If the plasticizing capacity is too low in relation to the shot size required, the chances are that the injected plastic will not yet be completely molten, whereas too high a capacity may result in thermal degradation of the plastic due to excessively long barrel dwell times.

Plasticizing, continuous The maximum capacity of a screw unit for continuous plasticizing is generally expressed as weight per hour and calculated from the recovery rate for thermoplastics. The interplay of many machine design and material variables, particularly screw design and back-pressure conditions, has made it impractical to establish any standards for plasticizing capacity and recovery rate for thermoset IMMs.

Plate, dispersion plug See *Nozzle plate, dispersion plug.*

Plunger In the plunger machine (as opposed to the screw type), the material is fed into the heating barrel [Fig. 1-19(a), (b)]. The plunger or ram forces the material through the cylinder, where it is heated by conduction from the barrel wall. As the material is forced forward, it passes over a spreader, or *torpedo*, within the barrel, which causes mixing. The plunger continues to force the material through the nozzle and into the mold. Different designs or versions are used with this basic concept of the plunger IMM, including combinations with screw types.

From the introduction of injection molding of plastics (1872) until the 1960s, this was practically the only method used. With the development of the screw-type injection molding machines during the 1960s, the plunger method practically became extinct worldwide. It is now used only in special cases such as processing thermoplastics unmeltable in screw machines; its main use is with special thermoset bulk molding compounds (BMCs) to produce parts of certain sizes or shapes. However, BMCs are also processed in screw machines.

Plunger prepack Prepacking, also called stuffing, is a method that can be used to increase the volumetric output per shot of the injector plunger unit by forcing additional reinforced plastic material into the heating barrel by means of multiple strokes of the injector plunger (only in plunger-unit-type IMMs).

plunger pre-position The positioning of the injection plunger, by either limit switches or pressure switches, so that total travel during injection is reduced. The primary purpose is to reduce the overall time by eliminating unnecessary plunger travel time during injection.

Pressure The injection molding pressure applied to the injection screw (or plunger) to force the melt from the barrel into the mold (psi or MPa).

Pump, high-volume A hydraulic pump used to pump a large volume of oil quickly into the injection cylinder during injection of the melt.

Pump, low-volume A hydraulic pump used to maintain pressure on the plastic until the gate(s) freeze.

Pump, positive displacement A pump which displaces hydraulic fluid at a constant rate over a wide range of conditions with no internal losses.

Pump, variable displacement A hydraulic pump whose output can be varied using electrical controls.

Rifled liner A liner whose bore is provided with helical grooves.

Rotating spreader A type of injection torpedo (for an injection molding plunger unit) that consists of a finned torpedo rotated by a shaft extending through a tubular injection ram behind it.

Rotometer A type of flow meter, often installed in the water lines, used to set water flow rate in the control of temperature of water-cooled molds or hydraulic oil. Flow is through a vertical transparent tube marked with a scale. A ball-shaped float (or other device) is inside the tube; it moves up and down according to the water flow rate. Rotometers are also used to control airflow (around the mold and elsewhere).

Safety block A spacer or other device in any machine that prevents movement of a member either under its own weight or through the actuation of a movement control.

Safety emergency stop devices An emergency stop device can operate mechanically (trip rod, button, cord, drop bar, etc.), hydraulically, optically, electrically/electronically, or by any other means that when activated will stop the machine immediately without contact or injury of people and products.

Safety gate and screen guards Movable barriers allowing the operator of equipment safe access to a fabricating area, such as the mold. When these barriers are moved or removed, the equipment will not operate until they return into the equipment's operating mode. Mechanical, electrical, and/or hydraulic interlock devices are used to interrupt operating circuits when the barriers are opened.

Safety glass Used on equipment requiring transparency with high performance requirements, safety (shatterproof) glass is a composite (laminate) consisting of two or more sheets of plate glass (usually tempered glass, flat or curved) with an interlayer of polyvinyl butyral plastic 0.20 to 0.40 in. (0.51 to 1.0 cm) thick between each adjoining pair of glass plates. The plastic, bonded (via an air-evacuated or -restricted heating system) to the glass, virtually eliminates shattering of the glass upon impact. This glass–plastic composite has been used in automobile windows since the 1930s.

Safety interlock A safety device designed to ensure that equipment will not operate until certain precautions are taken and set on the equipment.

Safety machine lockouts Proper locking out of a machine—for example, disconnecting the electrical circuit before starting repairs—protects the maintenance worker from accidental startups that could cause severe injury. Procedures are set up for lockout of a machine's electrical, hydraulic, and mechanical circuits. The National Safety Council recommends the following steps for proper lockout: (1) shut off all possible switches at the point of operation; then open the main disconnect switch; (2) snap your own lock on the main disconnect switch box, such as a padlock to which only you have the key; (3) check the lockout device and safety interlock to make sure the switch cannot be operated; (4) place a name tag on the shank of the lock to indicate that the machine has been locked out by you; (5) notify the supervisor when repair work has been completed so that the lock can be removed; and (6) take off the name tag and remove the lock.

Safety mechanism A device intended to prevent accidental actuation of tools.

Safety stop bars/devices In injection molding machines each movable platen has a mechanical safety stop bar or equivalent device. By its mechanical and physical action it will not permit a movable platen with its mold half to move. The platen remains in the open position until the machine is ready to operate with all safety interlocks properly set. Also called a drop bar.

Screen pack A device to permit trouble-free use of recycled plastics by protecting sensitive mold cavity surfaces against damage from foreign particles. It can be mounted behind the nozzle or up against the nozzle side of the stationary platen. A screen pack is also used with virgin plastic to ensure the melt is not contaminated with microscopic metal particles, or the like in an inefficiently operating IMM.

Screw See Chap. 3 for details.

Screw decompression The aim of screw decompression (also called suckback) is to decompress the plastic melt with the plasticator (injection unit) after the injection pressure stroke completes the mold filling. The screw is pulled back toward the hopper, eliminating drooling of the melt from the nozzle.

Screw pulling The screw can be removed from a barrel manually, which can be difficult and time-consuming, or it can be pushed out of the barrel automatically (hydraulically, etc.).

Servo control A control in which the principal objective is to follow a reference value that varies with time. With closed-loop servos and digital interfaces, faster flow of more information is achieved between the motion controller and the motors. This information allows for more precise adjustments, higher speeds, better repeatability, and better performance. The results are larger output (reduced cycle time, etc.), improved quality, and more predictable processes.

Servo-control-drive reliability Some servo drives have mean time between failures measured in decades. Proven reliability means years of machine uptime. Servo systems with brushless ac servo motors and solid-state drive control can provide extremely high reliability rates even in the most demanding environments. All-digital servo systems can pinpoint a fault for the shortest possible mean time to repair. By replacing mechanical line shafts and other gear-train assemblies, servos provide for simpler mechanical systems, reducing the mechanical complexity of a machine design.

Servo drive The use of ac rather than dc power for servo drives allows for greater consistency and repeatability through the molding cycle. The arrangement can result in positioning accuracy of ±0.1 mm.

Shot The amount of material fed into the mold for each cycle of a complete molding operation.

Shot, short Lack of sufficient plastic in the mold during injection molding to mold the desired part.

Shot size The amount of plastic that the IMM injects into a mold during one injection stroke. Shot sizes range from milligrams to hundreds of pounds. The usual range is from a few ounces to 10 lb. Superlarge IMMs have been built. Examples include the three-platen, four-tiebar, 10,000-ton IMM built by Billion of France, with a conventional central hydraulic clamping unit and a shot size of 390 lb (177 kg), using three injection units [100 ft ($30\frac{1}{2}$ m) long with 16-by-8-ft (5-by-$2\frac{1}{2}$ m) platens]. Husky of Canada has produced a two-platen, eight-tiebar, 8,800-ton IMM with a clamping cylinder on each tiebar and with a shot size of 140 lb (64 kg), using single (200-mm screw diameter) or dual (170-mm) injection units [1.8 by 1.5 ft (.6 by .5 m)].

Shot size capacity The maximum weight or volume of plastic which can be displaced or injected in a single stroke. When considering the shot size, the proper selection of screw diameter and *L/D* is critical to the manufacture of high-quality parts at economical cycle times. Generally 25 to 60% of a four-diameter full stroke on a 20/1 *L/D* screw is considered a good operating range when the recovery time is approximately 50% of the overall cycle, and given a screw–barrel combination with proper design to melt and mix the succeeding shot.

Shrinkage and tolerance With proper IMM process control and control of the plastic to be used, repeatable close tolerances are achieved (Chap. 5).

Silicon-controlled rectifier (SCR) A motor-drive speed control system that controls the speed of a dc current motor by use of rectified pulses of power.

Sprue break After injection and screw decompression (suckback), the nozzle may be moved back from the mold sprue bushing to give a small gap during the period when the mold is opened. The process is called sprue break.

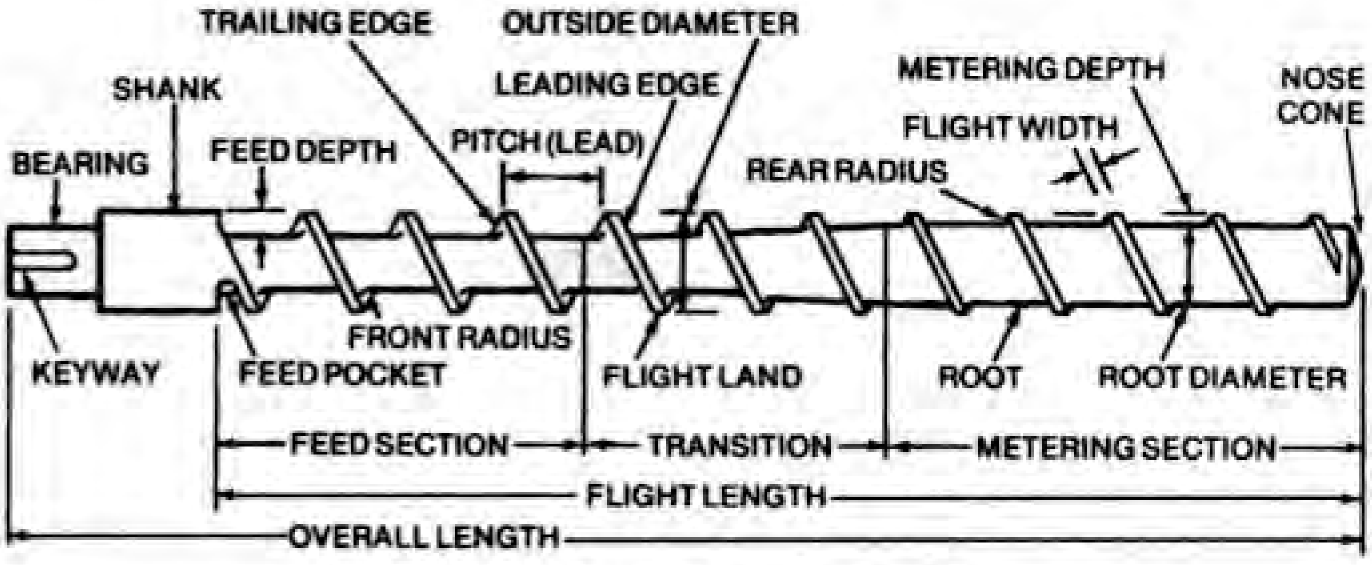


Fig. 3-1 General-purpose screw.

Fig. 3-2 Typical metering-type screw with barrel: D_s = screw diameter (nominal); ϕ = helix angle = 17.8°; s = land width = 0.250 in.; h_F = flight depth (feed); h_M = minimum flight depth for metering = 0.22 in.; L = overall length; δ = radial clearance = 0.005 in.; L/D = ratio of length to diameter = 16 to 24; h_F/h_M = compression ratio = 2.0 to 2.2.

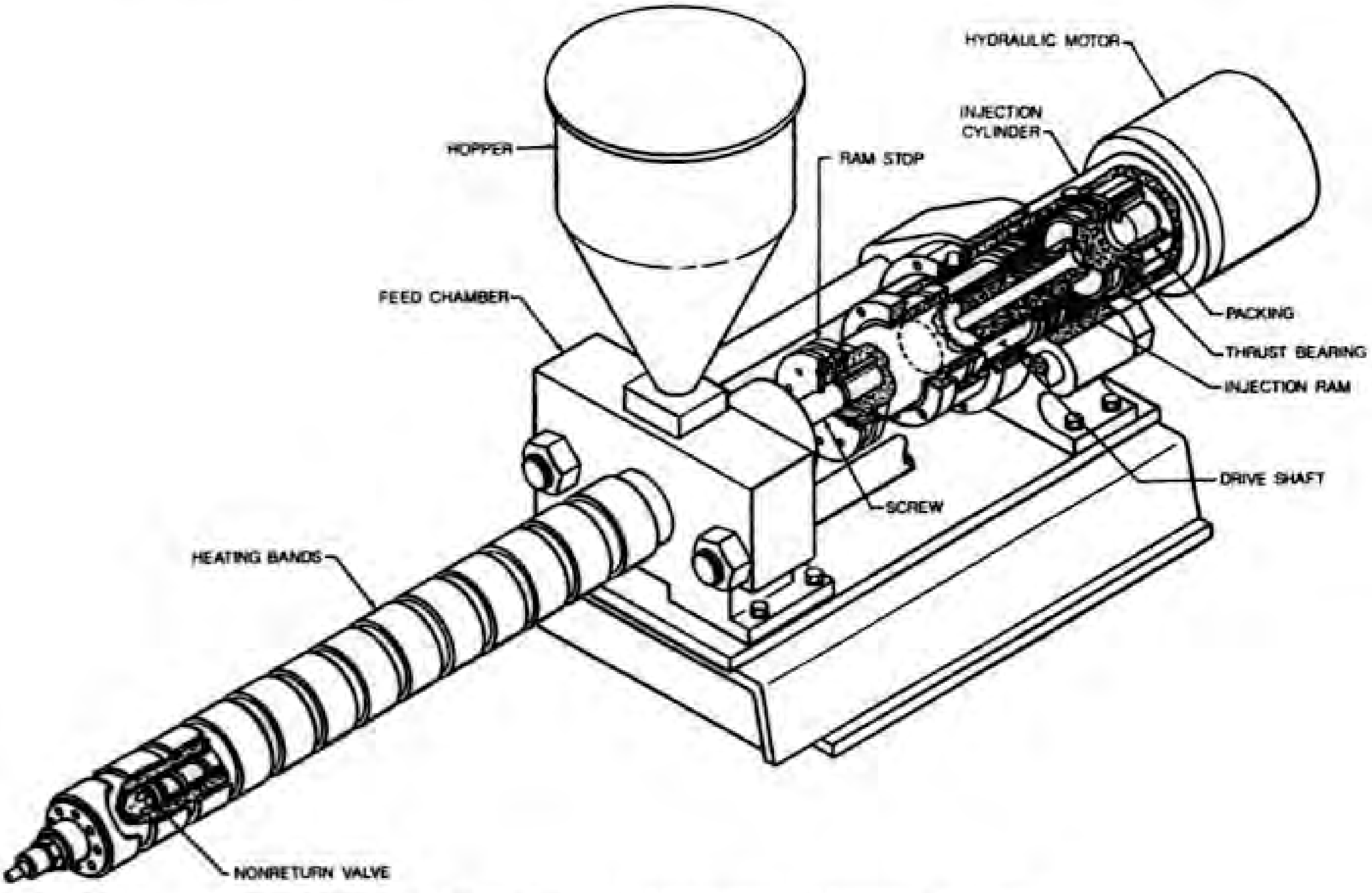


Fig. 3-3 Schematic of a reciprocating screw plasticator.

Table 3-1 Examples of dimensions in typical screw designs for different plastics

Dimension (in.)	Rigid PVC	Impact Polystyrene	Low-density Polyethylene	High-density Polyethylene	Nylon	Cellulose Acet/Butyrate
Diameter	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{2}{2}$	$4\frac{1}{2}$
Total length	90	90	90	90	90	90
Feed zone (F)	$13\frac{1}{2}$	27	$22\frac{1}{2}$	36	$67\frac{1}{2}$	0
Compression zone	$76\frac{1}{2}$	18	45	18	$4\frac{1}{2}$	90
Metering zone (M)	0	45	$22\frac{1}{2}$	36	18	0
Depth in M	0.200	0.140	0.125	0.155	0.125	0.125
Depth in F	0.600	0.600	0.600	0.650	0.650	0.600

the proper screw design is not used, products may not meet or maximize their performance and meet their cost requirements. Hard steel shaft screws usually have helical flights, which rotate within a barrel to mechanically process and advance (pump) the plastic. There are general-purpose and dedicated screw designs. The type of screw used is dependent on the plastic material to be processed.

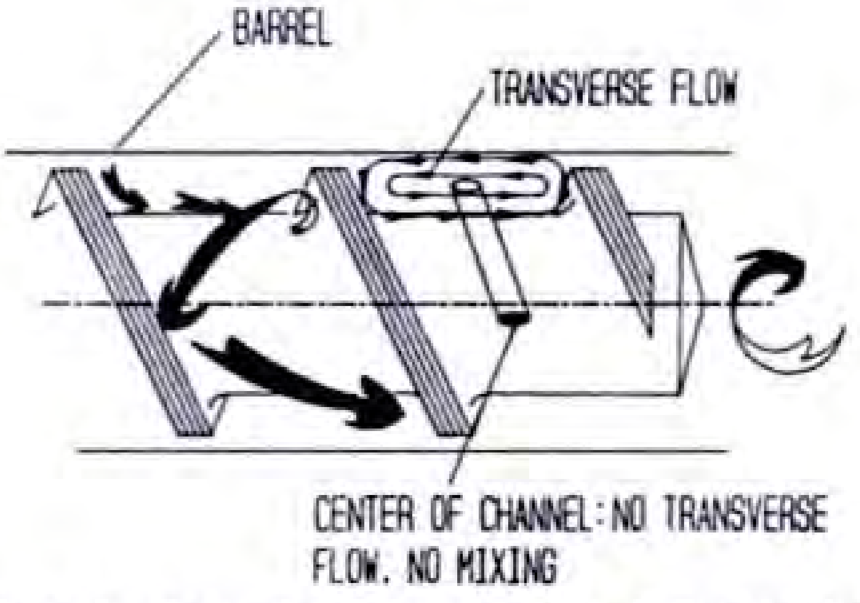


Fig. 3-4 Example of the plastic melt flow in the screw and barrel.

The *plasticizing capacity* is the amount of plastic that can be melted and homogenized with heat in the barrel per unit of time (lb/h or kg/h). If the plasticizing capacity is too low in relation to the shot size required, the chances are that the injected plastic will not be completely melted. With too high a capacity, thermal degradation of the plastic due to excessively long barrel dwell times can occur. The continuous plasticizing capacity is the maximum quantity of a specific plastic that can be raised to a uniform and moldable temperature in a unit of time. It is usually expressed in lb/h or kg/h.

The temperature of the melt has a direct effect on the cycle time. The heat that is used to melt the plastic material must be removed in the mold in order to cool and solidify the part before it can be ejected. The lower the temperature of the melt as it enters the mold, the less time it will take to remove the heat from that mold, and the shorter the total molding cycle (Chaps. 4 and 9).

Table 3-2 Examples of gradual-transition screws

Screw Diameter D [in. (mm)]	Feed-zone Depth h_1 [in. (mm)]	Metering-zone Depth h_2 [in. (mm)]
1.5 (38)	0.250 (6.35)	0.080 (2.03)
2.0 (51)	0.320 (8.13)	0.100 (2.54)
2.5 (63)	0.380 (9.65)	0.120 (2.79)
3.5 (89)	0.400 (10.16)	0.125 (3.17)

For IMMs the following general configurations are suggested:

Section	Upper Range (%)	Lower Range (%)	Recommended Fraction (%)
Feed	60	$33\frac{1}{3}$	50
Transition	$33\frac{1}{3}$	20	25
Metering	$33\frac{1}{3}$	20	25

The injection end performs two basic functions. First, it melts the plastic pellets and deposits the melt in front of the screw in the barrel, ready for injection. The controls used to perform this task include:

- Heat profile on the barrel (the temperature settings of the various heat zones)
- Screw rpm (the speed of screw rotation)
- Screw torque (the torque used to rotate the screw)
- Screw stroke (the distance the screw pumps back for the desired shot size)
- Back pressure (the amount of pressure required by the screw to pump the melt through to the front of the screw)

The second function of the injection end is to inject the melted resin into the closed mold. The controls for this function include:

- Injection pressure (the hydraulic pressure applied to the melt during mold filling)
- Holding pressure (hydraulic pressure applied after the mold is full to control packing of the cavities and shrinking of the molded pieces)
- Injection speed (the rate at which material is forced into the mold)
- Programmed injection (a way to vary the injection speed in stages during filling)

A nonreturn valve is also needed to ensure accurate and efficient injection. Although this device is not considered to be a control, the absence of such a valve would result in inefficient operation.

Other controls required for the injection function include:

- Shutoff nozzle (sometimes used to prevent melt from drooling out of the nozzle)
- Decompress (suckback) control (a way to hydraulically pull the screw back into position after the next shot is prepared, which helps eliminate drool)
- Sprue break (a method of pulling back the nozzle from the sprue bushing after injection to prevent nozzle freeze-off)

The controls to be mastered for efficient injection-end function are numerous, but the rewards of proper adjustment are great in terms of both part quality and the efficient cycle times that can be achieved. Knowledge of these various controls and how they interact to produce high-quality parts and efficient speeds is the heart of injection molding expertise (Chap. 7).

In many cases, controls can be retuned to shorten injection molding cycle times by 15 to 35%. A lack of knowledge and experience regarding control of the injection end is costing molders a lot of money, stemming from inefficient control setup, improperly conditioned and heated melt, and actual abuse of the clamp and mold equipment as machine operators experiment in an attempt to obtain better cycle times.

It is not an unusual practice to install a mold from a 10-year-old machine in a new piece of equipment. It is also not uncommon to use the mold-run information from the old machine to set up the new machine because it is quick and easy—or so it seems at first.

Generally speaking, the screw in a 10-year-old machine is not as efficient as the screw commonly found in today's state-of-the-art equipment. The heat profile required to run the mold in the old machine is usually much higher than is needed for the new, more efficient screw; hence, relying on the old mold-run data sets the melt temperature in the new machine hotter than it needs to be (Chap. 2).

As a result, the quality of the melt suffers. A high-quality melt has a uniform temperature throughout its mass. Because most plastics change in viscosity as the temperature changes, a melt without a uniform temperature profile is not going to flow readily into the mold and produce good parts.

Use of old mold-run data not only results in a higher than needed temperature; it also produces an uneven melt, as the more efficient screw processes the plastic through the barrel at a generally faster rate than was achieved on the older machine.

Plastics Melt Flow

To meet part quality and performance requirements, it is best to understand the molding process and, in particular, the heart of the process: plastic melt flow (57). The general science of flow is called rheology (Chap. 6). Rheology started many centuries ago, but a major landmark was the discovery of Poiseuille's law in the mid-nineteenth century. Poiseuille, who was interested in the flow of blood in the human body, found that the quantity of water flowing through a tube increased directly with the fourth power of its diameter and directly with the pressure. Also, the quantity decreased with increased viscosity and length of the tube. Years later, at the turn of the century, a man named Bingham developed the science and coined the name from the Greek "rheos," flow. It relates to the factors that influence flow in the injection molding process.

Flow of the plastic melt into the cavity of the mold affects the characteristics of the molded part as much as do the mold, the design geometry of the part, and the selection of the plastic itself. Flow affects orientation, warp, surface finish, strength, etc. It is necessary to control the flow of the melt into the cavity to control the process and make repeatable characteristics of the finished part.

Factors that influence flow are:

- Flow distance
- Wall thickness—cubed!
- Characteristics of the material
- Melt temperature
- Mold temperature and cooling rate (skin formation)
- Pressure

The mathematics of equating these factors has been worked out for some time, but until the arrival of computer programs, it was not extensively used because of its complexity. Now that it is practical to determine these factors and provide the conditions that can make the molding process optimum and repeatable, improvements can be accomplished in quality, cost, product design, and future planning.

Flow distance The geometry of the shot needs to be divided up into *flows*. When the path of the melt divides (as when the sprue intersects with the main runner or the main runner branches into subrunners, or when using more than one gate), a number of flows are distinguished. Each flow then is divided again into *sections*, or elements. These sections each have a channel shape—round, rectangular, tapered, for instance. Each section also has a specific wall thickness, width (or diameter), and length (distance). If the wall thickness changes, or the type of channel, another section is created. The width may change without a change in section, however. The volume of the section is determined and an average, or *equivalent*, width is used.

The gates are located intuitively prior to laying out the mold plan. Then, after the program is run, if the flows are found not to balance, the gates can be relocated again and again and new layouts made until a balance is obtained. It is so much less work and expense to do this on a computer that doing it by trial and error in steel should be a thing of the past.

In a like manner, sprues and runners can be sized to an optimum diameter and distance. Also, the economics of having a hot runner can be evaluated with more confidence (Chap. 4).

Wall thickness One of the early discoveries in the science of rheology was the importance of the thickness or diameter of the flow channel. In injection molded parts, the wall needs to be uniform and thick enough to flow, but thin enough to cool and stay fluid. Knowing what this thickness should be from the processing standpoint, therefore, is a major consideration when designing a plastic part. The designer usually considers thickness for strength and economy, but with knowledge from the processing standpoint, he or she can further optimize the wall thickness.

Characteristics of the material Every material has its own ability to be heated, moved, and cooled. This is caused by the physical characteristics of the polymer, which in turn depend on the molecular size, type, and configuration. The facility with which heat moves from one point to another in a body is called thermal diffusivity. It is measured by the thermal conductivity divided by the product of the density and specific heat at constant pressure. The thermal conductivity and specific heat vary with temperature, so the measurements needed for calculating flow are the values at melt temperature. The values published in the data files are at room temperature, so special values need to be obtained. Flow analysis software programs have a library of these rheology numbers for some materials, and some can be obtained from the manufacturers.

Viscosity is a concept that needs effort to understand. Molders know plastics are "hard to push." Viscosity, the resistance to flow is the opposite of fluidity. We know there is a temperature or a transition temperature range where the material softens enough to flow. There are a freezing temperature and a no-flow temperature. But plastics have an additional behavior that makes their viscosity change more than that of normal materials. This is the variation with *shear rate*. Shear rate is essentially fill speed. Each material, having its own molecular characteristics, has a specific viscosity vs. shear rate curve.

So each material responds in its own way to changes in temperature, pressure, and fill speed. The rheology numbers in a typical computer flow analysis program are:

1. Thermal conductivity (J/m-sec-°C)
2. Specific heat (J/kg-°C)
3. Density (kg/m^3)
4. Freezing temperature (°C)
5. No-flow temperature (°C)
6. Viscosity factor
7. Shear factor
8. Temperature factor

Shear rate (filling speed) The velocity of injection is one of the most critical controls in the molding process. This is because the viscosity of the polymer reduces dramatically with increasing injection rate. A maximum is reached whereby further increases in speed only use excess energy, and the optimum is at the lower fill rates. When the fill is too slow, small variations in speed will cause large variations in viscosity, which cause irregularities in the process and resultant shot.

It is very important to fill the cavity using volume as the cutoff and making sure the machine is using enough of its pressure capability to assure a uniform fill rate from shot to shot. The fill rate used should be an optimum rate for the material and the job. This rate can be found experimentally with successive tryouts, but can also be estimated from a computer program.

Melt temperature Flow needs a melt with a consistent and homogeneous temperature. It is affected more by shear-rate changes than by small temperature changes, but nevertheless the desired temperature needs to be controlled and held constant. At least half the heat is provided to the material by the mechanical work of the screw, so the temperature needs to be monitored on a regular basis by using a preheated needle pyrometer in an air shot.

Mold temperature and cooling rate The cooling of the shot, if not planned carefully, can cause many problems. Skin formation affects the flow. The cooling rate affects the cycle time. The appropriate temperature for the mold depends on the polymer, geometry of the shot, fill rate, and characteristics required in the finished part. The mathematics involved for the skin formation are proprietary for each flow analysis program and are well-kept secrets.

The water lines in the mold are difficult if not impossible to change once the mold is built, so here is a place where heat-transfer technology can be used to great advantage during the tool design. The computer analysts who provide these cooling layouts can provide both reduced cycle times and quality improvements.

Pressure This is the molding foreman's favorite! When something changes in the operation, raise (or lower) the injection pressure; the results are immediate. These changes often overcompensate and have a whipsawing effect on the process, making it difficult to get back to normal operation.

The injection pressure is leveraged at least 10 times, and lately machine cylinders and screws have been built to produce 20 and 30 times the injection pressure. Then there is a pressure drop as the melt passes through

Table 3-4 Materials for abrasion or corrosion protection of screws

Material	Finished Flight Hardness	Base Material Hardness	Base Tensile Strength (psi)	Resistance to Abrasion	Resistance to Corrosion	Comments
Cobalt base						
Stellite 6	49 Rc[a]	37 Rc	105,000	Good–excellent	Good	Widely used hard facing for abrasion resistance. Can be applied to most screw materials.
Stellite 12	50 Rc[a]	41 Rc	76,000	Good–excellent	Good	
Stellite 1	48 Rc	48 Rc	47,000	Good–excellent	Good	
Nickel-base colmonoy						
56	50–55 Rc	50–55 Rc	45,000	Good–excellent	Good–excellent	Provides excellent abrasion resistance and resists galling. Application to carbon-steel base results in some cracking.
5	45–50 Rc	45–50 Rc		Good	Good–excellent	
6	56–61 Rc	56–61 Rc	30,000	Excellent	Good–excellent	
Bimetallic coatings						
UCAR						
WT-1	70 Rc	N/A	N/A	Excellent	Poor	Provides excellent abrasion resistance; can be applied to all screw materials.
Nye-carb	60–65 Rc	N/A	N/A	Excellent	Good	
Ceramic coatings						
Chrome oxide	80 Rc	N/A	N/A	Excellent	Poor	Most abrasion-resistance materials currently used. Coatings are fragile.
Aluminum oxide	80 Rc	N/A	N/A	Excellent	Poor	
Chrome plating						
Hard chrome	70–72 Rc	N/A	N/A	Good–excellent	Good	Used mostly for corrosion resistance. If applied in suitable thickness, offers abrasion resistance.
Nickel plating						
Electroless nickel	45–50 Rc	N/A	N/A	Poor–fair	Excellent	Can be applied more evenly than chrome.

[a] Work-hardened.

Poor sliding on the screw surface can be caused by melted material sticking to the root of the screw channel or the sides of the flights. This is caused by heat traveling back from the hotter front portion of the screw. Most often, this occurs when the machine is allowed to stand unused. This problem can sometimes be cleared up by inserting larger pieces of plastic, like tabs or sliced-up parts, directly into the feed throat. This requires that the hopper be removed and caution exercised to keep hands out of the screw. The larger pieces will usually clean the melted material from the feed section enough, so that the pellets can do the remainder of the job. In extreme cases, this can also happen while the screw is turning if high frictional heat generated in the front is conducted back to the feed section, melting the plastic on the screw. In that case, the continuous supply of cold unmelted pellets cannot continually clean the melted material from the screw surfaces of the feed section. This can be remedied by water cooling the screw in the feed section.

Improvement in feeding is enhanced by increasing friction between the plastic and the barrel inner surface. As mentioned before, axial grooves in the inside wall of the barrel feed section will yield very high resistance to circumferential sliding and provide excellent solids conveying. This is not required except in extreme cases, such as processing HDPE.

The only significant control the operator has over feeding is the temperature settings in the rear of the barrel. These barrel temperatures can play an important role in the feeding characteristics of a screw–barrel–material combination. The goal is to set the temperatures to maximize the frictional force of the solid plastic against the inner wall of the barrel. This will inhibit sliding and promote feeding. If the temperature is too low, the frictional force will be too low and slipping will occur. If the temperature is too high, the solid will melt and will slide easily along the very fluid plastic, resulting in poor feeding. To aid in mixing and melt uniformity, barrier screws can be used.

This phenomenon is shown in Fig. 3-5 which describes a hypothetical resin. The resin feeding occurs at the point of maximum friction, point *C* on the graph. At this point, the melt film is sufficient and has high enough viscosity to cause sticking on the barrel surface. At point *A*, the inner surface of the barrel is not hot enough to form sufficient melt to cause sticking. At point *B*, the barrel is too hot, causing the melt to have a lower viscosity, with resultant easier circumferential movement and poorer feeding. All this also explains why feeding is sometimes improved by raising barrel settings and sometimes by lowering them. Of course, the hypothetical situation is only good for one situation involving a certain screw speed, resin and lot, operating pressure, and other parameters.

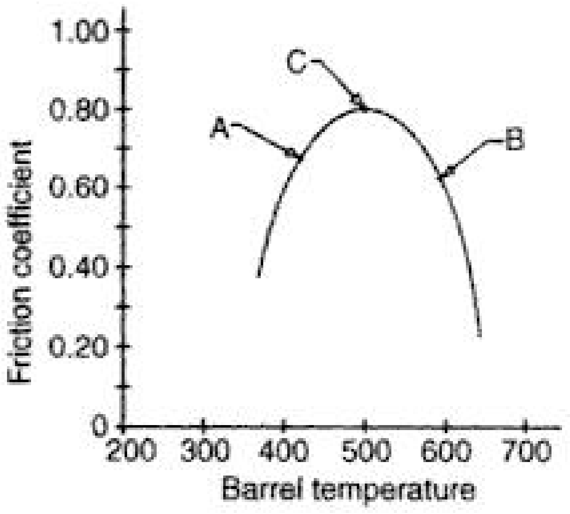


Fig. 3-5 Hypothetical plot of solid-plastic friction coefficient vs. barrel temperature.

Material effects The form of the material entering the feed hopper or feed section has an effect on processing success. Powders and fluffy regrinds, for instance, generally lead to more feed and processing difficulties than pellets, cubes, and heavier regrinds. The bulk density of the feed material determines how effectively the screw's feed flights are filled and how well the extrusion (injection plasticator) process can then commence. Most low-bulk-density regrinds and some powders (especially filled powders) will not readily flow down the hopper and through the feed throat to fill the feed flights adequately. When hopper flow problems are evident, special material-forcing devices, such as compacting screws in the hopper and/or feed throat, sometimes are used to ensure a filled screw feed flight. Alternatively, the materials that cause feeding difficulties can be pelletized or otherwise densified on other equipment to alleviate feed difficulties and hence processing inefficiencies on the production extruder.

Feeding melt to an extruder introduces difficulty in obtaining free flow through the feed throat area and may require a pressure-building source to push the material into the feed flights. Some processes drop a melted ribbon of material into the extruder's feed section, which makes a filled feed flight difficult to ensure. The screw feed flight design can help the feeding efficiency, but extrusion stability is not usually optimum.

Feed-throat opening designs can vary, depending on the manufacturer and the process. Today's typical, efficient throat design is a large rectangular opening directly above the screw. Through the years, feed openings have evolved from round shapes to oval to *obround* (lengthened oval-shaped) to rectangular. Today's rectangular throat design has an opening length of 1.5 to 2.5 times the barrel inner diameter. The larger feed openings allow a free flow of material even with moderately high regrind percentages to ensure properly filled screw feed flights. The only uses of small feed openings in this era involve hoppers with force-feeding screws (compactors) of force-fed melt-conveying extruders.

Tangential feed throats enter the screw area from one side and have added clearance around part of the screw's diameter. They are used for feeding rubber strips to allow partial wrapping around the screw.

Most extrusion processes perform with best product uniformity when the screw is operated with full feed flights. Sometimes, a metered feeder is used to run the process with starved feed flights for some processing reason; the extruder's stability must be acceptable or added processing devices must be used, such as melt pumps (see the discussion of melt pumping later in this section). Twin screw extruders appear generally less sensitive than single-screw machines to the starved feeding mode as far as output stability is concerned, but as the starving level is increased, even their output stability deteriorates.

Transition Section

The transition, or compression, section of a screw is the portion where the depth changes from the deep feed section to the shallow metering section. Because of a number of things that happen here, the design of the transition is critical to the performance of the screw. Some of the functions performed by the transition are (1) melting, (2) compaction and elimination of voids, and (3) pressure buildup.

Melting Although melting occurs in the feed and metering sections, most of it takes place in the transition section. This is particularly true of barrier screws and the more modern screws with longer transition sections. As the channel depth is decreased, the solid plug of plastic is compressed and rubbed against the heated barrel surface. This provides efficient frictional heating and melting plus some additional but less efficient conductive heating. At higher screw speeds, the percentage of frictional heating increases, but the throughput increases even faster. This causes the point at which 100% of the plastic is melted to shift further toward the discharge end of the screw. As this situation becomes worse, this point shifts all the way to the discharge and the throughput has exceeded the melting capacity of the screw. The solution is either a lower screw speed and reduced output, or a more efficient screw design. Barrel temperature settings are only marginally effective in solving these problems.

Melting is a major problem with olefin materials. At high rates, it is easy to exceed the melting ability of most screws and even to cause unstable melt (extrusion) and very rapid wear. This happens when the feed rate of the solids is so much greater than the melting capacity that solid blocks form in the transition. These blocks are compacted solid material squeezed tightly between the screw root and barrel. They form and rotate with the screw with no forward motion and no polymer pumping. Eventually, they melt and release. All this causes pronounced fluctuations in output, pressure, and stock temperature. In the extreme, these solid blocks can cause the catastrophic wear of both screw and barrel. These blocks push the screw against the barrel at very high forces. Again, the solution can be any of a number of things, including a screw redesign, a barrier type of screw, higher heat in the rear, or lower screw speeds and output.

Compaction and elimination of voids In the transition section, the polymer changes from compacted pellets with air spaces between to melted polymer without air bubbles. Usually, the bulk density of the resin at the feed throat is about one-half that of the melted resin without voids. The transition zone accomplishes this change by using a compression ratio of 2 : 1 or greater. A typical compression ratio for olefin materials is 3 to 4 : 1 for a conventional single-stage metering screw. If the compression ratio is too low, the possibility of air entrapment exists.

If the compression ratio is too high, the possibility of solid blocks is greater because the screw may not be able to melt the plastic as fast as the deeper feed section is delivering it to the transition. High compression can be obtained by decreasing the metering depth or increasing the feed depth or some combination of both. Usually, machine manufacturers will obtain high compression by reducing the depth of the metering section. This also makes the transition shallower and creates greater shear, mixing, and frictional heat. If the high compression is obtained by deepening the feed section, a cooler running screw will probably result. Naturally, the reverse applies to low-compression screws obtained by a deeper meter or shallower feed section. A low-compression screw having both shallow feed and meter will run hot.

Pressure buildup The transition zone also forces material to squeeze into a smaller space and thereby builds pressure. The more severe the transition or greater the volume change, the greater the potential for building pressure. In most single metering screws, the greatest pressure along the entire screw length occurs at the end of the transition or the beginning of the meter. This is particularly true of screws with long metering sections or high compression ratios. Pressure at the face of the parison die is zero, and as you go back upstream from that point, the pressure usually increases to a maximum at the discharge end of the transition.

Metering Section

The metering section controls the output of a properly designed and operated molding screw. The term "metering" comes from the idea of a constant-depth section metering out a smooth and exact amount of plastic. The concept is much like a mechanical gear pump metering out oil or any other fluid in precise and constant amounts. The modern metering screw does a good job of this, if properly designed. The metering section should accomplish at least the first of the following: (1) metering a uniform output, pressure, and melt temperature; (2) some final melting; (3) melt refinement; and (4) pressure holding in the barrel.

Metering The output of a metering screw is fairly predictable, provided everything else is under control.

Many designs have long metering sections in order to provide the maximum benefit of damping pressure, temperature, and output surges. The metering section can do some of this, but it is best to remember that these surges were created before the metering section.

Uniformity of output is most critical in molding operations. Here any variance of output rate, temperature, or pressure can cause changes in the melt front. In operations using accumulators or reciprocating screws, uniformity is still important but not quite as critical. Usually, a variation of output (surge) will be accompanied by a variation in melt temperature and quality. This nonuniform mass is stored in the accumulator or barrel front and then shot.

Final melting is usually done in the metering section. It is here that the screw is the shallowest and most efficient in melting the smaller unmelted particles that are suspended in the molten polymer. Frictional heat is highest here, as can be seen by the formula for shear rate shown below.

Shear rate Most of the energy that a screw imparts to the plastic material is by means of shear. The plastic is sheared between two surfaces moving in relation to each other. These surfaces are the barrel inner wall and root of the screw. The rate of energy imparted to the plastic increases as the shear rate increases. The shear rate increases as the relative speed of the two surfaces increases and the distance between the surfaces becomes less. Knowledge of the shear rate can be useful when there are problems with excessive shear causing high melt temperatures and burning of heat-sensitive materials. Low shear rate can cause poor mixing, low melt temperatures, and unmelted material. The actual shear rate at any single point along a screw can be calculated using the following formula:

$$S = \frac{DN}{19.1h}$$

where S = shear rate (reciprocal seconds)
D = screw diameter (in.)
N = screw speed (rpm)
h = screw channel depth (in.)

As can be seen from the formula above, the highest shear is in the metering section, because the channel depth is the smallest. Shear heating is a mechanical phenomenon and can be reduced only with a lower screw speed and output, smaller-diameter screw and reduced output, or greater channel depth with more output and less melt uniformity. With a screw properly designed for the material and output rate, the final melt temperature can be controlled by barrel temperature settings. Ideally, the screw should be deep enough so that a temperature somewhat below the desired melt temperature is obtained by frictional heat without conductive heat supplied by the barrel heaters.

The final desired melt temperature is then obtained by barrel pyrometer settings, primarily in the metering zone. In actual practice, many screws are supplied undersized for the required output of the molding press. This usually means that the output is obtained by high screw speeds with frictional heat override. Then it is attempted to achieve the desired melt temperature by cooling the barrel at the front. Of course, this is energy-inefficient and also an active contributor to high- and low-temperature gradients throughout the resin mass.

Pressure holding The pressure at which a screw can pump through a die or fill an accumulator depends largely on the configuration of the metering section. The longer and shallower the metering section, the greater its ability to maintain constant output or sustain pressure created at the end of the transition section.

This is due to a relative back flow, or reduced forward flow. The hydraulic resistance of the die or accumulator requires a higher pressure at the discharge end of the screw, corresponding to a flow in the opposite direction up the screw channel. This is just like a fluid running up a spiral square-shaped pipe. The longer and shallower the metering section, the greater its resistance to the back flow. A resin with greater melt viscosity will be less susceptible to it. The back-flow pressure gradient is overlaid by the greater and opposite pressure gradient developed by the transition section.

Elements of the Plasticating Processes

This section provides a theoretical explanation of the plasticizing action. Later a more practical review is presented. Since the 1950s, when the reciprocating screw injection unit was introduced, screw design concepts have been developed based on combining practical performance with theory of melt behavior (1). It is convenient to separate the process of reciprocating screw plastication into the elements of screw rotation, soak, and injection stroke. These elements may then be subsequently combined into an overall model (1, 7).

Screw Rotation

During screw rotation, polymer is conveyed along the screw channel owing to the velocity difference between the screw and

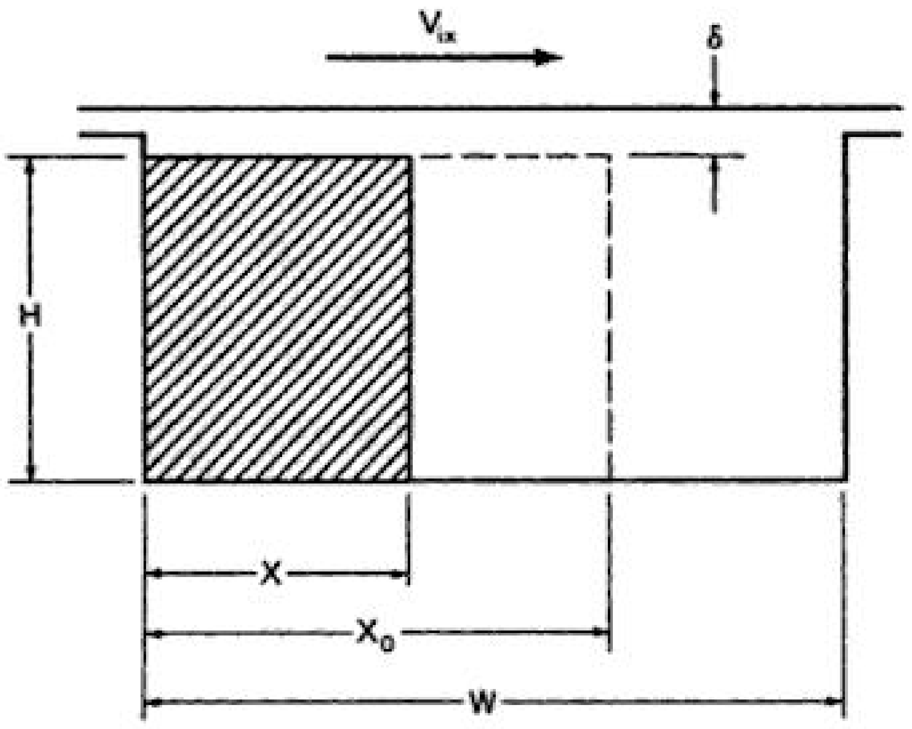


Fig. 3-10 Injection-stroke melting.

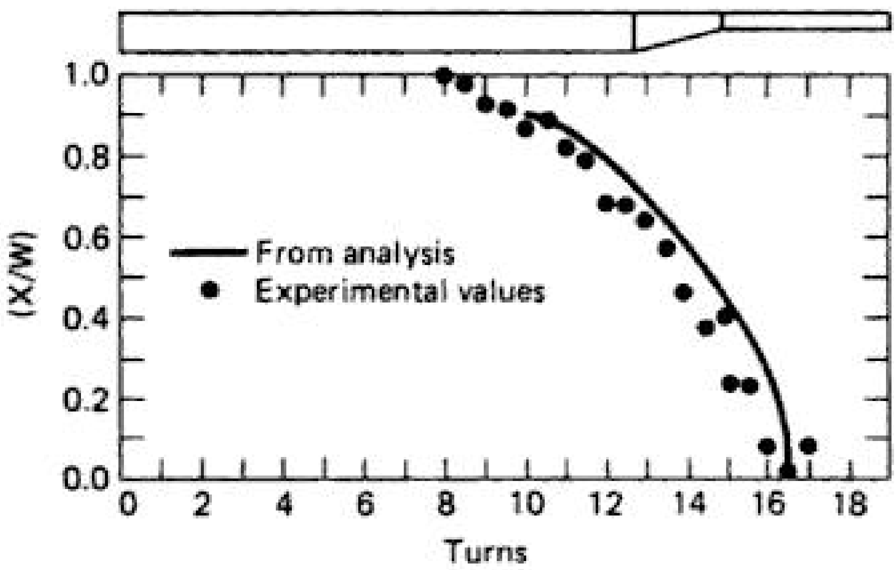


Fig. 3-11 Comparison of actual and predicted reduced solid-bed width profile at the end of injection.

heat transfer, as shown in Fig. 3-10. The relationship may be expressed in the following nondimensional form:

$$\frac{X}{W} = \frac{X_0}{W} \exp\left[\frac{-1}{t_i \delta H \rho_m} \cdot \frac{2k_m t_i^2 (T_b - T_m) + \mu (s_i \cos\theta)^2}{2C p_s (T_m - T_s) + 2\lambda}\right]$$

where X_0 = initial solid bed width
W = channel width
H = solid bed height

and the other symbols are as previously defined.

The form of the equation above indicates the contributions of both conduction and viscous dissipation. Almost invariably, in practice, the viscous dissipation term is small in comparison with the conductive term; hence, the melting is dominated by conductive melting. Even so, the degree of melting is generally significantly greater than would occur in a static soak because the melt film is maintained at a constant thickness and thereby provides a high degree of conductive heat transfer.

A consequence of the exponential form of the equation (above) is that a characteristic time constant may be evaluated for a given practical situation, during which a reduction in the solid bed width by a factor of 0.632 occurs. Typically, practical time constants lie in the range of 5 to 50 sec for most injection-stroke melting situations, which when compared with the injection time indicate the significance of the injection-stroke melting.

The validity of this model for injection stroke melting has been demonstrated, and it can provide a useful method for estimating the solid bed profile at the end of the injection stroke, as shown in Fig. 3-11.

Injection Pressure Required

The specific injection pressure applied by the screw to the melted material is affected by the amount of resistance the screw meets as it progresses during the injection stage (8). The pressure is directly proportional to the gauge reading of the hydraulic circuit pressure and may be calculated using the following equation:

$$P_1 = \frac{P_c \cdot A_1}{A_2} = \frac{F}{A_2}$$

where P_1 = specific pressure on material (bar or daN/sq cm)
P_c = gauge reading of the hydraulic circuit pressure (bar or daN/sq cm)
A_1 = cross-sectional area of the hydraulic injection ram (sq cm)
A_2 = cross-sectional area of the plasticizing screw (sq cm)
F = force applied by the hydraulic injection ram (daN)

The diagram appearing in Fig. 3-12 (applicable to Negri Bossi machines and

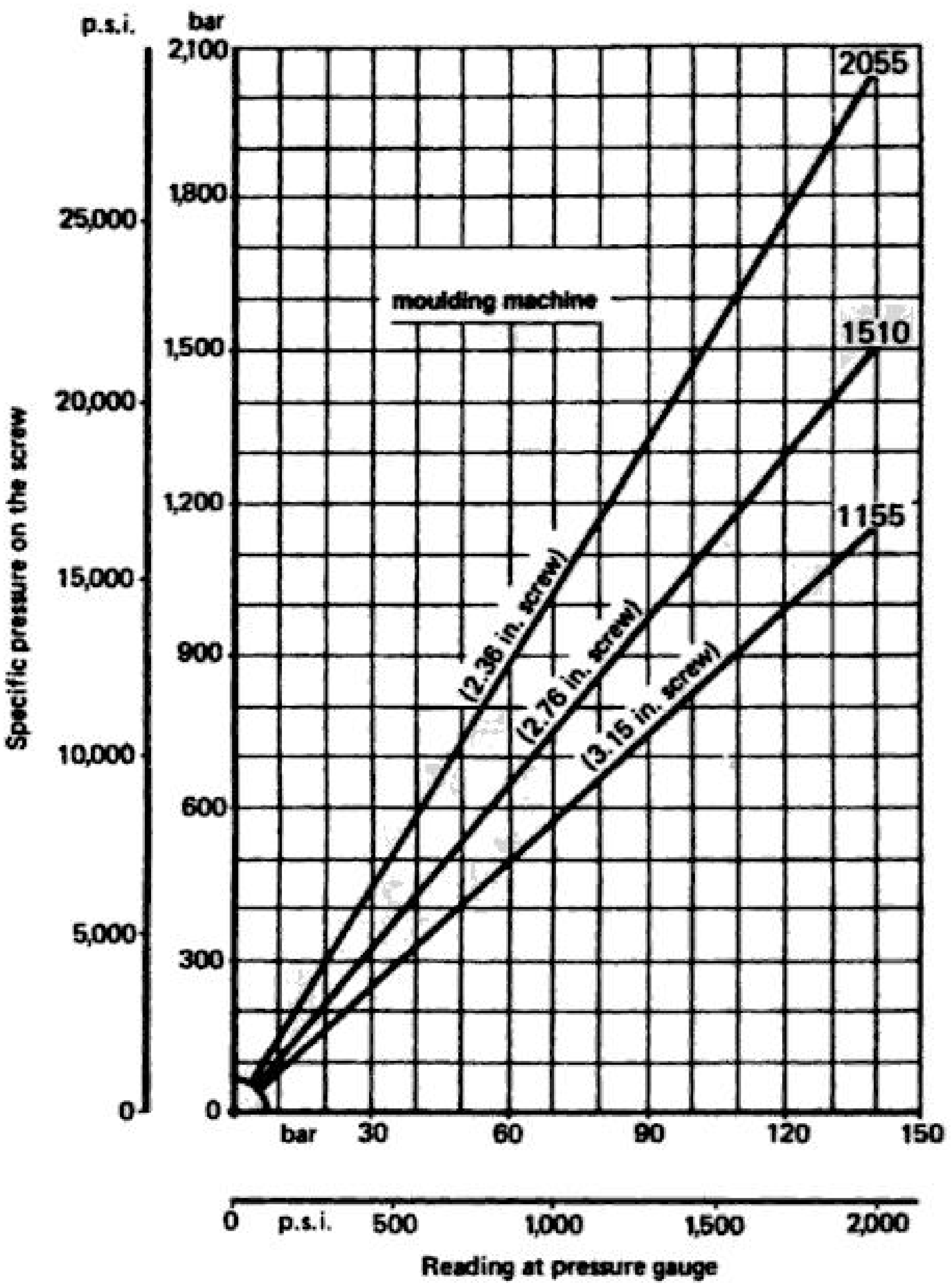


Fig. 3-12 Diagram to determine specific pressure on the screw melt.

included in their machine instruction manuals) simplifies calculations and may be used to determine the specific pressure on material when the hydraulic pressure gauge reading and plasticizing screw diameter are known.

A machine's maximum shot capacity is determined by the volume the screw generates as it moves multiplied by its volumetric yield. As the latter normally amounts to 0.85, the shot volume can be calculated from the following formula:

$$Q = \frac{\pi d^2}{4} \cdot c \cdot \eta$$

where Q = maximum shot volume in cubic centimeters
d = screw diameter in centimeters
c = screw stroke in centimeters
η = volumetric yield (approximately 0.85)

Also in this example, the diagram in Fig. 3-13 (applicable to a specific class of machines) allows the actual melt shot volume to be quickly determined as a function of the plasticizing screw stroke and diameter.

The third diagram in Fig. 3-14 allows us to choose correct values of the specific back pressure on the screw (i.e., on the molten material) during the plasticizing phase. In general, values from $\frac{1}{10}$ to $\frac{1}{20}$ of injection pressure can be adopted. Nevertheless, when glass-reinforced polymers have to be plasticized, lower back pressure must be selected in order to avoid breaking of glass fibers and consequent decrease of the molded part's

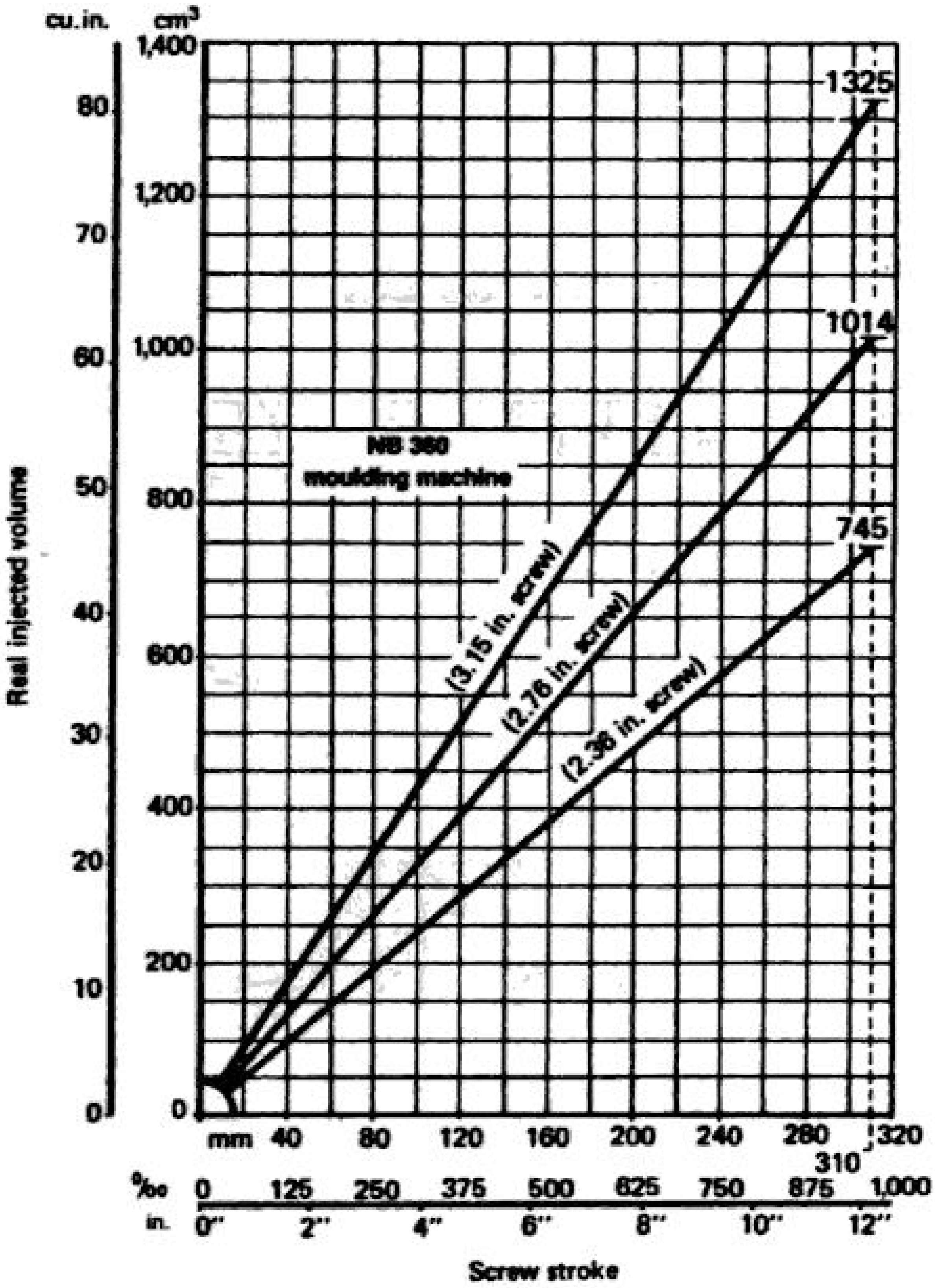


Fig. 3-13 Diagram to determine the actual shot size (injected volume).

mechanical strength. Once a machine's actual maximum shot volume is known, the corresponding maximum shot weight in grams of material can be obtained by multiplying the volume by the material's specific gravity.

Screw Plasticizing

The function of the IMM's heating cylinder is to thoroughly and uniformly convert (plasticize) the plastic feed material into a homogeneous heated plastic melt of controlled viscosity, and then force it into the clamped mold where the end product is formed (1, 7).

The main elements of a typical reciprocating screw injection unit are shown in Figs. 3-1 and 3-2: a screw occupying the bore of a cylindrical barrel, a motor used to rotate the screw, and an injection ram and cylinder used to provide axial movement of the screw relative to the barrel.

For processing thermoplastic materials, the barrel is generally equipped with electrical resistance heater bands around its circumference, and thermocouples are used to monitor the barrel temperature for control purposes. In some cases, where extremely precise control of barrel temperature is required, air blowers may be provided for additional cooling capability, or combination heating/cooling bands may be used. These have a provision for the circulation of a cooling fluid, normally water or oil, to provide additional cooling capability.

With thermoset plastics, the barrel is usually liquid-cooled to ensure more accurate temperature control. Electrical heater bands are not used. See the section on "Injection Molding Thermoset Plastics" in Chap. 6 for

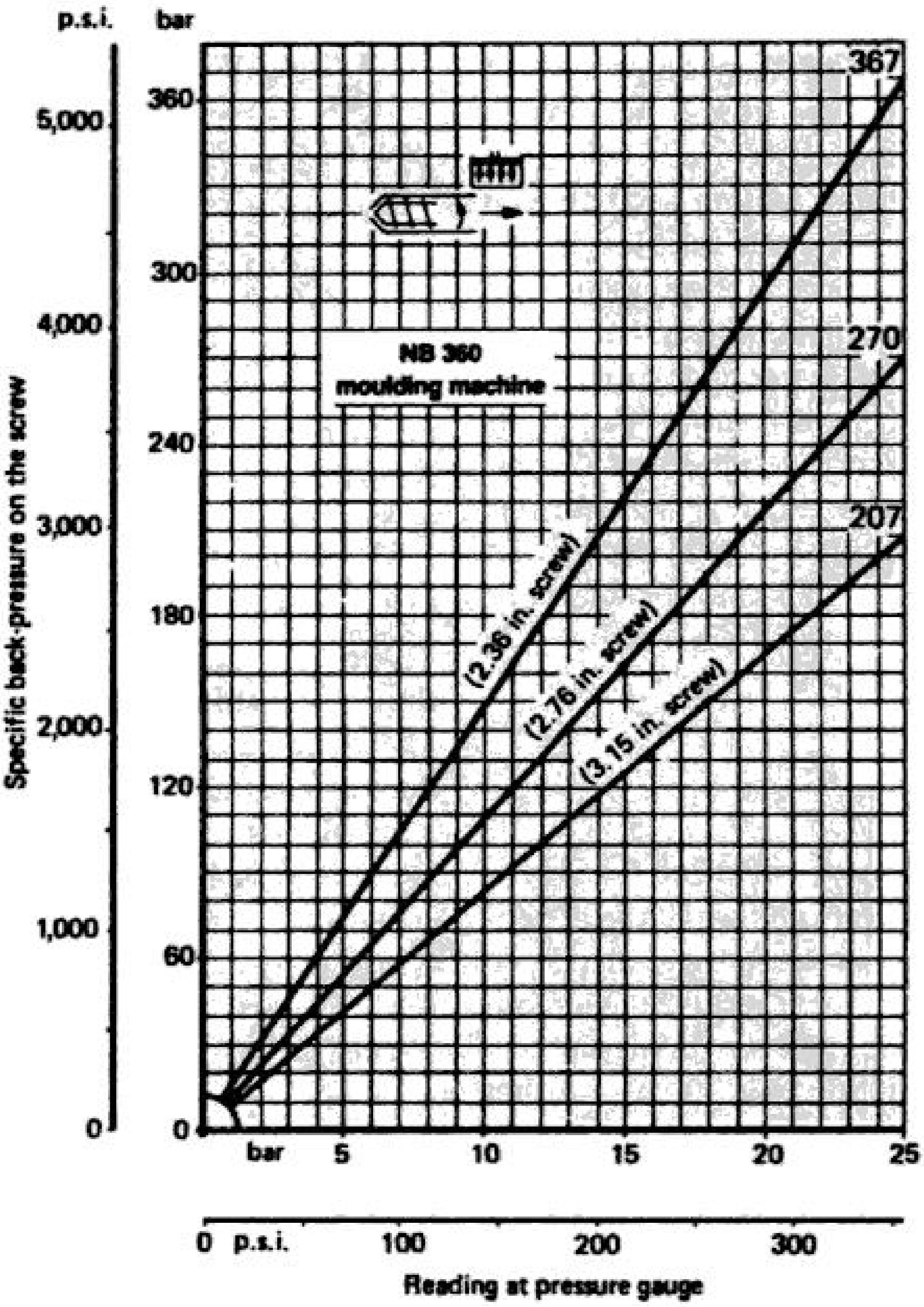


Fig. 3-14 Diagram used to determine the specific back pressure on the screw.

details. In this book, most of the review regarding plasticizing will concern the melting of thermoplastics, since most of the plastics (about 90%) processed are TPs.

The heating cylinder is a simple heat exchanger. Most cylinders have heavy steel walls with highly polished and hardened inner surfaces. For some purposes, the cylinder may be lined inside with a special corrosion-resistant material designed to resist the possible degradation products of thermally unstable resins.

It is important to note that only the cylinder temperature is directly controlled. The actual temperature of the plastic melt within the screw and as it is ejected from the nozzle can vary considerably, depending on the efficiency of the screw design and method by which it is operated. Factors that affect the melt temperature include the time the material remains in the cylinder; the internal surface heating area of the cylinder and screw per unit volume of material being heated; the thermal conductivity of both the cylinder and screw wall and the plastic material; the differential in temperature between the cylinder and the plastic; the wall thickness of the cylinder and of the stationary film (on the inner cylinder wall) of the plastic being heated; and the amount of turbulence in the cylinder.

Because of their molecular structure, plastics have low thermal conductivities; thus, it is difficult to transmit heat through them rapidly. In addition, plastic melts are very viscous, and it is difficult to create any turbulence or mixing action in them without the positive application of some form of mechanical agitation in the screw. The problem is further complicated by limitations of the length of time the plastic may be allowed to remain in the cylinder. In designing the screw, a balance must be maintained between the need to provide adequate time for proper heat exposure of material in the cylinder and the need to process maximum quantities of materials for the most economical operation.

In general, the heat-transfer problems have led injection screw designers to concentrate on making more efficient heattransfer devices. As a result, the internal design and performance of these units vary considerably, based on the material to be processed.

Screw Design Basics

The primary purpose for using a screw is to take advantage of its mixing action. Theoretically, the motion of the screw should keep any difference in melt temperature to a minimum. It should also permit materials and colors to be blended better, with the result that a more uniform melt is delivered to the mold (Figs. 3-15 and 3-16).

The design of the screw is important for obtaining the desired mixing and melt properties as well as the output rate and temperature tolerance in the melt. Generally, most machines use a single, constant-pitch metering-type screw for handling the majority of plastic materials. A straight compression-type screw or metering screws with special tips (heads) are used to process heat-sensitive thermoplastics, etc.

Fig. 3-15 General mixing action and flow of plastic in a screw based on an open discharge (A) and/or blocked discharge (B).

Fig. 3-16 Schematic of melt action in a screw. In area A, melting is by conduction; in B, melting is by shearing; C, contains partially melted plastic, and D, unmelted plastic (solid bed).

The helix angle affects the conveying and the amount of mixing in the channel. A helix that advances one turn per nominal screw diameter usually gives excellent results. This corresponds to an angle of 17.8°, which has been universally adopted. The land width is 10% of the diameter. The radial flight clearance is between the screw flight and the barrel; it is specified considering the following effects:

1. Amount of leakage flow over the flights.
2. Temperature rise in the clearance. Heat is generated in shearing the plastic, with the amount of heat generated related to the screw speed, design of the screw, and material.
3. The scraping ability of the flights in cleaning the barrel.
4. The eccentricity of the screw and barrel.
5. Manufacturing costs.

The length of the screw is the axial length of the flighted section. An important criterion of screw design is the ratio of the length to the diameter of the barrel (L/D). Long screws with a 20 : 1 L/D are generally used. An advantage of using a long screw can be that more of the shear heat is uniformly generated in the plastic without degradation.

Basically, a screw has three sections: feed, melting (transition), and metering. The feed section, which is at the back end of the screw, can occupy from zero to 75% of the screw length. Its length essentially depends on how much heat has to be added to the plastic in order to melt it. The pellet or powder is process of shot preparation is often termed *screw back*.

Once the new charge of polymer melt has been prepared, and when the solidified part in the mold cavity has been ejected and the mold reclamped, the subsequent molding cycle can begin. In general, there can be a period of time between the end of screw rotation and the start of injection; any such delay is termed *soak* or *idle time*.

The overall process of converting the polymer from a solid feedstock to a melt is termed plastication. Since the overall reciprocating screw process involves a sequence of different events, the overall plasticating process becomes quite complex. In subsequent sections of this chapter, the interrelationship between the various events and their effects on the plasticating process will be evaluated in detail.

Advantages of Screw Plasticizing

There are major benefits to using the screw plasticizing method, in which the melting is a result of the shearing action of the screw. As the molecules slide over each other, the mechanical energy of the screw drive is converted into heat energy, and the heat is applied directly to the material. This action, plus the mixing action of the screw, gives this plasticizing method several important advantages:

1. This high shearing rate lowers the viscosity, making the material flow more easily.
2. Good mixing results in a homogeneous melt.
3. The flow is nonlaminar.
4. The residence time in the cylinder is approximately three shots, compared to the eight to ten shots of a plunger machine.
5. Most of the heat is supplied directly to the material.
6. Because little heat is supplied from the heating bands, the cycle can be delayed by a longer period before purging.
7. The method can be used with heat-sensitive materials, such as PVC.
8. The action of the screw reduces the chances of material holdup and subsequent degradation.
9. The preplasticizing chamber is in front of the screw.
10. The screw is easier to purge and clean than a plunger machine.

Regarding the injection end specifications, the following items at least are included:

1. Type: reciprocating screw or screw-pot
2. Diameter of the screw
3. L/D ratio
4. Maximum weight in ounces (or kilograms) of polystyrene that can be injected in one shot; alternatively, the volume of material per shot
5. The plasticizing capacity, which is in effect the amount of material that can be melted per unit time with the screw running continuously. In injection molding the screw runs about one-half of the time.
6. Maximum injection pressure on the screw, usually 20,000 psi (138 MPa).
7. Other specifications that will be provided by the manufacturer and are dictated by the above.

Length-to-Diameter Ratios

Based on the requirements for plastics melting characteristics, different L/Ds are used. There are screw and barrel L/Ds (Fig. 2.50). For a screw, it is the length from the forward edge of the feed opening to the forward end of the screw flight (not including tips, pressure cones, and nonreturn valves) divided by the screw diameter. The ratio is often expressed with its denominator reduced to 1; for example, a 24/1 screw has a screw length 24 times its diameter. To calculate the L/D ratio use the following formula:

$$\frac{L}{D} = \frac{\text{flighted length of screw}}{\text{outside diameter of screw}} = \frac{\mathrm{FL}}{D}$$

The nominal diameter D is normally used. For example, a typical $2\frac{1}{2}$-in.-diameter screw might have an actual diameter of 2.493 in., but we use 2.500 for the above calculation.

Typical data on screws are given in Table 3-1. The flight length *FL* does not include the length of the check valve, in the case of an injection screw. The SPI and SPE have alternative methods for determining the flight length for the calculation of the *L/D* ratio. In the first method, they consider only the enclosed and flighted portion of the screw and eliminate that portion exposed in the feed port. This means that you must deduct the axial length of the extruder or injection feed port from the flighted length of the screw. The two methods for *L/D* ratio calculation are presented below:

Method 1:

$$\frac{L}{D} = \frac{\mathrm{FL} - \mathrm{PL}}{D}$$

(where PL = axial length of the feed pocket in the barrel)

Method 2:

$$\frac{L}{D} = \frac{\mathrm{FL}}{D}$$

Here are some of the reasons for using a large or a small *L/D* for screw and barrel length:

Advantages of small L/D

1. Less residence time in the barrel, keeping heat-sensitive materials at melt temperature for a shorter time, thus lessening the chance of degradation.

2. Occupies less space.

3. Requires less torque, making strength of the screw and amount of power less important.

4. Less investment cost initially and for replacement parts.

Advantages of large L/D

1. Allows a screw design for greater output or recovery rate, provided sufficient torque is available.

2. Screw can be designed for more uniform output and greater mixing.

3. Screw can be designed to pump at higher pressures.

4. Screw can be designed for greater melting with less shear and more conductive heat from the barrel.

Compression Ratios

The compression ratio is used to give an idea of the amount the screw compresses or squeezes the plastic. The intent is to divide the volume of a flight in the feed section by that of a flight in the metering section. Actually, the standard simplified method is usually employed, where the depth in the feed section, h_1, is divided by the depth in the metering section, h_2:

$$\text{Compression ratio (CR)} = \frac{\text{depth of feed}}{\text{depth of meter}} = \frac{h_1}{h_2}$$

The compression ratio should be high enough to compress the low-bulk-density unmelted plastic into the solid plastic without air pockets (bubbles). High percentages of regrind, powders, and other low-bulk-density materials will be helped by a high compression ratio. However, a high compression ratio can overpump the metering section.

A common misconception is that engineering and heat-sensitive plastics call for a low CR. This is true only if it is decreased by deepening the metering section, and not by making the feed section shallower. The problem of overheating is more related to channel depths and shear rates than to CR. As an example, a high CR in polyolefins can cause melt blocks in the transition section, leading to rapid wear of the screw and/or barrel. For TSs the CR is usually 1, so that accidental overheating does not occur and cause the plastic to solidify in the barrel. Barrels for TSs are usually heated using a liquid medium, so that very accurate control of the melt occurs with no overriding the maximum melt heat. With overheating TS melt solidifies. If it solidifies, the CR of 1 also permits ease of removal by just unscrewing the solidified TS from the screw. A CR of 1 is also used for TPs when the rheology so requires.

Typical compression ratios are given in Table 3-5.

Table 3-5 General guide to compression ratios for thermoplastics

Low-compression screw (1.2 to 1.8 compression ratio)	Acrylics Acrylic multipolymer ABS and SAN Polyvinyl chloride, rigid
Medium-compression screw (2.0 to 2.8 compression ratio)	Acetal (Delrin 100) Cellulosics (acetate, propionate) Nylon (low melt index) Phenylene oxide-based resin (Noryl) Polycarbonates Polyethylene (medium to low melt index) Polypropylene (medium to low melt index) Polystyrene (crystal and impact) Polyvinyl chloride (flexible)
High-compression screw (3 to 4.5 compression ratio)	Acetal (Delrin 500 and 900; Celcon) Fluoroplastics (Teflon 110) Nylon (high melt index) Polyethylene (high density) Polyethylene (high melt index) Polypropylene (medium to high melt index)

Note: Depending on the melt index and heat (shear) sensitivity of material, compression ratios may differ from those indicated.

Rotation Speeds

The rotation speed is the number of revolutions per minute (rpm) of a screw. The screw is rotated in order to fill the cylinder with plastic material for the next shot. As the plastic is pushed forward and into the mold cavity or cavities, the screw acts as a ram and pushes plastic melt. Some of the heat necessary to plasticize the material, in addition to the screw action, comes as a result of rotating the screw. The faster it rotates, up to a point, the higher the temperature; however, too fast rotation causes slippage of the material, so that the temperature levels off or even decreases. Although the higher speeds are one means to higher heating, it does not follow that a high screw speed should be used. The target is to adjust the speed based on material and cavity filling requirements. Lower speeds will give more uniform temperatures, reduce wear on the IMM, and reduce the residence time at the front end of the injection cylinder.

Processing Thermoplastics or Thermoset Plastics

Since practically all plastics processed are thermoplastics (TPs), most of the literature on screw design concerns processing TPs. Screws for that purpose can have CR 1, but more often have larger CRs (Table 3.5). Figure 3-18 is an example with CR $3\frac{1}{2}$. When processing thermoset (TS) plastics, the screw is usually limited to a compression ratio of

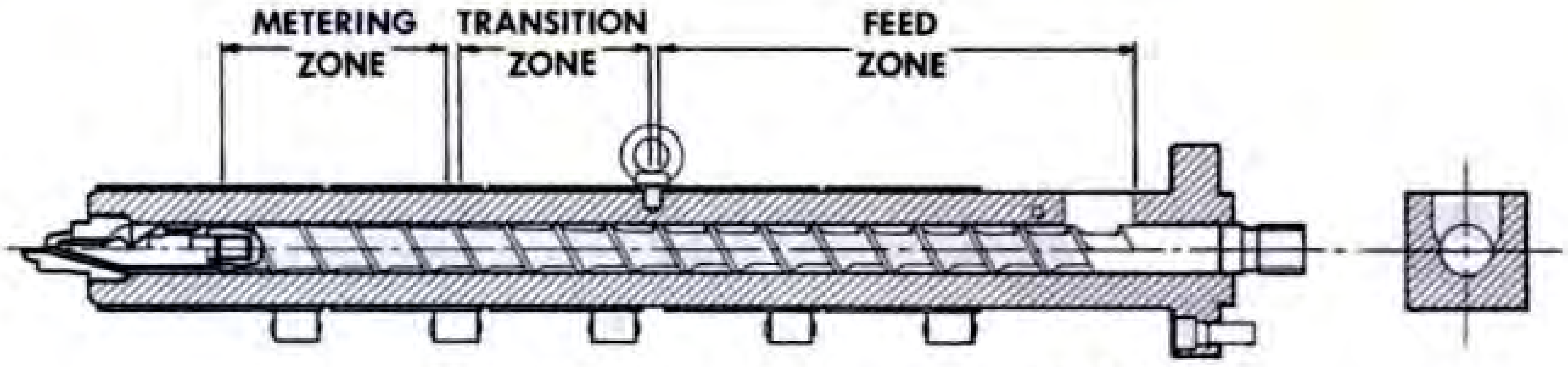


Fig. 3-18 Thermoplastic screw with CR $3\frac{1}{2}$.

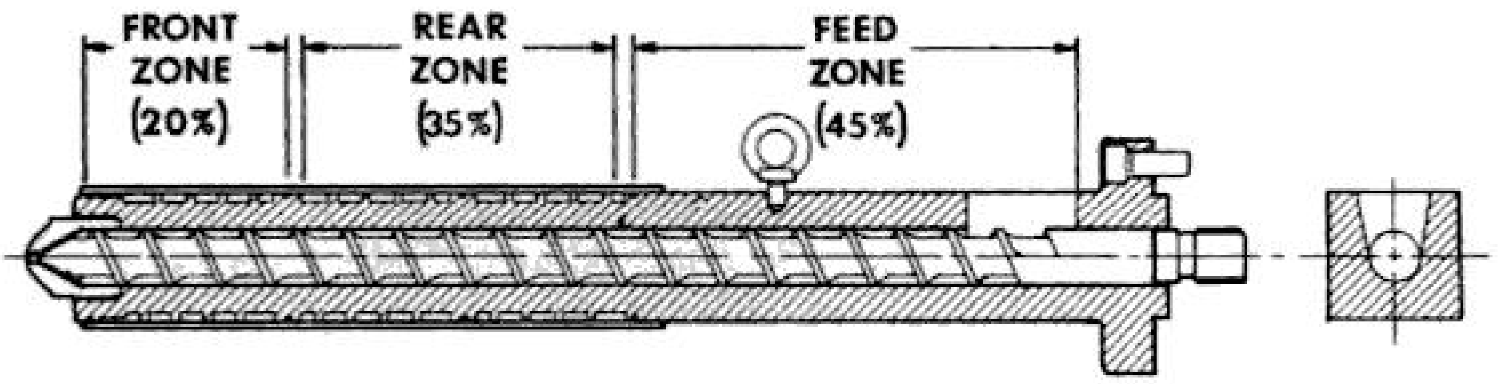


Fig. 3-19 Thermoset screw with CR 1.

one to avoid possible overheating during plastication; Fig. 3-19 is an example with CR 1. If overheating occurs, the TS will solidify in the barrel. If it does, the screw must be removed from the barrel and the solidified TS removed from the screw, as well as from the plasticator nozzle and (usually) the inside of the mold.

Screw Actions

The constantly turning screw augers the plastic through the heated barrel, where it is heated to a proper temperature profile and blended into a homogeneous melt. The rotation causes forward transport. It is the major contributor to heating the plastic once the initial barrel heat startup occurs. The melting action through the screw is as follows:

1. The feed section initiates the conveying of the solid. Sliding with low friction on the screw and high friction on the barrel enhances this action. In this section, there is also some compacting and a little heating of the plastic.

2. At the beginning of the transition, the plastic is further heated and more compression occurs. The solid plastic is forced against the barrel, causing a sliding action. This frictional heat creates a thin film of melted plastic on the inner barrel surface.

3. As the plastic proceeds down the transition zone, there is more melting and more compression. Usually most of the melting takes place in the transition zone. Here the plastic is divided into three parts: a compacted solid bed, a melt film along the barrel surface, and a melt pool (Fig. 3.16). The melt pool is formed as the melt film is collected by the advancing flight. Most of the melting continues to be the result of sliding friction of the solid bed against the heated barrel. This is a rapid and efficient melting action, similar to melting an ice cube by pushing it against a hot grinding wheel.

4. The channel depth continues to decrease as plastic progresses down the transition zone. Melting continues and the width and volume of the solids bed decrease, while the width and volume of the melt pool increase. Unfortunately, as the channel gets shallower, the shear rate increases. Now the already melted plastic continues to be heated. With too much heating, the plastic can be degraded.

5. Continuing downstream through the plasticator, the solids bed breaks up; the unmelted plastics are distributed throughout the channel like ice cubes in water. The efficient melting by friction of the solid bed against the barrel tends to stop. Now only less efficient melting occurs where heating in the melt continues in the shallow metering zone. Within this zone, complete melting action should occur.

6. Plastic continues down the shallow metering section to its exit from the plasticator (screw and barrel). There is a possibility that unmelted plastics or the melt has nonuniform temperature and viscosity. This nonuniformity usually results in poor product performance, color mixing, and so on. Improved mixing can be obtained by reducing the screw's channel depth, but then overheating and reduced output occur. A better method of feeding plastics from the hopper can alleviate or solve this problem. A constant-depth metering section is not considered a good mixer for this purpose. This is because the smooth, laminar flow patterns desired for metering cause the different portions of melt to continue to move without mixing. Screw design plays an important part in eliminating

the problem (see the subsection on Stabilizing via Screw Return Time in the section on Cavity Melt Flow Analyses in Chap. 7).

The features common to all plastics screw plasticators are screw(s) with matching barrel(s) that have at least one hopper (feeder) intake entrance for plastics, and one discharge port for exit of the melt. The essential factor in the pumping process is the interaction between the rotating flights of the screw and the stationary barrel wall. If the plastic is to be mixed and conveyed at all, its friction must be low at the screw surface but high at the barrel wall. If this basic criterion is not met, the material may rotate with the screw without moving at all in the axial direction and out through the nozzle. The clearance between the screw and barrel is usually extremely small.

Mechanical Requirements

Screws always run inside a stronger and more rigid barrel. For this reason, they are not subjected to large bending forces. The critical strength requirement is resistance to torque. This is particularly true of the smaller screws with diameters of 2.5 in. (6 cm) or less. Unfortunately, the weakest area of all screws is the portion subjected to the highest torque. This is the feed section, which has the smallest root diameter. A rule of thumb is that a screw's ability to resist twisting failure is proportional to the cube of the root diameter in the feed section. Finite element analysis (FEA) software has been used to obtain a more accurate determination of the stress levels.

Torque

It is the torque that does the work of melting by rotating the screw in a stationary barrel. The rotational quantity called torque is the product of the tangential force and the distance from the center of the rotating member. For example, if a 1-lb (0.454-kg) weight were placed at the end of a 1-ft (0.3-m) bar attached to the center of the screw, the torque would be 1 ft × 1 lb or 1 ft-lb (1.36 N-m). Torque is related to horsepower (hp), which equals [torque (ft-lb) × rotation speed (rpm)]/5252 or [torque (N-m) × rotation speed (rpm)]/7124. The torque output of an electric motor of a given power depends on its speed. A 30-hp (22-kW) motor has the following torques at various speeds: 87.5 ft-lb (119 N-m) at 1800 rpm, 133 (181) at 1200, and 175 (238) at 900.

Torque vs. Speed

The speed of a motor is determined by its design. Changes in speed and torque can be accomplished by transforming the output speed of the motor by using a gear or pulley train. The torque then varies inversely with the speed. During startup, the torque decreases as the speed increases. As an example, if an ac motor is used, it will develop a starting torque of almost twice the running torque. The screw has to be protected against overload to prevent screw breakage. This is not a problem with hydraulic drives.

The drive must supply enough torque to plasticize at the lowest possible screw speed, but not enough to mechanically shear the metal screw. Different torque requirements are used to meet the requirements of the different plastics. As an example, much higher torque is required to plasticize PC than PS. The strength used limits the input power. Using too little torque to turn the screw means the heater bands are providing too much of the energy required to melt the plastic, usually as a result of poor or no temperature control. Plastication efficiency suffers in these conditions, and mixing problems and/or long, inconsistent recovery times are likely results.

Injection Rates

Machines can operate to move the plastic melt into a mold at different injection rates. Generally, the faster rate permits molding thinner parts and reducing cycle time. With typical reciprocating screw injection molding machines in use today, the injection rate capability varies with machine size, particularly the injection-unit shot size.

initial temperature in the screw plasticator; in order to preheat the material but not melt it in the screw's feed section prior to entering the compression zone. Crystalline material requires higher initial heating to ensure that it melts prior to reaching the compression zone (see the section on Plastic Structures and Morphology in Chap. 6). Careful implementation of these procedures produces the best melts, which in turn produce the best products (see the subsection on Melt Temperature Profiles in the section on Temperature Controllers in Chap. 7).

Barrel Heating

Heating the barrel requires the use of heater band(s) wrapped around the outside of the cylinder. They act as heat exchangers that control the melt temperature. Their controllers permit developing the required temperature profile to produce its best melt characteristic. Several types of heater bands are used. They include cast aluminum (heaters with coolers are available) calrod electrical elements in grooved aluminum elements, ceramic, and mica. The cast types are more expensive, but do better job of distributing the heat and are particularly effective at controlling cooling.

The ceramic heater band has a unique heating capability that is similar to that of a high-temperature electric furnace. The built-in insulation acts to minimize unwanted temperature changes along the barrel. Mica and other types of band heaters are primarily conductive and require an intimate fit with the component being heated. Surface irregularities such as grooves in machined barrels form voids under the bands, leading to hot spots and premature heater failure. Surface irregularities do not affect ceramic heaters' heat transfer efficiency.

Although ceramic heater bands are more expensive than mica bands, that is more than compensated by (1) longer heater life with consequently less downtime for band replacement, (2) power efficiencies and economies made possible by extremely effective ceramic fiber insulation, and (3) the use of fewer bands on a given installation [e.g., two $1\frac{1}{2}$-in. (38-mm) wide mica bands can be replaced with one 3-in. (76-mm) wide ceramic band]. However, since each type of band heater has certain advantages and disadvantages, one must study the requirements of the IMM.

Cooling

The usual IMM plasticators used in processing TPs do not require any cooling action. The barrel heat temperature profiles are controlled so that no significant overheating occurs. However when processing certain TPs that are very heat-sensitive, cooling devices are used, such as water-cooling coils around the barrel and/or fans to blow cool air around it (3).

With TS plastics the usual barrel contains a water-cooling jacket, which may be in sections so that controlled cooling can take place. TSs requires close temperature control, since any overshooting will cause the plastics to solidify in the plasticator. Then the plasticator screw has to be removed and all solidified plastics removed. Water cooling can eliminate overheating.

Occasionally a hole drilled through a screw is used for cooling it. This technique is principally used in certain extruders. Some improvement in plastic melt is possible by circulating cooling water or oil through the cored center section(s) of the screw, at least the feed section. The amount of cooling required in this "pipe" is dependent on screw design and operating parameters. Cooling is more critical for larger-diameter screws, because the larger volume of melt flow requires more cooling. Superior extrusion may be achieved by optimizing cooling, but reduced output rates and/or surging may result unless proper processing temperatures are maintained. A primary area for cooling is at the feed entrance from the hopper.

The main objective of screw cooling is to enhance the ability of the screw to advance the solid plastic feed at the steadiest possible rate. This is accomplished by providing a more constant and lower coefficient of friction between the screw shank and the plastic. In so doing, the screw is able to rotate inside the mass of unmelted plastic solids while the transport of plastic melt takes place inside the barrel surface through the scraping action of the rotating screw flights.

Melt Performance

As reviewed melt produced by the screw is not perfect, that is, melt is not uniform in temperature, consistency, or viscosity. With the passing of time, melt performance has always improved via screw designs including barriers and different screw mixing actions and availability of more uniform plastic materials. With certain plastics and conventional screw designs, temperature within the screw channel can vary by 200°F (111°C). This is an extreme case, but it helps to explain that selecting plastic (particularly regrind) is important. The more uniform the melt output the better product performance, repeatability, and reduced cycle time.

Residence Time

The residence time is the amount of time a plastic is subjected to heat during fabrication. Its effects differ for virgin plastics and for recycled plastics, whose properties are affected by previous fabrication and granulation. Excessive residence time can have minor or major undesirable effects on the properties of the plastic during the next processing step and/or in the finished product. This can occur even when the same plastic (from the same source) and same fabricating machine are used as in a previous successful operation. Various thermal tests are available to detect these conditions (434).

Melt Cushions

The purpose of a melt cushion is to keep the melt injected in the mold under pressure until it solidifies and completes its shrinkage. To do so, a ram screw stroke injects a small metered amount of additional plastic shot. Thus, when the stroke is completed and the mold filled, a *cushion* of melt just a few millimeters thick is maintained between the screw or ram tip and the nozzle. The result is greater compactness and lower shrinkage of the product.

Melt Shear Rate

Most of the energy a screw imparts to the plastic is by means of shear between the screw and barrel surfaces. The rate of energy imparted increases as the shear rate increases. The shear rate increases as the relative speed of the two surface increases and as the distance between the surfaces decreases.

Melt Displacement Rate

The nominal displacement rate is the rate of flow of melt from the screw into the mold during the injection portion of the molding cycle in cu in./sec (cu cm/sec). The actual displacement rate is usually slightly less, due to factors that reduce the flow rate, such as thickness and length of cavity, absence or amount of mold venting, plastic viscosity, melt and mold venting, melt and mold temperature distribution, and gate size(s). Of these factors, insufficient gate size is probably the most common, followed by lack of adequate venting. The actual rate is determined by first taking a full shot, determining the precise time for the shot, and weighing the shot. Convert weight to volume by dividing shot weight (g) by the plastic's specific gravity and multiplying by 16.36. The resulting volume of melt shot (in cu in.), divided by the time period (sec), results in a displacement rate for the plastics used in a specific machine with specific control settings.

Shot Size

The shot size is the maximum (theoretical) calculated swept volume (or trapped volume in a plunger unit), in cu in. (or cu cm), that can be displaced by a single stroke of the injection screw (being used as a plunger). It is assumed that there is no leakage. (In *intrusion molding*, where the screw continues to rotate as it injects, the additional volume displaced by screw rotation is included.) The capacity is also expressed by weight in ounces, pounds, or kilograms. However, the more precise method is by volume, since plastic densities vary.

When the shot size is specified by weight, either the plastic is specified or the general industry type is used. The latter is general-purpose polystyrene (GPPS). During molding, the usual shot size used is up to about 80% of the plasticator available capacity. The lower the percentage, the greater the potential for a residence-time problem, particularly with heat-sensitive plastics (Table 3.6).

The theoretical machine shot size, or capacity, in cu in., is 1.734 times the shot size in oz divided by the specific gravity. Thus a 32-oz, 250-ton IMM using plastic with a 1.06 specific gravity will have a shot size of $1.734 \times 32/1.06 = 52.35$ cu in.

Recovery Rate

The recovery rate is the volume or weight of a specified processable material discharged from the screw per unit of time when operating at 50% of injection capacity. A high recovery rate can shorten the cycle time and eliminate one of the reasons for the use of a nozzle shutoff valve.

Table 3-6 Machine capacity in relation to cost per hour

Cost/h	Capacity			
(sec)	kN	tons	cu cm	cu in.
18	445	50	81.1	4.95
23	670	75	162	9.9
25	890	100	213	13.0
28	1,110	125	267	16.3
30	1,335	150	324	19.8
32	1,780	200	374	22.8
34	2,225	250	533	32.5
37	2,670	300	640	39.0
40	3,115	350	852	52.0
43	3,560	400	959	58.5
46	4,005	450	1,065	65.0
49	4,450	500	1,600	97.5
54	5,340	600	1,865	113.8
58	6,230	700	2,556	156
65	7,120	800	2,917	178
72	8,010	900	3,195	195
80	8,900	1,000	4,392	268

Screw–Barrel Bridging

When an empty hopper is not the cause of machine output failure, plastic may have stopped flowing through the feed throat because of *screw bridging*. An overheated feed throat, or startup followed with a long delay, can build up sticky plastics and stop flow in the hopper throat.

Plastics can also stick to the screw at the feed throat or just forward from it. When this happens, plastic just turns around with the screw, effectively sealing off the screw channel. The screw is said to be *bridged* and stops feeding the plastic. The common remedy is to use a brass rod to break up the sticky plastic and/or to push it down through the hopper. More details on this subject is contained in Chapter 11 under the heading of Troubleshooting Guides, Screw Wear Guide, and Maintenance.

Vented Barrels

Overview

Problems can occur in a plasticator melt. There may be melt that must be freed of gaseous components that include moisture, air, plasticizers, and/or other additives as well as entrapped gases released by certain plastics. Gas components such as moisture retained in and on plastics have always been a problem for all processors. They result in many problems develop with the products (splay, poor mechanical properties, incorrect dimensions, etc.). This situation is of particular importance when processing hygroscopic plastics. One major approach to this problem is to use plasticators that have vents in their barrels to release the contaminants. The other major approach is to dry the plastic, as reviewed in the section on Drying Plastics in Chap. 10. It may be very difficult to remove all the gases prior to fabrication, particularly from contaminated powdered plastics, unless the melt is exposed to vacuum venting (for most vented screws, a vacuum pump is connected to the vent's exhaust port in the barrel). Venting of the melt in the mold cavity is sometimes used, as in the arrangement shown schematically in Fig. 2.41.

The standard machines operate on the principle of melt degassing. The degassing is assisted by a rise in the vapor pressure of volatile constituents, which results from the high melt temperature. Only the free surface layer is degassed; the rest of the plastic can release its volatile content only through diffusion. Diffusion in a nonvented screw is always time-dependent, and requires long residence time. Thus, a vented barrel with a two- or three-stage melting screw is used.

Those with one vent use a two-stage screw that looks like two single screws attached in series. Where the two meet, there is a very shallow channel section, so that when the melt reaches that section, no melt pressure exists. In turn, gaseous materials are released through a port opening. With those having two vents, a three-stage screw is used that provides another stage to eliminate contaminants. The first stages of the transition and metering zones are often shorter than the sections of a single-stage conventional screw. The melt discharges at zero pressure into the second stage under vacuum instead of pressure. The first-stage melt must not be hot enough to become overheated in the second stage. And the first stage must not deliver more output per screw rotation at discharge pressure than the second stage can pump through the barrel under the maximum normal operating pressure. This usually means that the second-stage metering section must be at least 50% deeper than the first stage. The pumping ratio (PR) as applied to two-stage vented screws gives a measure of the ability of its second stage to pump more than the first stage delivers to it. Too high a PR will tend to surge, and too low a PR will tend to cause vent melt flow (434).

In practice the best metering-section depth ratio (pump ratio) is about 1.81 : 1. The ratio to be used depends on factors such as screw design, feedstock performance, and operating conditions. There is likely to be melt flow through the vent (avoid this situation) if the compression ratio is high or the metering-section depth ratio is slightly too low. If the metering-section depth ratio is high, there is a gradual degradation of the output. With the screw channel in the vent area not filling properly, the self-cleaning action is diminished, and the risk of plate-out increases. In any case, sticking or smearing of the melt must be avoided, or degradation will accelerate.

Vent bleeding is the unplanned escape of melt through the vent during vented-barrel processing. Vent flow problems are usually blamed on the screw design, but more often are due to a bad design of the *vent diverter*. The function of the decompression volume (vent section) of the screw is simply to generate a partially filled channel with no pressure. The vent diverter's function is to accept the moving melt and move it into the next section of the screw.

The cause of vent melt flow can be determined by one of two tests. First remove the diverter, rotate the screw slowly, and observe the degree of fill. If it is $\frac{1}{3}$ or less, the problem is almost certainly the diverter. The other method is to run for a few minutes at open discharge at the normal screw speed. If vent flow begins, it is the diverter that is a fault, as the screw is working against no discharge pressure.

There are other factors that can cause vent flow besides the diverter or screw design. They include the melt foaming, screw/barrel wear, improper vent location, and excessive pressure.

There is a hopper feeder venting system that can be used. It is also called starve feeding. It uses a controlled material-feeding device that may be necessary in any case to maximize the operation of a vented system. It is a useful device for many reasons. It determines the amount of plastic that is being feed into the screw, thereby controlling the output of the first stage of a two-stage screw. This action should eliminate all causes of possible vent bleeding and plugging of the vent hole. Also, by partially filling the screw flight channels, the device allows the surface moisture that is being driven off the plastic a place to evaporate to the atmosphere. Finally, it can govern the amount of shear and energy that is delivered to the plastic via the screw geometry, provide different shear history, etc.

Basic Operations

Injection molding operations can turn to vented barrel (VB) machines as an alternative to predrying, processing hygroscopic plastics, and mold products with critical appearance requirements. The basic idea of venting (Fig. 3.20) is to extract moisture and other troublesome volatiles (such as residual monomers and low-molecular-weight impurities) from the melted plastic in the barrel. Such volatiles produce splays, streaks, bubbles, etc. that ruin the appearance of the part, degrade its properties, and interfere with plating (16, 158). VBs can be used on virtually all thermoplastics where moisture or other contaminants create quality problems.

Hygroscopic plastics The hygroscopic nature of many widely used thermoplastics can result in severe molding problems unless entrained moisture is removed prior to molding (see the section on Drying in Chap. 6). Excessive moisture can result in appearance defects, such as splay, or even losses in physical properties. One approach to removing entrained moisture is to predry the material, but in most cases a more viable approach is the use of a vented-barrel molding machine without predrying. In this case, the polymer is devolatilized after it has been melted, and because the vapor pressure of water at typical melt temperatures is high, devolatilization can be accomplished rapidly. Moreover, at typical melt temperatures other (nonaqueous) undesirable volatiles may also be removed by using a vented-barrel molding machine.

Devolatilization from the melt stream is made possible by the use of a two-stage screw and barrel incorporating a vent port as shown in Fig. 3-20. The first stage of the two-stage screw accomplishes the basic plasticating functions of solids feeding and melting. During this process, significant material pressures are generated.

Molten polymer leaving the first stage of the screw enters a decompression section with a large cross-sectional area such that the channel does not completely fill with melt. As a result, the melt pressure drops to essentially atmospheric pressure, and volatiles

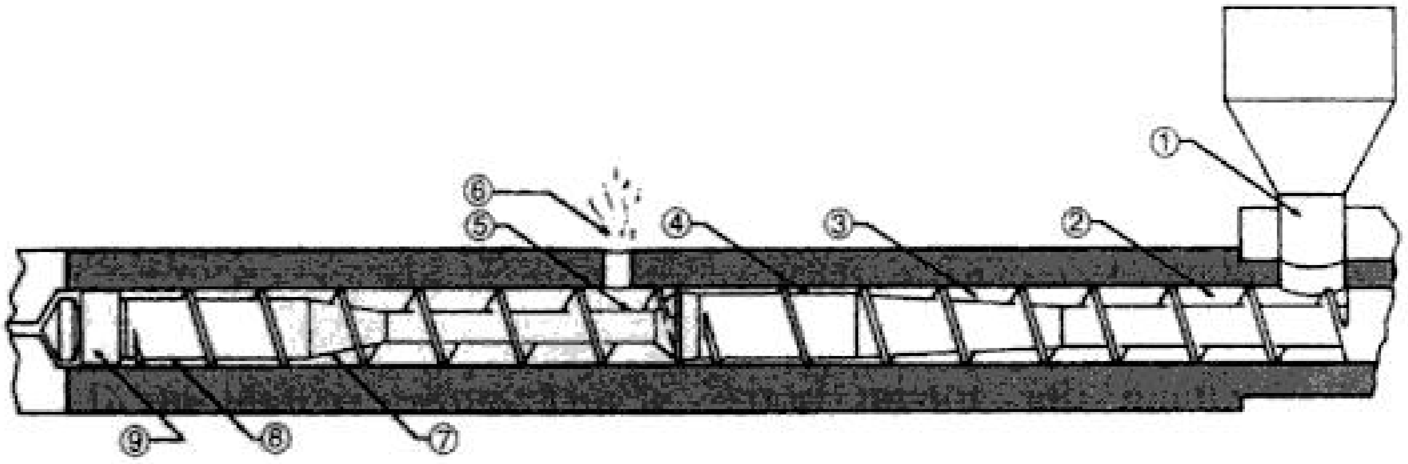


Fig. 3-20 Simplified schematic of a vented injection barrel. (1) Wet material enters from a conventional hopper. (2) The pellets are conveyed forward by the screw feed section, and are heated by the barrel and by some frictional heating. Some surface moisture is removed here. (3) The compression or transition section does most of the melting. (4) The first metering section accomplishes final melting and even flows to the vent section. (5) Resin is pumped from the first metering section to a deep vent or devolatilizing section. This vent section is capable of moving quantities well in excess of the material delivered to it by the first metering section. For this reason, the flights in the vent section run partially filled and at zero pressure. It is here that volatile materials such as water vapor escape from the melted plastic. The vapor pressure of water at 500° is 666 psi. These steam pockets escape the melt, and travel spirally around the partially filled channel until they escape out the vent hole in the barrel. (6) Water vapor and other volatiles escape from the vent. (7) The resin is again compressed, and pressure is built up in the second transition section. (8) The second metering section evens the flow and maintains pressure so that the screw will be retracted by the pressure in front of the nonreturn valve. (9) A low-resistance sliding-ring nonreturn valve works in the same manner as it does with a nonvented screw.

Since the function of the devolatilization zone is to provide residence to enable volatiles to escape from the recirculating melt, a high heat input is not necessary. Consequently, the barrel temperature should be set at a level just sufficient to maintain the desired melt temperature, this being generally a lower setpoint than in the melting zone.

The final-pumping-zone temperature is selected to adjust the final melt temperature to that required for molding, and to provide a lower melt viscosity to reduce the pressure drop through the nonreturn valve to avoid any loss in pumping capacity.

Screw speed Since devolatilization is a rate-sensitive diffusion process, a long devolatilization time ensures a large reduction in volatiles. Consequently, unless an auxiliary starve feeder is used, the lowest screw speed that maintains an adequate throughput, consistent with cycle-time requirements, should be used. This will provide the slowest transition of material through the devolatilization zone, and hence the greatest devolatilization time. However, when an auxiliary feeder is used, higher screw speeds may be advantageous:

1. Since higher shear rates, and hence higher levels of viscous dissipation, occur in the melting zone, higher melting rates can be generated.
2. When extremely low melt viscosity prevents the second stage from generating sufficient pressure to retract the screw without material backup into the devolatilization zone, a higher screw speed can provide a higher drag flow component to counteract the reverse pressure flow.
3. Since the conveying rate in the devolatilization section is a product of screw speed and degree of fill, when the rate is controlled externally by the auxiliary feeder a higher screw speed will reduce the degree of fill and hence provide better devolatilization.

Back pressure In conventional molding, application of back pressure is used to improve the melting characteristics of an otherwise marginally performing screw. However, as shown in Fig. 3-20, the first stage of a two-stage screw is hydraulically isolated from the second stage by the unfilled devolatilization zone. Consequently, back pressure cannot be used to affect melting.

Applying back pressure affects the second zone only and serves to increase the reverse pressure flow component. This will necessitate a longer filled length of the second stage to produce adequate conveying, and thus the length of unfilled channel will be reduced and devolatilization impaired. In an extreme case, back filling can progress to the vent port, and vent bleed will occur.

The only practical advantage of back pressure lies in the additional mixing it induces in the second stage. In rare instances, this additional mixing may be advantageous. However, the additional length of a two-stage screw is almost always sufficient to ensure adequate mixing without the application of back pressure.

Residence time Certain polymers, notably polycarbonate and thermoplastic polyesters, are hydrolytically degradable and may suffer undesirable depolymerization effects due to chemical reaction of moisture with the polymer prior to devolatilization. Consequently, the residence time of material in the first stage of the screw should be minimized, and in practice this implies that a high throughput rate is required. Average residence time is long for extended cycle times and small shot utilization. Consequently, care is necessary in correctly sizing the injection unit for the application. In cases where the potential for significant hydrolytic degradation exists, process conditions may be altered to compensate, for example, by reducing the melt temperature in the melting and devolatilization zones.

Advantage summary There are a large number of meaningful advantages to vented injection molding machines, as opposed to the use of hopper or central drying systems:

1. *Eliminates predrying.* A vented injection unit removes moisture more completely without a dryer. Often, a dryer cannot do the job completely in a reasonable time period.

2. *Rapid startup and color or material changes*. You do not have to wait for hours when starting up or changing colors or materials. This increases machine and personnel utilization.

3. *Superior parts*. The improved melt, free of volatiles, renders higher-quality parts with excellent appearance and better physical properties. Splay marks are eliminated from appearance parts and parts to be plated.

4. *Energy-efficient*. The vented machine uses less energy. Btus are not lost while material stands in large hoppers at elevated temperatures for long periods. Dryers are large users of energy.

5. *Removes other volatiles*. Water vapor is not always the only volatile contaminant that should be removed. The vent removes other undesirable materials that come off at temperatures not possible in a dryer. Of course, the escape of volatiles is easier from a melted and agitated plastic. This has been very effective in solving mold and ejector pin plate-out problems.

6. *Eliminates dryer maintenance*. Dryers are high-maintenance items with clogged filters, heater element burnout, and contaminated desiccant beds. Even in shops with good routine maintenance programs, it is common to operate with ineffective dryers for long periods before it is noticed. When this happens, quality goes down and scrap accumulates.

7. *Lessened contamination and material handling*. There is no need to clean out large, complicated hopper dryer systems on every material or color change. The simple, lightweight, standard hopper is easier to clean.

8. *Less space required*. The hopper dryer requires a large volume in order to obtain up to 5 h of drying time. This means a heavy, large, and high hopper that may not fit into the space available.

9. *Eliminates dryer variability*. The variation in part quality and appearance due to changes in dryer performance is eliminated. The vent operates the same all the time.

10. *Greater use of regrind*. The improved moisture-removal ability of the vent allows the use of larger percentages of regrind. The vent also allows the storage of materials in open containers.

11. *Reduced mold venting*. The removal of volatiles from the vent reduces the mold-venting problem. It can also eliminate the problem of clogged mold vents.

Barrel-Venting Safety

It is a common practice to plug a vented barrel and use it the same way as a solid parallel machine. In such cases, on rare occasions the internal pressure can exceed the strength limit of the bolts retaining the plug, so that the plug is released violently from the barrel. To prevent this hazard a number of safety precautions are taken. Retaining bolts with more than enough strength should be used. Also, the barrel should be oriented downward or away from the operator (even with no plug, in case the vent opening becomes overloaded with melt and is forced out). A pressure gauge at the head of the barrel can provide a preliminary warning at a maximum safe pressure value, followed by shutoff of the machine at higher pressures if practical (otherwise, all persons in the plant should be alerted). Finally, one can install shear pins and/or a rupture disk (if not already installed), and ensure that the machine is heated adequately at the forward barrel end (see the section on Safety in Chap. 2).

Screw Designs

Even in today's high-technological world, the art of screw design is still dominated by experience, trial and error having shown the exact capabilities of the screws for a particular plastic operating under specific conditions. However, computer models (based on proper data input and, very important, experience of a person with a setup similar to the one being studied) play a very important role. When new materials are developed or improvements in old materials are required, one must go to the laboratory to obtain rheological and thermal properties before computer modeling can be performed effectively. New screws improve one or more of the basic screw functions of melt quality, mixing efficiency, melting performance along the screw, melt heat level, output rate, output stability, and power usage (energy efficiency) (see the section on Rheology and Melt Flow in Chap. 6).

Design Basics

Thus, this technology is still basically empirical, and it is often proprietary. However, scientific approaches to screw design based on an analytical melting model can be used. The production rate of acceptable melt from a screw, which is its most important characteristic, is often limited by its melting capacity. The melting capacity in turn depends on the plastic properties, the processing conditions, and the particular geometry of the screw. Once the melting capacity is predicted, the screw can be designed to match it.

Design Performance

The rotating helical-flighted screw mechanically plasticizes, with the help of heat and pressure at a controlled flow rate, and advances a melt through the barrel. Plastic in the screw channel is subject to changes during operation. Each operation of the screw subjects the plastic to different thermal and shear situations.

Consequently, the plasticizing process becomes rather complex. However, it is controllable and repeatable within the limits of the equipment and material capabilities. A fixed screw speed, screw pitch, and channel depth determine output. A deep channel screw is much more sensitive to pressure changes than a shallow screw. At low pressures a deep channel will provide more output; however, the reverse is true at high pressures. Shallower channels in general tend to give better mixing and flow patterns.

A screw feature that influences melt behavior is its length-to-diameter ratio *L*/*D*. The denominator of the ratio is conventionally reduced to 1 for uniformity, so that a 24/1 screw has a screw length 24 times its diameter. Based on the melt characteristics, there are various reasons for having short or long *L*/*D*s. Advantages of a short screw are: (1) less residence time in the barrel, so that heat-sensitive plastics are exposed to heat for a shorter time, thus lessening the chance of degradation; (2) a smaller plasticator; (3) less torque required, making screw strength and power required less important; and (4) less investment cost initially and for replacement parts. Advantages of a long screw are: (1) it allows for greater output and melt recovery rates; (2) the screw can be designed for greater mixing and more uniform output; (3) the screw can be designed to operate at higher pressures; and (4) the screw can be designed for greater melting with less shear and more conductive heat from the barrel.

Mixing and Melting Devices

A screw without special mixing elements may not do a good mixing job, mainly because of the nonuniform shear acting in a conventional screw channel. Mixing is distributive and/or dispersive. Distributed and dispersive mixing are not physically separated. In dispersive mixing, there will always be distributive mixing. However, the reverse is not always true.

In distributive mixing, there can be dispersive mixing only if there is a component exhibiting a yield stress and if the stresses acting on this component exceed the yield stress. In order for a dispersive mixing device to be efficient, it should have the following characteristics:

1. The mixing section should have a region where the plastic is subjected to high stresses.
2. The high-stress region should be designed so that exposure to high stresses occurs only for a short time.
3. All fluid elements should experience the same high stress to accomplish uniform mixing.

In addition, it should follow the general rules for mixing: minimum pressure drop in the mixing section, streamline flow, complete

Fig. 3-22 Melting mechanism during the injection molding cycle.

barrel-surface wiping, to the extent compatible with ease of manufacture of the mixing section.

In plasticators, barrier-type mixing devices can be used in the screws. Dynamic mixers are often used to improve screw performance. Static mixers are sometimes also inserted at the end of the plasticator. Proof of their success is shown by their extensive use worldwide, especially in extruders (3). Each type of mixer offers its own advantages and limitations. Such mixers are usually installed as near as possible to the end of the metering zone. Where practical they should be located in a region where the melt viscosity is not too low.

With some of these installations, because they may have to operate at a lower speed to avoid problems such as surging, independently driven mixers can be used so machines can operate at optimum speed. Other benefits of independently driven mixers involve feeding capability and performance. For example, metering pumps can inject liquid additives with precision directly into the mixer.

There has been developed an almost universally accepted model of melting in a single screw for injection molding [used extensively in extrusion equipment (3)]. This model is the basis for most computer simulations. It has been demonstrated to be correct by many freeze tests (Fig. 3-22). A sketch of this universal model is shown in Fig. 3-23; an explanation of the melting action is also included.

All the above information indicates the following relationships between metering-

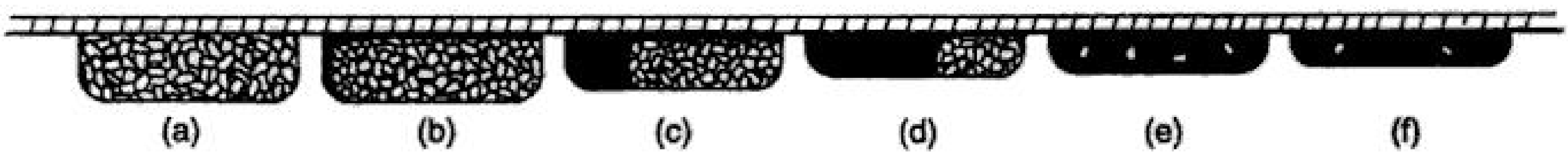


Fig. 3-23 Melt model for standard screw. (a) The feed section initiates solids conveying. This is enhanced by sliding (low friction) on the screw and high friction on the barrel. Of course, when the plastic sticks to the screw and slides on the inside surface of the barrel, it just goes around with the screw and never moves forward. In the feed section, there is also some compaction and a little heating of the resin. (b) At the beginning of the transition, the resin is further heated and more compression occurs. The solid resin is forced against the barrel, causing a sliding friction. The resulting heat creates a film of melted polymer on the inner barrel surface. (c) As the plastic proceeds down the transition, there is more melting and more compression. Usually most of the melting takes place in the transition. Here the polymer is divided into three parts: a compacted solids bed, a melt film along the barrel surface, and a melt pool. The melt pool is formed as the melt film is collected by the advancing flight. Most of the melting continues to be the result of sliding friction of the solids bed against the heated barrel. This is rapid, efficient melting something like melting an ice cube by pushing it against a hot grinding wheel. (d) The channel depth continues to decrease as we progress down the transition. Melting continues, and the width of the solids bed decreases, while the width of the melt pool increases. Unfortunately, as the channel gets shallower, the shear rate increases. Now the already melted polymer continues to heat. This is normally undesirable. (e) Further down, the solids bed breaks up, and the unmelted pellets are distributed throughout the channel like ice cubes in water. The efficient melting of the solids bed by friction against the barrel stops. Now only less efficient melting continues. This is something like heating the water to melt the ice cubes. It will finally get the job done, but it is slow and much less efficient. Overheating of the melt continues in the shallow metering section. (f) The plastic continues down the shallow metering section to the discharge. It is possible that there remain unmelted pellets or portions within the melt having higher or lower temperatures and viscosities. Then the melt is nonuniform, giving poor properties and color mixing. Greater mixing can be achieved by reducing the channel depth, but this must be done at the expense of more overheating and less output per revolution. The constant-depth metering section is not a good mixer. This is because smooth laminar flow patterns are established, causing the different portions of melt to continue to move in a fairly constant circular pattern. This does not mix the dissimilar portions of melt.

zone depth and the desired results:

Desirable results	**Obtained by**
High output	Deep screws
Low melt temperatures	Deep screws
Melt quality	Shallow screws

A solution is needed that can provide good mixing and product uniformity at high production rates without excessive stock temperatures. The answer has been found in a variety of mixing and barrier screws designed to overcome these problems. Some of the more common mixing devices are described and illustrated below.

Dulmage mixer The Dulmage screw has one or more Dulmage sections incorporated as an integral part of the screw, usually located at the discharge end. The Dulmage screw was one of the first mixing screws and was developed by Fred Dulmage of Dow Chemical Co. It has a series of semicircular grooves cut on a long helix in the same direction as the screw flights. There are usually three or more such sections, interrupted by short cylindrical sections. This interrupts the laminar flow, and it divides and recombines the melt many times. In this way, it works something like a static mixer. It is still used on foam screws and other applications (Fig. 3-24).

Mixing pins Around 1960, several companies started to place radial pins in the screw root. These pins tend to interrupt the laminar

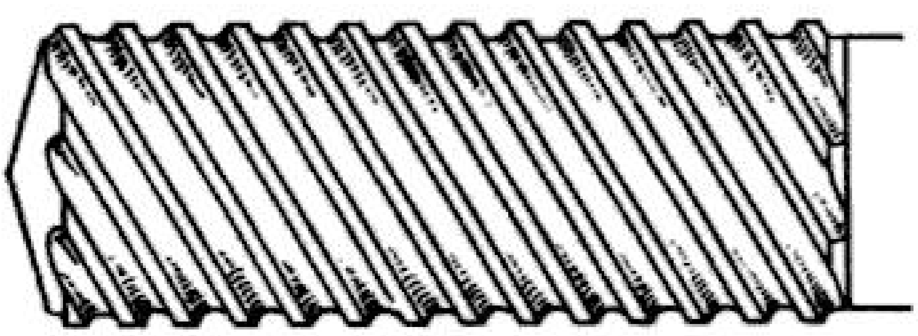
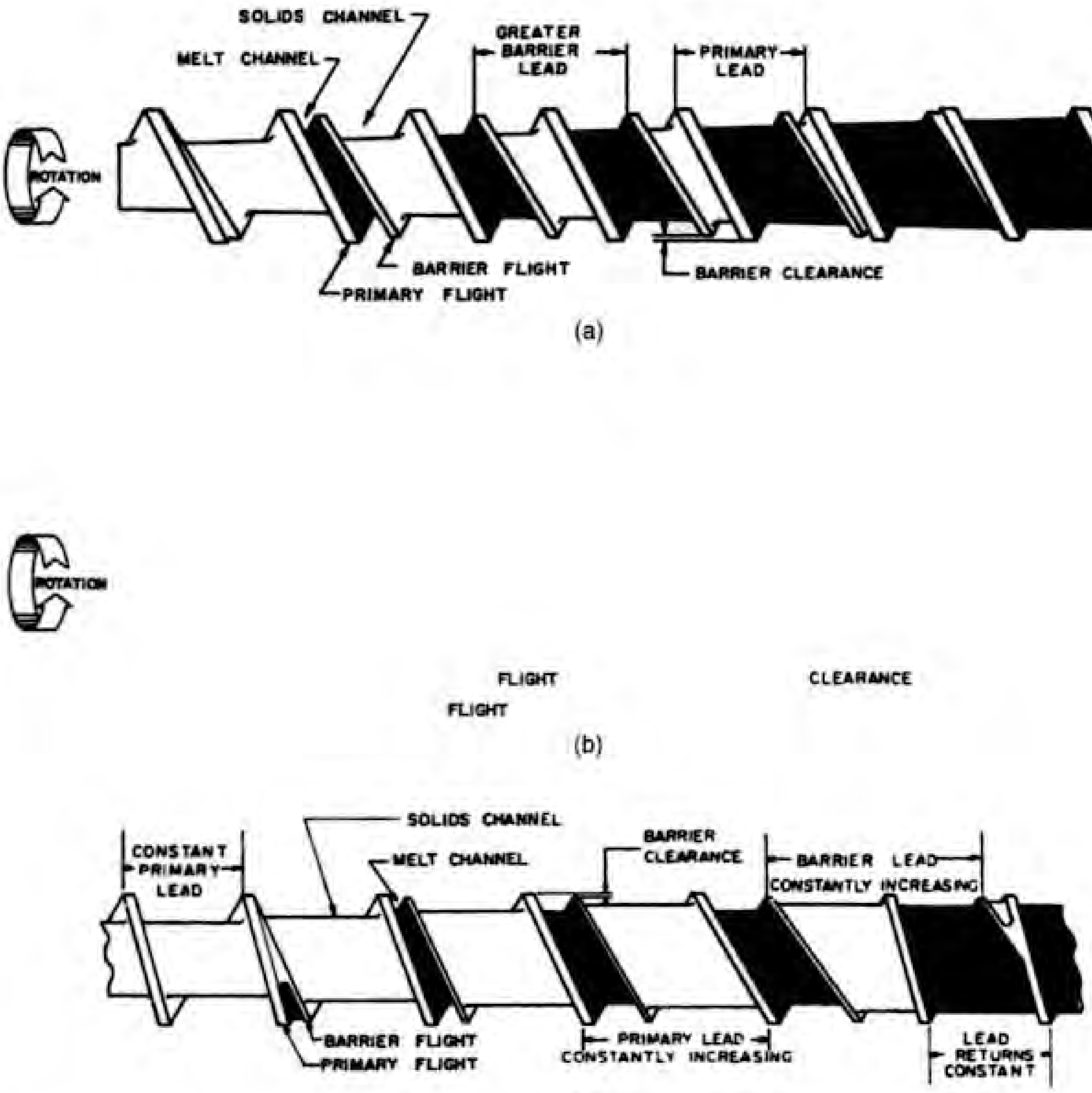


Fig. 3-24 Dulmage mixer.



(a)

(b)

(c)

Fig. 3-29 A few of the more important and popular barrier screws (all patented). (a) The *Uniroyal* screw is the original barrier screw. The barrier flight starts on the front side of the primary flight at a greater lead, and it disappears into the back side of the primary flight. The channels are essentially close-ended, and the depths on either side of the barrier usually the same. There are many ways the channel widths and depths can vary. This screw is also sometimes referred to as the Maillefer screw. (b) The *MC-3* screw (trademark of Hartig Division) starts the barrier flight from the front side of the primary flight just like the Uniroyal screw. The greater lead of the barrier makes it move away from the primary flight, creating the melt channel. After it has gone a certain distance, the lead changes back to the same lead as the primary flight, and the two flights run parallel for most of the barrier section. The melt channel becomes deeper and the solids channel progressively shallower. At the end, the barrier flight is terminated and the depths all end up at the metering level. The solids channel is open at the discharge end. (c) The *VPB* screw (trademark of Davis Standard Division) uses variable leads. The barrier flight starts from the front side of the primary flight and continually increases its lead until it ends in the root at the end of the transition. This gives an increasing width of the melt channel in order to accept more and more melt. The width of the solids channel remains constant, causing the lead of the primary flight to constantly vary also. Both channels are open at the end of the transition.

is worthwhile to compare this with the melt model of the conventional screw (Fig. 3-23).

Figure 3-29 reviews some of the more important and most popular mixing screws used by industry. By comparing these barrier screws, you can appreciate how many different types exist.

These types of screw designs provide high-efficiency melting by different and sometimes radically opposed means. Usually, the

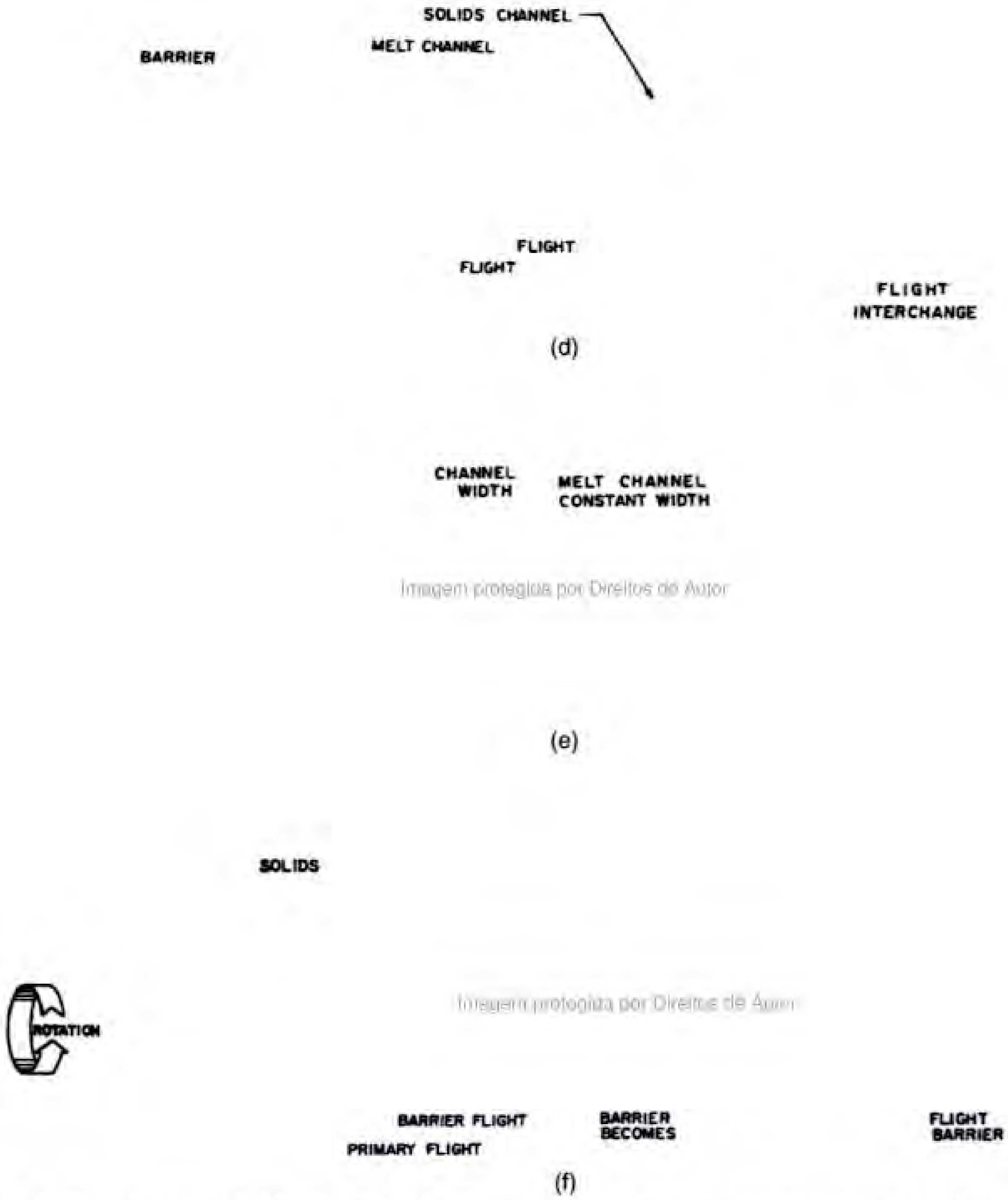
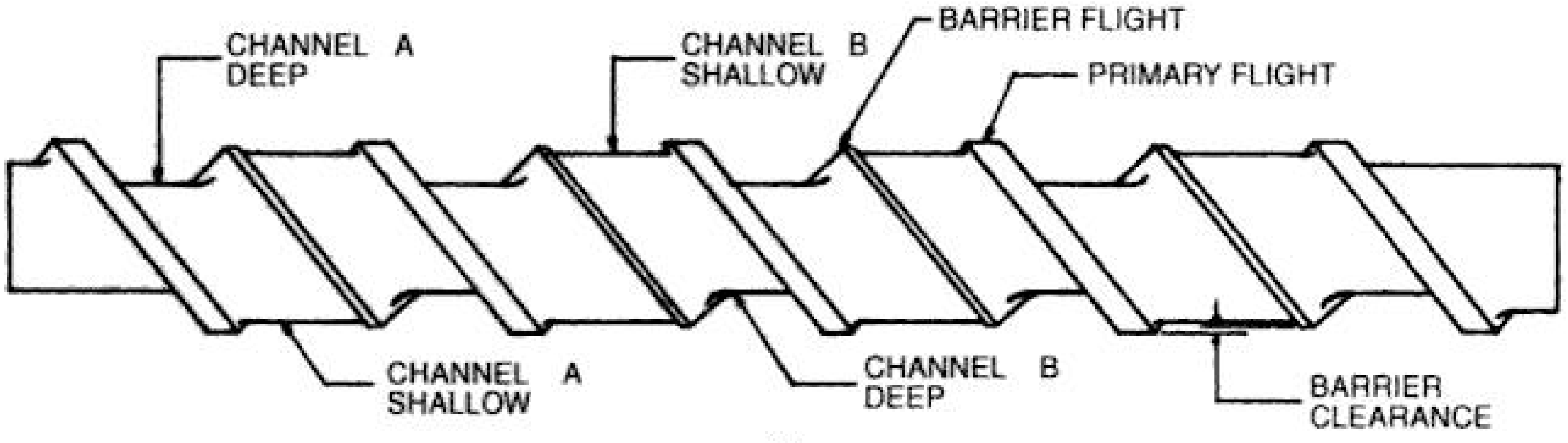


Fig. 3-29 (*Continued*) (d) The *Double Wave* screw (trademark of HPM Corp.) has two equal-width channels separated by an undercut barrier flight. The roots of each channel go up and down like a wave. The channel depth on one is shallow, while the channel across the barrier is deep. This screw continually reverses, forcing melted polymer back and forth across the barrier. The material in the channel is alternately subjected to high and low shear. Usually, these double-wave mixing sections are located in the metering section where the plastic has already been melted. The channels are open at both ends and run parallel. (e) The *Efficient* screw (trademark of New Castle Industries, Inc.) has a conventional feed section, usually with square pitch. At the beginning of the transition, the primary lead increases substantially, providing space for a new barrier flight and melt channel. After the width of the new melt channel has been established, the flights and channels remain parallel through the transition section. The solids channel remains approximately the same width as in the feed section. The barrier flight ends and the open-ended melt channel merges with the solids channel at the end of the transition. (f) The *Barr II* screw (trademark of Robert Barr, Inc.) begins the barrier flight from the root of the screw at the beginning of the transition. The open-ended melt channel is created and the flights run parallel to the end of the mixing section. The depth of the solid channel decreases, and the depth of the melt channel increases. Near the end, there is a flight interchange, where the primary flight becomes the barrier flight and vice versa. This promotes mixing. The barrier flight disappears into the channel root, and the melt channel is open-ended.



(g)

Fig. 3-29 (*Continued*) (g) The *Willert II* screw (trademark of W.H. Willert Inc.) starts a second flight from the back side of the primary flight at the beginning of the transition. This flight has a lesser lead than the original primary flight, causing it to move away from that flight and creating a melt channel. This new flight is full-diameter and becomes the new primary flight. After it has separated the proper distance, it changes its helix angle and runs parallel to the new barrier flight. The barrier flight is really a continuation of the original primary flight, except that it is undercut, like all barrier flights. The solids channel is deepened in the area where the new melt channel is created so that the conveying action will not be choked off. The melt channel becomes deeper and the solids channel shallower as you progress down the transition. Near the end of the screw, the primary and barrier flights interchange for added mixing. Both channels are open at the discharge end.

melting rate is controlled by providing a barrier between the solid bed and the melt pool to assure that the solid bed does not break up prematurely and become encapsulated in the melt.

An example of this concept, introduced by George Kruder of HPM (Fig. 3-29d), is called a Double Wave screw. The conventional feed and melting zones are employed until the point at which about 50% of melting is completed. There the melt and solids are mixed together. This is accomplished by varying the metering channel depth in a sinusoidal pattern. The mixing action alternates between very shallow, high-shear zones and rather deep, low-shear zones. The effect of this action is to promote the distributive mixing of the solid bed melt (which has been thoroughly broken up) with the melt pool.

Specialized Screw Designs

Low-shear screws Some injection molding operations may require complete melting, but with minimal strains or stresses applied to the melt. Minimizing induced strains is required when an otherwise high level of mixing would destroy some desired inhomogeneous feature of the material; a typical example occurs in the injection molding of mottled or marbelized products using a polymer feedstock consisting of dissimilarly colored components. In this example, a high degree of melt mixing can result in uniformly colored product. Minimizing applied stresses may be required to avoid physical degradation of the feedstock, as, for example, in the injection molding of polymers reinforced with long glass fibers. In this case, breakage of the reinforcement during processing may result in an insufficiently strong product.

A specialized shear screw design (U.S. Patent 4,299,792, 1981) is shown in Fig. 3-30, consisting of a flighted section just long enough to provide adequate conveying and moderate compaction to initiate melting, followed by a deep flightless section to supply extensive material residence that enables conductive heat transfer from the barrel to

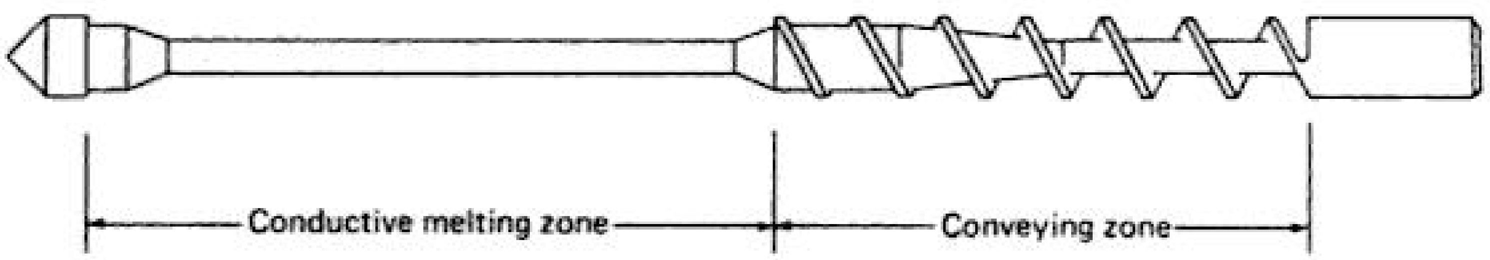


Fig. 3-30 Low-shear screw.

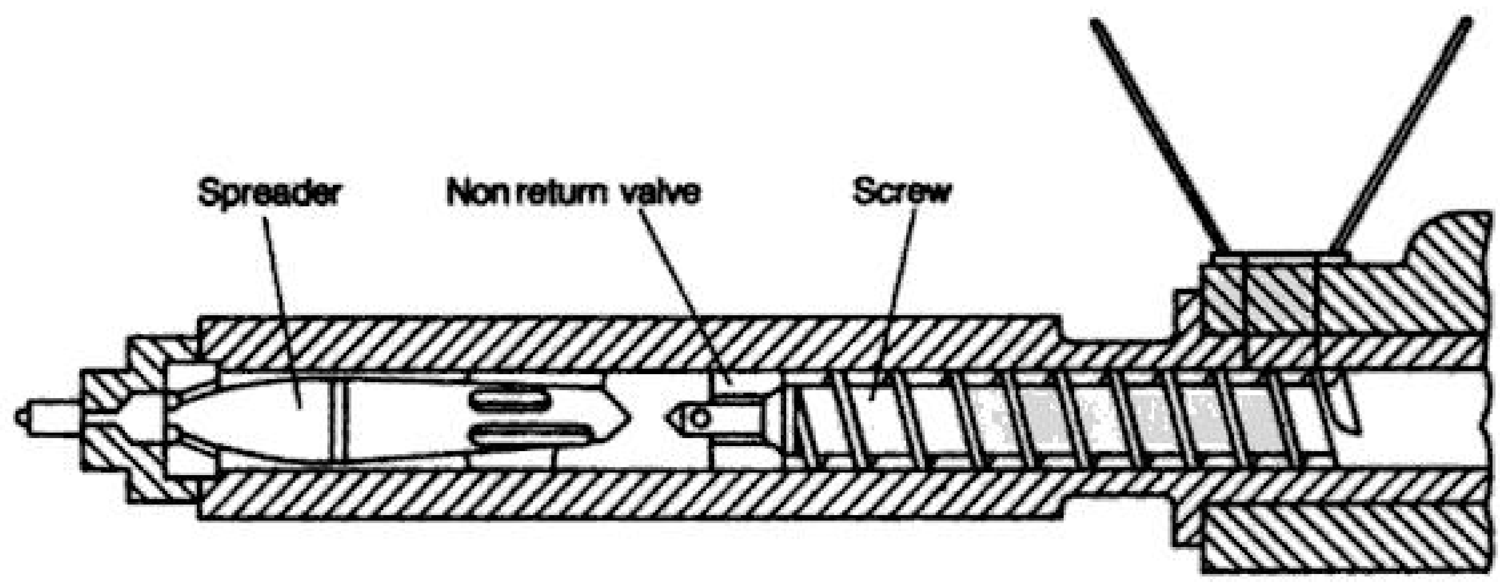


Fig. 3-31 Example of a marbleizing screw.

provide a major contribution to melting. The absence of screw flights in the latter section of the screw, in effect, substitutes an essentially two-dimensional simple strain field for the more complex three-dimensional strain field encountered in a fully flighted screw channel and significantly reduces mixing. The localized high shear stresses associated with recirculatory flow in a fully flighted section are similarly avoided.

Marbleizing screws Molded parts can be produced that resemble variegated marble (like marble cake). The surface has an attractive appearance of two or more colors. It is produced by not developing the "ideal" melt during the extrusion (plasticizing) action (Fig. 3-31). A worn-out screw may be satisfactory, or a screw such as the low-shear (Fig. 3-30) screw.

Screw Tips

With two-stage IMMs there are no special screw tips required beyond those for reciprocating IMMs. However, special designs have been developed to improve the movement of melt (Fig. 2.10). The reciprocating screw machine uses the screw as a plunger. As the plunger comes forward, the material can flow back into the flights of the screw. For low-melt-viscosity, thermally stable plastics, a nonreturn valve is attached to the front of the screw to prevent material backflow. Figure 3-32 shows a sliding-ring nonreturn valve, the most widely used configuration. However, a number of different check valves have been designed and used, such as those shown in Fig. 3-33.

With the ring type of valve, the ring is in the forward position while plasticizing so that melt can flow past the seat and through its hollow portion of the screw. When the screw operates as a plunger, the ring moves into the back position. Basically, the flow path must be

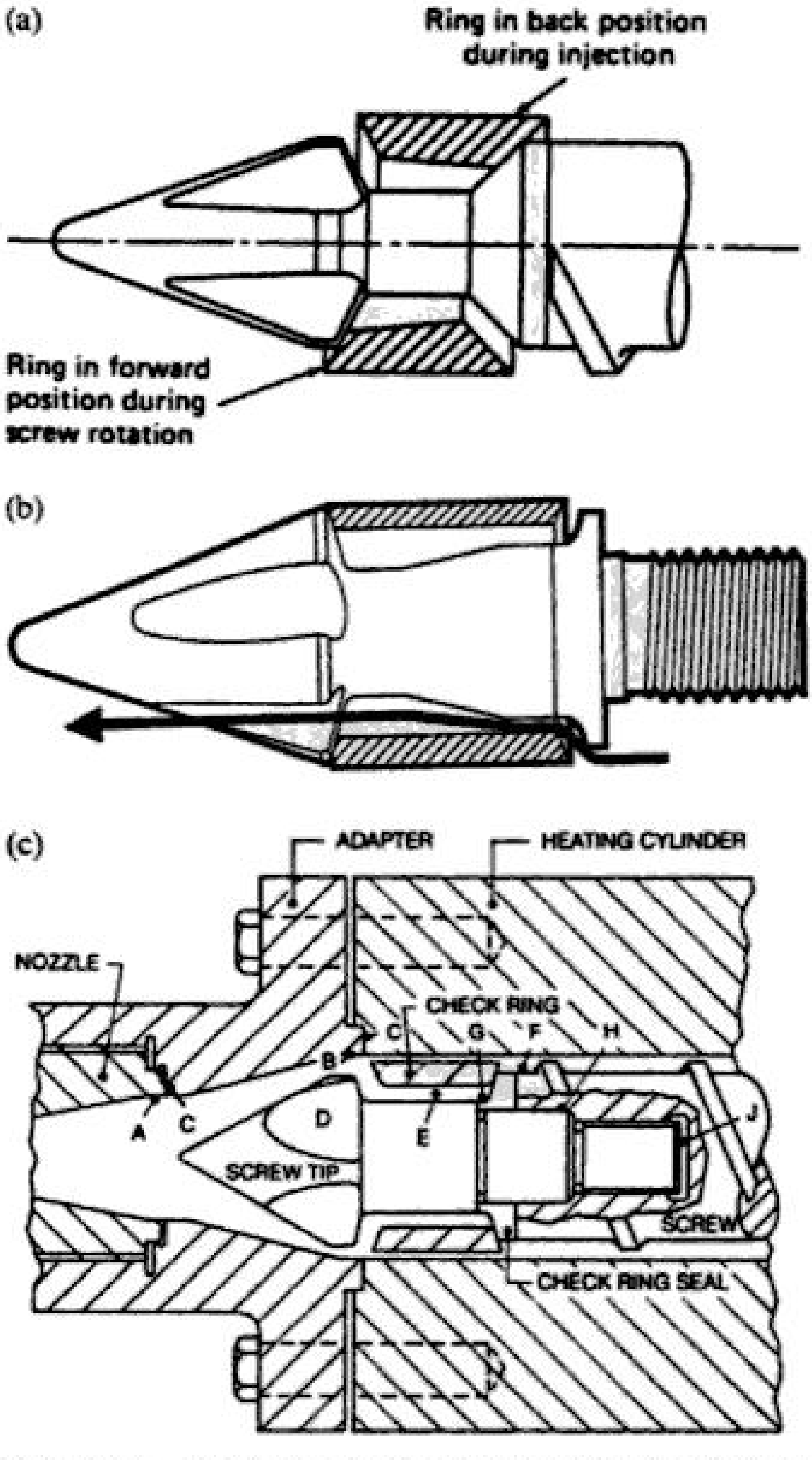


Fig. 3-32 Sliding nonreturn valve: (a) Schematic of ring (split) to show forward and backward motions. (b) Melt flow pattern. (c) Valve with adapter.

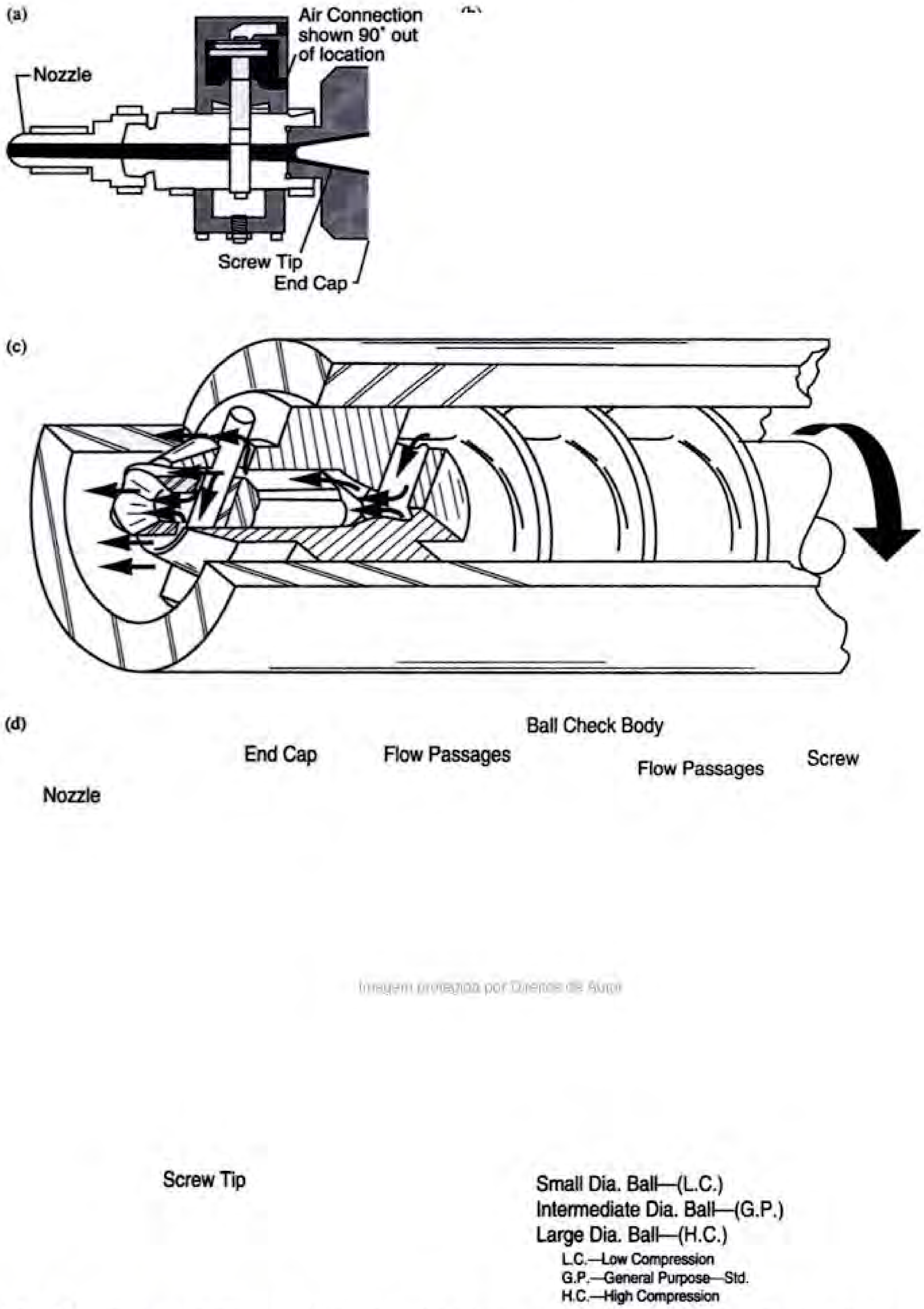


Fig. 3-33 Designs of different check valves: (a) Air-operated (or hydraulic) shutoff valve. (b) Nonreturn valve with movable pin d attached to tip b, controlling movement of ring c with seat ring e, conical sealing surface f, and thread-shaped surface g. (c) Moving-pin forward-open and backward-closed valve. (d) Ball check valve. (e) Spirex spring check valve. (f) Dray DNRV check valve.

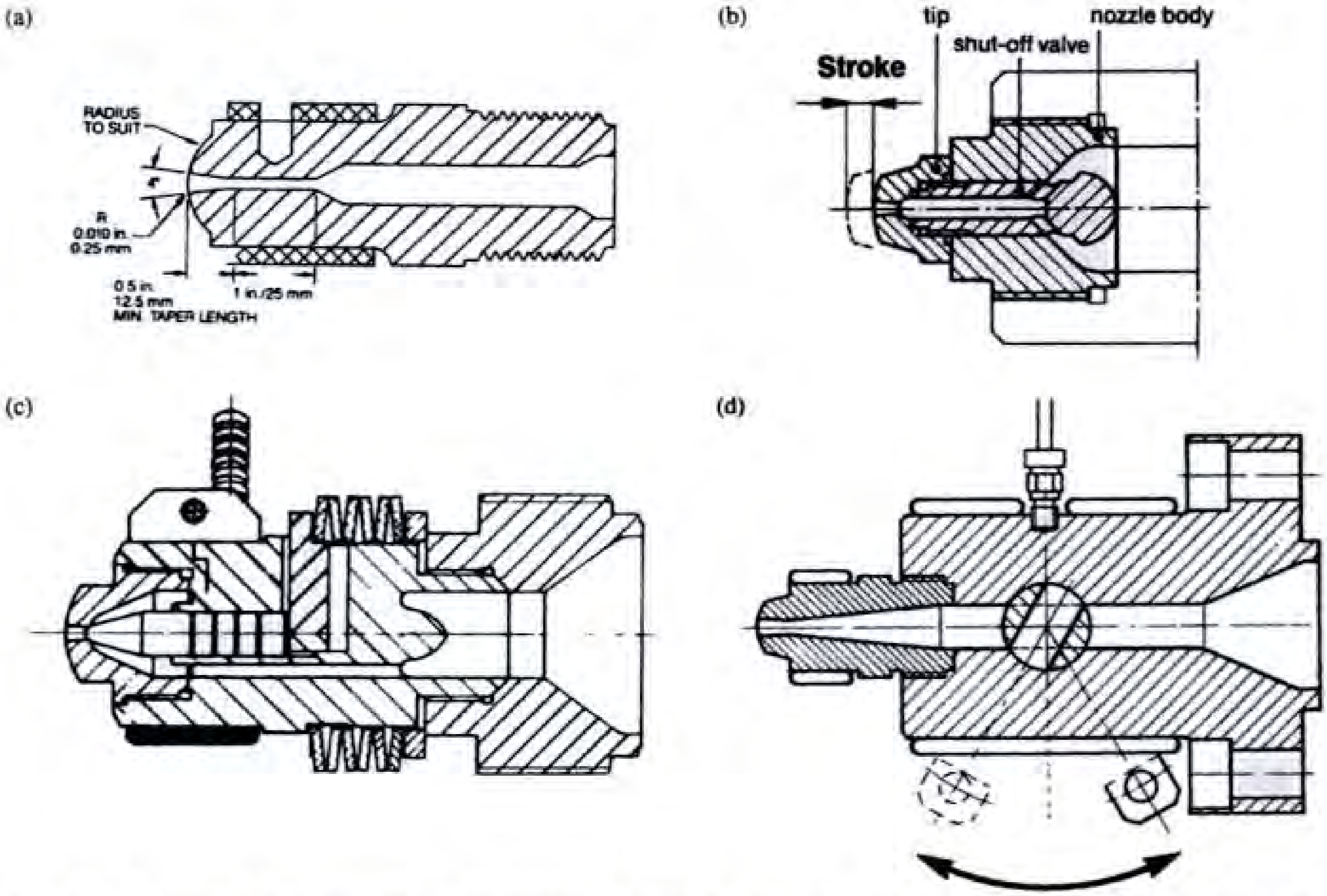


Fig. 3-35 Nozzle designs: (a) Conventional reverse tapered nozzle. (b) Sliding shutoff nozzle. (c) Spring-operated valve nozzle. (d) Mechanical shutoff nozzle, usually operated hydraulically.

piston outward, shutting off the melt outlet (7). Figure 3-35 also shows a spring-operated valve nozzle and a mechanical shutoff nozzle. (Also see the shutoff, Fig. 3-33.) There are also restrictive nozzles such as static mixers and filtering types, but they can cause material hangup and degradation. These restrictive nozzles, as well as others such as the shutoff type, can significantly reduce the maximum cavity pressure and are to be avoided when possible.

Each type of nozzle has its advantages and disadvantages based on the material being processed and type of injection molding machine to be used. Standard steel nozzles can be used successfully, as an example, but nozzles of stainless steel can offer better protection against black specks in long production runs with heat-sensitive and certain other kinds of materials.

Influence of Screw Processing Plastics

Generally a screw's best performance will be at less than 50% of shot capacity. Performance falls when you exceed this, due to the reduction in effective screw L/D as the screw moves back and inventory time is reduced (1, 7).

Most machinery manufacturers rate their screws according to the SPI Screw Plasticating Code. Using these data is quite simple. The screw recovery in ounces per second indicates how many seconds to allow in the machine cycle for screw recovery. For example, if the shot size is 10 oz (0.3 kg) and the recovery rate 1 oz (0.03 kg/sec), the screw recovery will be 10 sec.

Half of the pound-per-hour figure will be the expected output of molded product. For example, 400 lb/h (182 kg/h) should result in 200 lb/h (91 kg/h) of product. The reason is that the pound-per-hour figure is calculated on screw running time only and does not allow for machine cycling time. Thus, a test cycle is based on 50% screw running and 50% machine cycling.

Amorphous and crystalline plastics (Chap. 6) have different heats of fusion, so a screw that is good for one usually is not good for the other. As amorphous pellets are heated, they gradually soften and form a layer of melt. By the time the material reaches the transition zone of the screw, it is a mixture of melted and unmelted material. The semifluid mixture can then fit into the smaller flight volume of the transition zone.

This ability of amorphous materials to soften and melt over a fairly long range allows the use of a smaller *L*/*D* screw ratio and low compression ratio. The feed section also can be rather short.

Crystalline pellets, on the other hand, retain their shape until they have absorbed sufficient heat and melt all at once. This means that pellets in the screw retain their shape as they reach the transition section of the screw. The volume of pellets cannot fit into the reduced-volume flights of the transition section, so until the plastic melts, the screw may stall during its backward travel.

A longer screw, coupled with a higher compression ratio, is desired for these materials. The larger *L*/*D* allows more time to heat the pellets before they reach the transition section. The higher compression ratio means reduced flight depths in the metering section to reduce the possibility of unmelted material getting through.

Melt Quality

Screw geometry IMM suppliers provide a general-purpose screw (GPS) with their equipment unless the customer makes a specific request otherwise. There are many reasons for this standard practice. A GPS is designed to handle most of the many different thermoplastics available (particularly commercial types). It is obvious that this screw cannot handle all these materials with equal efficiency; it may be most efficient on amorphous plastics and not so efficient on crystalline plastics, or the reverse. What screw is supplied as standard depends on the markets served by the machinery manufacturer.

It has become common practice to rate the screws by *L*/*D* ratio, which is nothing more than a ratio of the length to the screw diameter. The longer the screw, the greater the amount of material in the screw under heat at all times. Therefore, a long (large *L*/*D*) screw would be beneficial for crystalline plastic because of the longer exposure time available for heating and melting the plastic. However, other factors of screw design (flight configuration, flight depths, compression ratio, and pitch) have a distinct bearing on screw performance.

Flight configuration concerns how much of the screw length is devoted to the feed section, the transition (compression) section, and the metering section. Each section plays an important part in the screw's performance. (Details were given at the start of this chapter.) For any given *L*/*D*, changing these three sections can change the performance of the screw. As an example, a long feed section with a short metering section will create a screw with high throughput, but poor quality. With a reduced feed section and long transition and metering sections, the output will be reduced, but the melt quality greatly improved. To aid in improving heat buildup, a preplasticator with or without external heaters can be used to improve melt performance (Fig. 3-36).

Flight depths affect performance in that a shallow feed section limits performance because the amount of plastic picked up by the screw is limited. Deep flights in the metering section allow unmelted plastic to move through. The higher the compression ratio, the lower the output but the better the quality.

Residence time The process of heating and cooling thermoplastics can be repeated indefinitely by granulating scrap, defective parts, etc. During the heating and cooling cycles of injection molding, the plastic develops a "time to heat" history, or *residence time*. With only a few repetitions of the recycling, the properties of certain plastics are not significantly affected by residence time. However, for some TPs they can be. The amount of residence time is also critical during the initial processing of virgin material. If the temperature is higher than required and/or the hot melt is in the barrel longer than necessary, the residence time is increased and problems arise in plastics behavior during injection into the mold and/or the molded finished part.

Ideally, one wants a good-quality melt, no more or less than required. However, if the

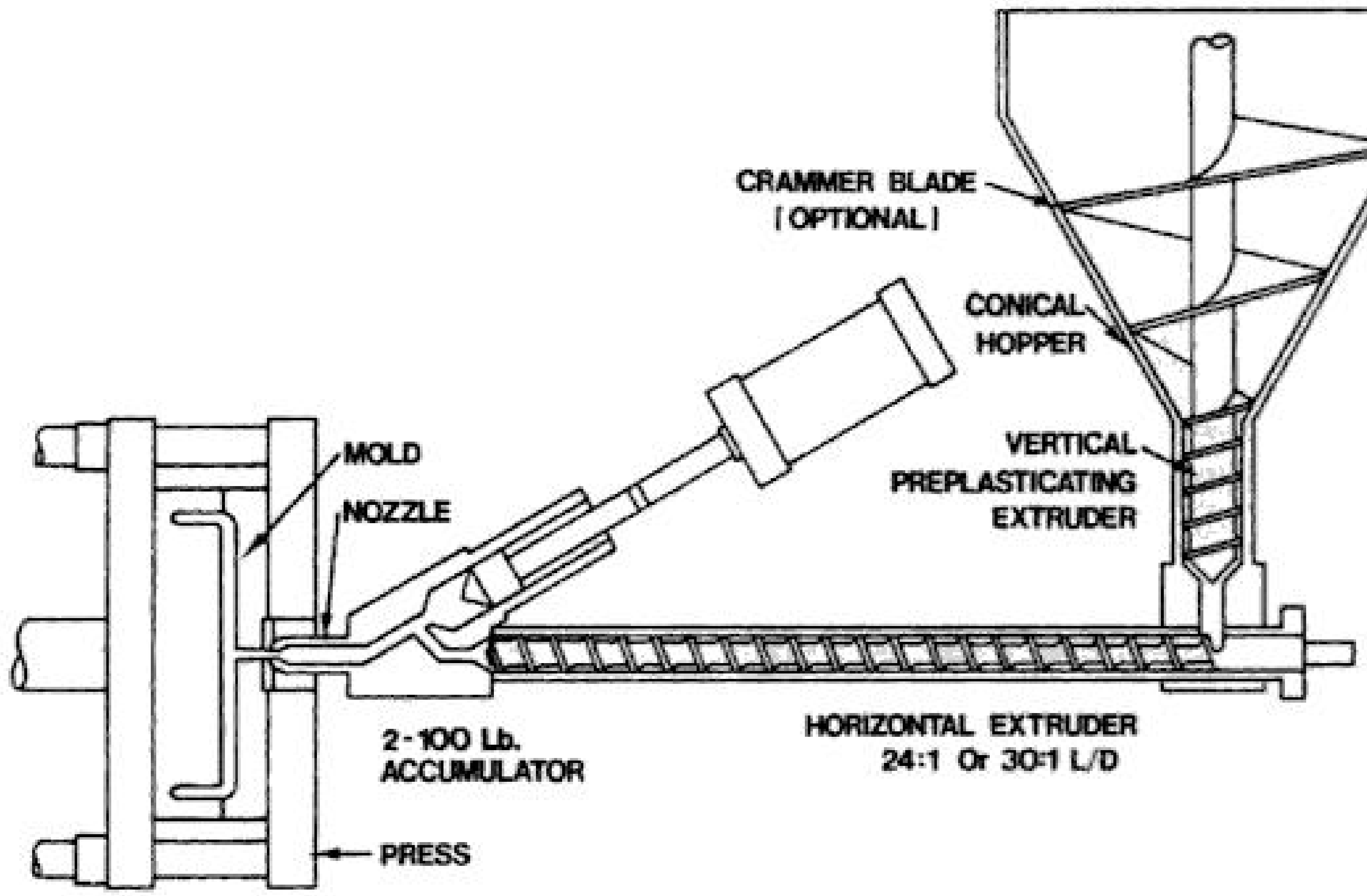


Fig. 3-36 Preplasticator use with a two-stage IMM.

processor desires to obtain more plasticated material per hour (as an example) than the screw can provide, the temperature in the barrel is raised. This can result in a poor-quality melt that necessitates longer cycle times.

Some machinery manufacturers tell their customers that they can use up to 80% of the machine's shot capacity. However, the average shot size used by most molders does not exceed 50% of maximum capacity. What is involved here is residence time.

In operating the screw to plasticate the next shot, a certain heat profile is used to bring the plastics to the desired temperature by the time it comes off the end of the screw. The plastic moves along the screw in increments, depending on the shot size. Each time the screw operates to pump back, it feeds a slug of cold pellets along the feed section of the screw. Once this has been accomplished, the screw sits motionless until it is required to inject the previously prepared shot into the mold. Then the screw pumps back, and the process starts all over again.

Depending on the capacity of the screw, the shot size required for the particular molding, and the overall cycle time of the operation, the operator can determine how long the plastic must be exposed to heat to bring it to the desired temperature and condition. Another factor to consider is the effect of the screw stroke. As the screw pumps back, the length of the feed section is reduced. This action has a bearing on feeding capability as well as heat exposure. In general, a feed stroke of three diameters is about the maximum for good performance (298). However, most machines today are using a stroke of four diameters to obtain a larger shot size.

The reason for studying the residence time is that even though you are using the proper injection molding machine as far as clamp capacity is concerned, you may not have enough screw capacity. The shot capacity of the screw is not always the best indicator of machine performance. Even at 50% shot capacity, the residence time created by the desired cycle time may not prove enough for the plastics in the barrel to ensure a good-quality melt. (In this example, not enough residence time was used; in most cases, it is too long.)

It is important to understand residence time because of its effect of limiting cycle time and part quality. Raising the temperature of the barrel may help, but usually creates other problems. Fortunately, most molding jobs are in the range of 20 to 25% shot capacity or less, so residence time problems do not appear. However, if the mold permits a faster cycle and the desire is to run as fast as possible, residence time is a factor. Experience indicates that a residence time of less than 1.5 min usually means that you are on the edge. However, long residence time is not a problem if you anticipate it and thus use a lower temperature.

Materials of Construction

Different materials of construction are used to meet the requirements of the different plastics being processed. As an example, bimetallic barrels offer extensive durability when processing abrasive materials such as glass- and mineral-filled plastics, certain engineering plastics, and granulated/recycled plastics. In contrast, when processing unfilled nylon continuously, the probability is that you will have to replace a worn out screw about every six months. These questions are discussed below under the subheading Screw Wear Protection.

Screw Outputs

The rate of output (throughput), or the speed at which plastic is moved through the plasticator, has been pushed continually higher as a result of design advances in screws, IMM equipment, and plastic materials. Output rates generally range from a few kilograms to tons per hour on single-screw machines. (With twin-screw extruders using large diameters, output rates range from a few kilograms to at least 30 tons per hour.) A rough estimate for output rate (OR) in lb/h can be calculated by using the barrel's ID in inches and using the following equation: $\mathrm{OR} = 16\ \mathrm{ID}^2$; for kg/h multiply by 0.4536.

The output of a screw is fairly predictable, provided that the melt is under control and reasonably repeatable. With a square-pitch screw (a conventional screw where the distance from flight to flight is equal to the diameter), a simplified formula for output is $R = 2.3D^2hgN$, where R is the rate or output in lb/h (kg/h), D is the screw diameter in in. (mm), h is the depth in the metering section in in. (mm) (for a two-stage screw use the depth of the first metering section), g is the specific gravity of the melt, and N is the screw rotation speed (rpm).

This formula does not take into account back flow and leakage flow over the flights. These flows are not usually a significant factor unless the plastic has a very low viscosity during processing or the screw is worn out. The formula assumes pumping against low pressure, giving no consideration to melt quality and leakage flow of worn screws.

With all these and other limitations, the formula can still provide guidance as follows:

1. It can serve as a general guide to the output of the screw.

2. If the actual output of the screw is significantly greater than calculated, it is caused by high compression ratios that overpump the metering section. Sometimes this is desirable, but it can lead to surging and rapid screw wear if it is excessive.

3. If the output is a lot less, it usually indicates a feed problem or a worn screw or barrel. The latter can be determined by measurement. A feed problem can, on occasion, be corrected by changes in barrel temperature settings. More often, the problem is caused by other items, such as screw design, shape and bulk density of the feedstock, surface condition of the screw root and barrel ID in the feed area, feed-throat design, or screw temperature.

Influence of Screw and Barrel Wear on Output

There are two types of wear. One is mechanical, such as adhesive and abrasive wear. The other is corrosion, which produces pitted surfaces. Adhesive wear is caused by contact between the flight and the barrel. The screw and barrel are engineered to minimize such contact, but some is unavoidable. The plastic material being processed can significantly influence the abrasive and/or corrosive actions.

Wear does not occur suddenly but builds up over months of machine operation. It finally shows itself in one of several ways. The examples to be discussed concern reciprocating screw machines, since they have the major wear problems; but wear also occurs in two-stage IMMs, including the breaking of nonreturn valve rings. There can be loss of shot control or consistency, requiring increased feed to make up for melt slippage back over the valve and screw. Screw recovery time can increase. There can be a decrease in product quality. The cycle time increases due to higher-temperature melt.

Mechanical wear is usually in the part of the screw where the feed section ends and the transition starts. It is usually caused by the use of high back pressure, an improper heat profile, or a worn nonreturn valve that restricts flow.

Often the plastic is filled with talc, glass, or other materials that do not melt but form slugs and can cause scrubbing of the screw and barrel, particularly the roots of screw flights. This action continues until the flight is worn away. The barrel is likewise worn in the corresponding area. A change in the heat profile in the rear and center zones of the barrel will usually eliminate this problem. The plastic must start to melt as it reaches the end of the feed zone in order to move easily into the transition zone. If the screw returns in an erratic manner, the plastic does not have the required temperature, and screw and barrel wear result.

Another complication can be that the shot size and the cycle time do not allow sufficient residence time for the plastic to melt properly as it passes through the barrel. A usual guide is that if the residence time is less than $1\frac{1}{2}$ min, there may be a cold condition.

Influence of the Material on Wear

Corrosive wear due to plastic materials usually occurs in the front of the screw and barrel. The major wear is in the metering section of the screw, at times extending a little into the transition section. Most of the wear problem is with the barrel core and the screw root. It leads to darkening of the screw and pitting of its surface. Note that certain plastics and fillers (nylon, phenolic, etc.) when heated degrade, giving off corrosive gases and/or liquids.

This wear usually occurs during startup and shutdown when the melt is not moving on cycle and sits in the barrel under heat. The long soaking time of the barrel on startup and shutdown can cause degradation of the plastic when it is in contact with the steel screw and barrel. The ratio of wear of the barrel to that of the screw's root is usually about 2:1. The barrel ID enlarges at twice the rate of the decrease of the root of the screw. This difference occurs because the heat source comes from the outside of the barrel. The screw root is not as hot as the barrel's interior surface.

When a nonreturn valve is new, it will fit the barrel closely, preventing leakage of melt during injection. When the barrel ID changes due to wear, leakage begins to occur during injection. If the barrel wear reaches 0.010 to 0.012 in. (0.025 to 0.030 cm), the ring on certain nonreturn valves can break. Then the IMM does not operate efficiently.

Screw Wear

The wear in screw plasticators generally causes an increase in the clearance between screw flight and barrel (Fig. 3-37). It often occurs toward the end of the compression section. This type of wear is more likely to occur when the screw has a high compression ratio. Regardless of where it occurs, the plasticator's melting capacity is reduced. If the wear is serious enough, it will cause the products to exit at a slower rate or (more likely) to have lower quality. In addition to adhesive wear (caused by metal to metal contact under high stress), abrasive wear (galling), and corrosion wear (chemical reaction/mechanical attack on the sliding surfaces), screws are subject to laminar wear (affecting thin outer layers of metal at interfaces) and surface-fatigue wear (micro- or macroscopic separation from the surfaces).

Production Variations

As screw flights and the insides if barrels wear, the pumping ability of the screw is diminished. Some materials and some additives will cause higher wear than others; for example, linear low-density polyethylene (LLDPE) will cause more wear than conventional LDPE or polypropylene. Many fillers, such as titanium dioxide (used for white coloring) and reinforcing fibers, also create high-wear situations. Under some conditions, people tend to run a poorly performing screw long after it should have been changed. Converting the cost of a screw into an equivalent volume of plastic or into a profit per day will determine the payback for a change. Assume a screw cost $30,000 to $40,000 each with output at 3,000 lb/h (1,400 kg/h) of a $0.40/lb plastic. If you waste 100,000 lb (45,400 kg) of plastic, you have thrown away cost of a new screw. A new screw would have saved 33 h of processing. It pays to replace the screw.

Screw Wear Protection

Most screws are made of medium-carbon-alloy steel, usually heat-treated and hardened to 28 to 32 RC (see Table 3-3 Materials of Construction). It is then nitrided (gas or ion) or chrome-plated for better wear resistance. Screws with improved abrasion resistance can be made of vanadium bearing tool steel hardened to 54-56 RC. Cost and brittleness generally limit such screws to less than 90-mm diameter. Materials with improved corrosion resistance include precipitation-hardened (pH) stainless steel and nickel alloys. The outer surface of the flights is the area of the screw most susceptible to wear. The most common means of protecting that area is to weld on a hard-facing alloy.

Coatings Different wear-resistant and protective coating techniques, such as having the screw flight land hardened, are used to meet different requirements according to whether the plastic being processed is corrosive, abrasive, clinging, etc. Types of coating used include chrome plating, nickel plating, and impregnation with carbon, silicon carbide, tungsten carbide, boron, cobalt, etc (see Table 3-4).

Purging

The purging of the plasticator—that is, removing all plastics from it—is normally done on changing material colors (particularly going from a dark to light color) and on shutdown, at the end of a production run. Agents used for this purpose are listed in Table 3-7. See also the section on Cleaning Molds and Machine Parts in Chap. 4.

Table 3-7 Guidelines for purging agents

Material to be Purged	Recommended Purging Agent
Polyolefins	HDPF
Polystyrene	Cast acrylic
PVC	Polystyrene, general-purpose, ABS, cast acrylic
ABS	Cast acrylic, polystyrene
Nylon	Polystyrene, low-melt-index HDPE, cast acrylic
PBT polyester	Next material to be run
PET polyester	Polystyrene, low-melt-index HDPE, cast acrylic
Polycarbonate	Cast acrylic or polycarbonate regrind; follow with polycarbonate regrind; do not purge with ABS or nylon
Acetal	Polystyrene; avoid any contact with PVC
Engineering resins	Polystyrene, low-melt-index, HDPE, cast acrylic
Fluoropolymers	Cast acrylic, followed by polyethylene
Polyphenylene sulfide	Cast acrylic, followed by polyethylene
Polysulfone	Reground polycarbonate, extrusion-grade PP
Polysulfone/ABS	Reground polycarbonate, extrusion-grade PP
PPO	General-purpose polystyrene, cast acrylic
Thermoset polyester	Material of similar composition without catalyst
Filled and reinforced materials	Cast acrylic
Flame-retardant compounds	Immediate purging with natural, non-flame-retardant resin, mixed with 1% sodium stearate

Table 3-8 Guidelines for plastic changes

Material in Machine	Material Changing to	Mix with Rapid Purge and Soak	Temperature Bridging Material	Follow with
ABS	PP	ABS	—	PP
ABS	SAN	SAN	—	SAN
ABS	Polysulfone	ABS	PE	Polysulfone
ABS	PC	ABS	PE	PC
ABS	PBT	ABS	PE	PBT
Acetal	PC	Acetal	PE	PC
Acetal	Any material	PE	—	New material
Acrylic	PP	Acrylic	—	PP
Acrylic	Nylon	Acrylic	—	Nylon
TPE	Any material	PE	—	New material
Nylon	PC	PC	—	PC
Nylon	PVC	Nylon	PE	PVC
PBT	ABS	PBT	PE	ABS
PC	Acrylic	PC	—	Acrylic
PC	ABS	PC	PE	ABS
PC	PVC	PC	PE	PVC
PE	Ryton	PE	PE	Ryton
PE	PP	PP	—	PP
PE	PE	PE	—	PE
PE	PS	PS	—	PS
PETG	Polysulfone	PETG	—	Polysulfone
Polysulfone	ABS	Polysulfone	PE	ABS
Polysulfone	ABS	Cracked acrylic	—	ABS
PP	ABS	ABS	—	ABS
PP	Acrylic	Acrylic	—	Acrylic
PP	PE	PE	—	PE
PP	PP	PP	—	PP
PS	PP	PP	—	PP
PVC	Any material	LLDPE or HDPE	—	New material
PVC	PVC	LLDPE or HDPE	—	PVC
PPS	PE	PPS	PE	PE
SAN	Acrylic	Acrylic	—	Acrylic
SAN	PP	SAN	—	SAN

This action consumes substantial nonproductive amounts of plastics, labor, and machine time. It is sometimes necessary to run hundreds of pounds of plastic to clean out the last traces of a dark color before changing to a lighter one; if a choice exists, process the light color first. Sometimes there is no choice but to pull the screw for a thorough cleaning (Table 3-8).

There are few generally accepted rules on purging agents to use and how to purge: (1) try to follow less viscous with more viscous plastics; (2) try to follow a lighter color with a darker color plastic; (3) maintain equipment by using preventative maintenance; (4) keep the materials handling equipment clean; and (5) use an intermediate plastic to bridge the temperature gap such as that encountered in going from acetal to nylon.

Ground or cracked cast acrylic and PE-based (typically bottle-grade HDPE) materials are the main purging agents. Others are used for certain plastics and machines. Cast acrylic, which does not melt completely, is suitable for virtually any plastic. About one pound for each ounce of injection capacity is usually used.

PE-based compounds containing abrasive and release agents have been used to purge the "softer" plastics such as other olefins, styrenes, and certain PVCs. These purging agents function by mechanically pushing and scouring residue out of the plasticator. Other techniques use chemical agents.

Removal of extraneous materials (impurities) from a substance or mixture can be accomplished by one or more separation techniques. A pure substance is one in which no impurities can be detected by any experimental procedure. Though absolute purity is impossible to attain, a number of standard procedures exist for approaching it to the extent of 1 ppm or even less.

Patents Influence Screw Designs

It is widely recognized that screw design is extremely important in providing high output, good melt quality, and in many cases extensive mixing. As a consequence, many special design features have been invented and patented. U.S. patent laws help stimulate the creation of new inventions by granting exclusive rights to the inventor (or the assigned owner) for an extended period—formerly 17 years but now often longer; see the subsection on Patents in the section on Legal Matters in Chap. 16.

Some owners of special screw designs choose to license other firms to build their patented designs, but many owners do not license their inventions. The strategy followed by most hardware vendors is to use all the legal methods available to optimize the performance of screw design features. Rarely do they have an opportunity to study how their optimized designs perform in comparison with their competitors' patented screw designs. There usually is no opportunity to test a competitor's optimized screw design, since design features may differ for each application.

Terminology

Aspect ratio The ratio of length to diameter (L/D) for a plasticator screw or barrel hole.

Auger The action of the rotating screw in advancing the plastic from the unmelted to melted stages.

Axis A reference line of infinite length drawn through the center of the rear of the screw shank and the center of the discharge end.

Blister ring A raised portion of the root between flights of sufficient height and thickness to effect shearing of the melt as it flows between the blister ring and the inside wall of the barrel.

Checkup When purchasing a screw, it is important to inspect it fully, at least for outside diameter, channel profile, shank dimensions, and overall length.

Coating Different coating systems are used to meet different requirements of the screw (see the subsection on Screw Wear Protection above).

Constant-lead screw Also called uniform-pitch screw. A screw with a flight of constant helix angle.

Cushioning See *Melt cushioning.*

Decreasing-lead screw A screw in which the lead decreases over the full flighted length, usually of constant depth.

Depth The perpendicular distance from the top of the screw thread to its root.

Drive motor A motor that rotates the plasticating screw.

Face The flight extending from the root of the screw to the flight land. The rear face is the side toward the feed section, and the front face is the side toward the meter end of the screw.

Flight crack A hairline crack in the flight surfacing material of a screw. This is not a problem as long as pieces do not come out of the surface. That usually occurs next to the edge of the flight; if it does the screw must be repaired.

Flight cutback A portion of the screw at the discharge end that is not flighted. This is normally included in the definition of the flight length.

Flight length The overall axial length of the flighted portion of the screw, from the start of the feed pocket (throat) to the front end of a register. Flight length does not include any valves (nonreturn etc.)

Flight pitch, square A great many screws have a pitch equal to the diameter of the screw (maximum diameter of the flight). Such a screw is called a square-pitch screw and has a helix angle of 17.7°.

Flight rear face Also called trailing edge. Face of flight extending from the root of the screw to the flight land on the side of the flight toward the feed opening.

Front radius The radius at the intersection of the front (melt-pushing side) of the flight and the screw root. Usually this radius is smaller than the rear radius, and it may change from one portion of the screw to another.

General-purpose screw GP screws are designed to suit as wide a range of plastics as possible. They will not be the ideal answer for specific plastics. As an example, a screw designed for a semicrystalline (usually called crystalline) material must provide, initially at least, more heat input than an amorphous thermoplastic. Thus, when a specific material is going to be used for a long run, it becomes economically very beneficial to use a dedicated screw, whose design of a screw is determined by data on the melt flow or by theoretical characteristics of the plastics.

Heat treatment To improve performance and reduce wear on screws, different heat treatments (annealing) are used, based on the screw material of construction and plastics to be processed. Treatments include flame hardening, induction hardening, nitriding, and precipitation hardening.

Hub Portion immediately behind the flight that prevents the escape of the plastic.

Hub seal A sealing device to prevent leakage of plastic back around the screw hub, usually attached to the rear of the feed section.

Identification At times no one knows what kind of screw is being used, since the machine OEM installed it. It is in your best interest, for assuring product performance, to find out what you have in case it needs replacement, etc.

Key The mechanism by which torque is transmitted from the drive to the screw.

Leakage flow In the metering section, leakage flow is the backward flow of plastics through the clearance between the screw flight lands and the barrel. It is usually an insignificantly small negative component of the total plastic flow.

Marbleizing A marbleizing (mottling) screw is one that produces little or no mixing, to obtain decorative effects. A typical application is a woman's cosmetic case, where a swirling or grainy effect is desired in the plastic coloration. One such design has a low compression ratio, with a good portion of the screw consisting of the feed section. A short taper and usually an one-flighted metering section with few flights follows it. A multiflighted screw can be used so that colorants largely stay in their own channels until exiting. Another method is just to use a worn-out screw. Such a system does not reproduce exactly the same pattern, though it may be close. For exact duplication, coinjection processing is used.

Material starve feeding Feeding through a controlled metering device (screw auger, belt, etc.) of material going through a feed hopper so that the screw in a plasticator receives less material than what it can handle. The purpose is to provide a better and/or better-controlled melt.

Melt cushioning To keep melt injected in the mold under pressure until it solidifies and shrinks, the ram plasticizing stroke and consequently the metered amount of plastic to be injected in the plasticator must be set slightly in excess of the shot size. The purpose of this action is to ensure that as the stroke is completed and the mold filled, a cushion of melt just a few millimeters thick is maintained between the ram and nozzle. The result is greater compactness with little or no shrinkage of molded products (see *Thickness adjustments* below).

Mixing Different screw designs are used to meet various plastics' melt requirements. As an example, the Spirex Pulsar mixing screw is used where low shear action is required. The Spirex Z-mixer is for higher-shear melts.

Mixing section A section added to some plasticating screws, at the output end, that thoroughly mixes the plastic.

Multiple flighted screw A screw with more than one helical flight such as double-flighted (double-lead, double-thread, or two-start), and triple-flighted, etc.

Multiple-stage screw A screw with one or more special mixing sections, containing changes in the flight helix, choke rings, venting, or torpedos, that combine feeding, mixing, and metering.

Nonreturn valve A valve to prevent return flow. Different designs are used to meet different plastic melt flow and/or costs requirements. They greatly influence the product quality.

Performance Evaluation of screw performance usually starts with a comparison with other screws if available. The parameters that should be considered include the following: (1) output rate, (2) extrudate melt temperature, (3) extrudate melt quality, (4) extrusion stability (pumping consistency), and (5) energy usage. Different processes will require different values for each of the parameters listed, and these values must be known for accurate screw design selection.

Pitch, square See *Flight pitch, square*.

Planetary A multiple-screw device in which a number of satellite screws, generally six, are arranged around one longer and larger-diameter screw. The portion of the central screw extending beyond the satellite screws provides the final pumping action, as in a single-screw extruder. This screw system provides special compound mixing actions as well as the discharge of volatiles toward its hopper end when processing powders such as dry-blended PVC.

Plasticating Preparing the melt via the screw and barrel actions.

Plasticator frictional heat The heat generated within the stock as a result of mechanical working between the rotating screw and the stationary barrel.

Plasticizing The melting and mixing action occurring during plastication.

Plastic volume swept The volume of material which is displaced as the screw (or plunger) moves forward. It is the effective area of the screw multiplied by the distance of travel.

Plate dispersion plug Two perforated plates held together with a connecting rod and placed in the nozzle to aid in dispersing a colorant in a plastic as it flows through the orifices in the plates.

Pocket The feed pocket exists on most screws and is located at the intersection of the bearing and the beginning of the flight.

Pushing flight The face or edge of the screw flight that drives the plastic forward towards the barrel exit.

Screw compression ratio The value obtained by dividing the developed volume of the screw channel at the feed opening by that of the last flight prior to discharge. For thermoplastics, typical values range from 2 to 4, also expressed as 2 : 1 to 4 : 1; with thermosets, it usually is 1. The value is rounded off to a whole number or simple fraction such as $3\frac{1}{2}$, or $2\frac{1}{4}$.

Screw compression zone See *Screw transition zone.*

Screw, constant-lead See *Constant-lead screw.*

Screw, constant-taper A screw of constant lead and uniformly increasing root diameter over the full-flighted length.

Screw core A hole in the screw for the circulation of a heat-transfer medium (liquid) or installation of a heater.

Screw core plug The plug used in the core to modify the length (or depth) of the core.

Screw core tube An interior pipe or tube used to introduce a heat-transfer medium into the screw core in conjunction with a rotary union assembly.

Screw decompression zone, vented In a vented barrel, the decompression zone exists between the first and second compression zones and allows venting of volatiles without the escape of plastic melt.

Screw diameter The diameter developed by the rotating flight land about the screw axis.

Screw diametral clearance The difference in diameters between the screw and barrel bore.

Screw drag flow In the metering section, the drag flow is the component of total material flow caused by the relative motion between the screw and barrel; it is equal to the volumetric forward displacement of the plastic in the screw channel. The plasticator output is equal to the drag flow less the sum of the pressure flow and leakage flow.

Screw drive The entire electric and mechanical system used to supply mechanical energy to the input shaft.

Screw feed section The portion of a screw that picks up the material at the feed opening (throat) plus an additional portion downstream. Many screws, particularly those for extruders, have an initial constant-lead and -depth section, all of which is considered the feed section. This section can be an integral part welded onto the barrel or a separate part bolted onto the upstream end of the barrel. The feed section is usually jacked for fluid heating and cooling.

Screw feed side opening An opening that feeds the material at an angle into the side of the screw.

Screw flight The outer surface of the helical ridge of metal on the screw.

Screw flight depth The distance in a radial direction from the periphery of the flight to the root. The location of measurement should be specified.

Screw flight front bottom radius The radius of the fillet between the front face of the flight and the root.

Screw flight front face The face of the flight extending from the root of the screw to the flight land on the side of flight toward the discharge. It is the same as the pushing flight or leading edge.

Screw flight full length The overall axial length of the flighted portion of a screw, excluding nonreturn valves, smear heads, etc. in an injection molding screw.

Screw flight helix angle The angle of the flight at its periphery relative to a plane perpendicular to the screw axis. The location of measurement should be specified.

Screw flight land The surface at the radial extremity of the flight, constituting the periphery of the screw.

Screw flight land hardening The wear surfaces (primarily of flight lands) are usually protected by welding special wear-resistant alloys over these surfaces. There are many different types.

Screw flight land width, axial The distance in an axial direction across one flight land.

Screw flight lead The distance in an axial direction from the center of a flight at its periphery to the center of the same flight one turn away. The location of measurement should be specified.

Screw flight number of turns The total number of turns of a single flight in an axial direction.

Screw flight pitch The distance in an axial direction from the center of a flight at its periphery to the center of the next flight. In a single-flighted screw, pitch and lead will be the same, but they will be different in a multiple-flighted screw. The location of measurement should be specified.

Screw flight rear face See *Flight rear face.*

Screw heat treatment See *Heat treatment.*

Screw hub See *Hub.*

Screw, constant-lead See *Constant-lead screw.*

Screw decreasing-lead See *Decreasing-lead screw.*

Screw leakage flow See *Leakage flow.*

Screw materials The majority of screws and barrels are made from special steels. Low-alloy steels are sometimes used with wear-resistant liners.

Screw mechanical requirements Screws always run inside a stronger, more rigid barrel. For this reason, they are not subjected to high bending forces. The critical strength requirement is resistance to torque. This is particularly true of the smaller screws with diameters of $2\frac{1}{2}$ in. (6.4 cm) and less. Unfortunately, the weakest area of a screw is the portion subject to the highest torque. This is the feed section, which has the smallest root diameter. A rule of thumb is that a screw's ability to resist twisting failure is proportional to the cube of the root diameter in the feed section.

Screw melt cushion See *Melt cushioning.*

Screw melt performance With screws, particularly injection types, the melt is not perfect, that is, it is not uniform in temperature, consistency, or viscosity. With the passing of time, melt performance has been improved via screw designs, such as the barrier screws and different screw mixing actions. Nonuniform melt can also be due to variability in the plastic. With certain plastics and conventional screw designs, the temperature within the screw channel can vary by 200°F (111°C). This is an extreme case, but it helps explain that selecting the correct (or best) screw for a particular plastic is important. The more uniform the melt output, the better the product performance.

Screw melt zone The zone (section) where the plastic has been plasticized by heat and pressure.

Screw metering zone A relatively shallow portion of the screw at the discharge end with a constant depth and lead, usually having the melt move three or four turns of the flight.

Screw, metering-type A screw that has a metering section.

Screw mixing and melting A screw without special mixing elements does not do a good mixing job, mainly because of the nonuniform shear action in a conventional screw channel. Mixing is distributive and/or dispersive. Distributive mixing is the mixing of regular fluids, that is, fluids without a yield point (a plastic with a yield point does not deform when the applied stresses are below a critical stress level, the yield stress). Dispersive mixing is the mixing of a fluid with a solid filler, that is, a plastic with a yield point. The objective in dispersive mixing is to break down the particle size of solid filler below a certain critical size and evenly distribute the filler throughout the mixture. An example is the manufacture of a color concentrate in which the breakdown of the pigment agglomerates below a certain critical size is crucial.

Distributive and dispersive mixing are not physically separated. In dispersive mixing, there will always be distributive mixing. However, the reverse is not always true. In distributive mixing, there can be dispersive mixing only if there is a component exhibiting yield stress and the stresses acting on this component exceed the yield stress. In order for a dispersive mixing device to be efficient, it should have the following characteristics: (1) the mixing section should have a region where the plastic is subjected to high stresses, (2) the high-stress region should be designed so that exposure to high stresses occurs only for a short time, and (3) all fluid elements should experience the same high stress level to accomplish uniform mixing. In addition, they should follow the general rules for mixing: a minimum pressure drop in the mixing section, streamline flow, complete barrel surface wiping action, and easy-to-manufacture mixing section.

Screw, multiple-flighted See *Multiple-flighted screw.*

Screw, multiple stage See *Multiple-stage screw.*

Screw pitch, square See *Flight pitch, square.*

Screw plunger stroke The distance the plunger moves.

Screw plunger transfer molding A combination of reciprocating screw injection molding and transfer molding. Plastic is heated just as in a conventional IMM, and the melt is injected into a pot in the mold. As in conventional transfer molding, a transfer ram then forces the melt from the pot through a system of runners into cavities of the mold (or a sprue into a single cavity).

Screw pulling The screw can be removed from the barrel manually, which can be difficult, time-consuming, and risky, or it can be pushed out automatically (by hydraulic action, etc.). The automatic approach eliminates the need for special extraction devices and reducing chances of screw damage.

Screw pump ratio For two-stage, vented screws, a measure of the ability of the second stage to pump more than the first stage delivers to it. In extrusion, a high pump ratio will tend to cause surge, and a low compression ratio to cause vent flow.

Screw radial clearance One-half the diametral screw clearance.

Screw rear bottom radius The radius of the fillet between the rear face of the flight and the root.

Screw rebuilding and repair Screws and barrels are expensive components. When they are damaged or worn, it is often desirable to repair rather than replace them. It is a common practice to rebuild a worn screw with hard-surfacing materials. Quite often, the rebuilt screw will outlast the original one. This is always true if the original screw was flame-hardened or nitrided. The larger the screw diameter, the more economical screw rebuilding becomes. The rebuilding of a $4\frac{1}{2}$-in.-diameter 24 : 1 *L/D* screw costs approximately two-thirds the price of a new flame-hardened screw and half the price of a new stellited screw. It usually does not pay to rebuild 2-in.-diameter and smaller screws.

Repairs are also made on other parts of screws, such as internal thread, splines, etc.

Screw recovery rate The volume or weight of a specified processable material discharged from the screw per unit of time, when operating at 50% of injection capacity. The SPI test procedure is used. A high recovery rate can shorten the cycle time and eliminate one of the reasons for a nozzle shutoff valve.

Screw restriction or choke ring An intermediate portion of a screw offering resistance to the forward flow of material.

Screw, reverse-flight See *Reverse-flight screw.*

Screw root or stem The continuous central shaft, usually of a cylindrical or conical shape, of a screw.

Screw seal A sealing device to prevent leakage of plastic back around the screw hub, usually attached to the rear of the feed section.

Screw shank The rear protruding portion of the screw, to which the driving force is applied.

Screw, single-flighted A screw having a single helical flight.

Screw speed The number of revolutions per minute (rpm) of the screw.

Screw speed control Many processes require speed controls. The performance and reliability of these controls are very similar to those of temperature controls—you get what you pay for. Early speed controllers, like temperature controllers, were mechanical. Speeds were held to within 5%, resulting in poor plastic melt control. When better speed control is desired, the solution is the same as in temperature control; only the equipment names are changed. A device is added to the motor, and an *integral* characteristic is provided, corresponding to the automatic reset in temperature control. It brings the speed closer to the set point. A *derivative* characteristic, corresponding to the heating-rate control in temperature control, heat, ensures a prompt response to any upsets.

The arguments for the use of integral or derivative control of speed are the same as for temperature. Different systems are available, including the all-digital speed control on machines that require speed control. These controls permit accuracies of 0.5% or less. An all-digital phase-locked-loop system permits all motors in a machine and/or a processing line to be synchronized with each other exactly or in a desired speed ratio, just as if they were mechanically geared together.

Screw taper A tapered (conical) transition section in which the root increases uniformly in diameter.

Screw temperature zone A section of the flow path of the plastic that is controlled to the optimum temperature for that zone. Extruders typically have three to six zones on the barrel and a number of zones downstream in the adapter, screen changer, die, and postextrusion treatment areas. IMMs typically have two to four zones on the barrel and nozzle and a number downstream in the mold.

Screw, thermoset type A typical TS screw (with an L/D of 1) has a water-cooled barrel. Control of the temperature of TS plastics is very critical during plasticizing in the screw–barrel; if it goes just slightly too high, it solidifies in the barrel, requiring screw pulling. Thus, one uses an L/D of 1 and a water-cooled barrel.

Screw thrust The total axial force exerted by the screw on the thrust bearing (screw support). For practical purposes, it is equal to the melt pressure times the cross section of the barrel bore.

Screw thrust bearing The bearing used to absorb the thrust force exerted by the screw.

Screw-thrust-bearing rating at 100 rpm The pressure (in psi or MPa) that can be sustained under normal operating conditions, for a minimum bearing life (B-10 rating from the Bearing Manufacturers Association) of 20,000 h.

Screw tip, injection When the melt is forced into the mold, the screw plunger action can cause the melt to flow back into the screw flights. Generally, to prevent this, with heat-sensitive plastics such as PVC and thermosets, a plain or smearhead screw tip is used. For other plastics, this is not adequate, and a number of different check valves are used. These devices work in the same manner as a check valve in a hydraulic system, allowing fluid to pass only in one direction. They are of sliding-ring or ball-check design, and are supplied by many manufacturers.

Screw torpedo An unflighted cylindrical portion of the screw, usually located at the discharge end but sometimes located in other sections, particularly in multistage screws.

Screw torque The work of melting is partly done by rotating a screw in a stationary barrel. The rotational moment of force, called *torque*, is the product of the tangential force and the distance from the center of the rotating member. For example, if a 1-lb (4.45-N) weight were placed at the end of a 1-ft (0.305-m) bar attached to the center of the screw, the torque would be 1 ft × 1 lb or 1 ft-lb (1.36 N-m). Torque is related to power by

$$\text{power (hp)} = \frac{\text{torque (ft-lb)} \times \text{rotation speed (rpm)}}{5{,}252} = \frac{\text{torque (N-m)} \times \text{rotation speed (rpm)}}{7{,}124}$$

Screw transition zone The section of a screw between the feed zone and metering zone in which the flight depth decreases in the direction of discharge; plastic in this zone is a mixture of melting solid and liquid.

Screw volumetric efficiency The volume of material discharged from the machine during one revolution of the screw, expressed as a percentage of the developed volume of the last turn of the screw channel.

Screw wear All screws wear, particularly at the outer surface of the flight, and screw wear influences, melt performance and thus, eventually, part performance. Some screws wear rapidly and others slowly, depending on factors such as (1) screw, barrel, and drive alignment; (2) straightness of screw and barrel; (3) screw design; (4) uniformity of barrel heating; (5) material being processed; (6) abrasive fillers, reinforcing agents, and pigments; (7) screw surface materials; (8) barrel liner materials; (9) combination of screw surface and barrel liner; (10) improper support of the barrel; (11) excessive loads on barrel discharge end; (12) corrosion caused by polymer degradation; (13) corrosion caused by additives such as flame retardants; and (14) excessive back pressure on injection recovery.

To detect screw and barrel wear, keep a log of output (lb/h-rpm or kg/h-rpm). Operators tend to increase the rotation speed to compensate for wear, resulting in higher melt temperatures. A monthly check of specific output will provide information on wear.

Screw wrap-around transition zone A transition section in which the root is always parallel to the axis of the screw.

Shank The rear protruding portion of the screw, to which the driving force is applied.

Single-flighted screw See *Screw, single-flighted.*

Sprue break After injection and screw decompression (suckback), the nozzle may be moved back from the mold sprue bushing to give a small gap while the mold is opened. This action is called screw break. It may be required for handling certain plastics or for preventing the plasticator heat from penetrating the mold.

Suckback Also called screw decompression. Slight retracking of the screw after the melt is molded, the part has solidified, and

Table 4-1 Examples of plasticizing processing temperatures[a]

Polymer	Type	T_g, °F (°C)	Processing Temperature, °F (°C)
Polyetheretherketone (PEEK)	Semicrystalline	290 (143)	650 (343)
Polyphenylene sulfide (PPS)	Semicrystalline	185 (85)	630 (332)
Polyaryleneketone	Semicrystalline	400 (204)	700–780 (371–416)
Polyarylene sulfide	Amorphous	410 (210)	625–650 (329–343)
Polyetherimide (PEI)	Amorphous	Varies: 450 (232) to 545 (285)	Varies: 575–650 (302–343) to 650–700 (343–371)
Polyarylether	Amorphous	476 (247)	650 (343)
Polyethersulfone (PES)	Amorphous	510 (266)	575 (302)
Polyamide-imide (PAI)	Amorphous	470 (243)	650 (343)
Polyimide	Pseudothermoplastic	470 (249)	680 (360)
		482 (250)	660 (349)
		536 (280)	660 (349)
		536 (280)	660 (349)

[a] Typical commodity TPs use about 400 to 550°F (204 to 288°C).

If due to machine and plastic variables rejects develop, then one moves the machine controls to achieve higher temperatures and/or lower pressures and thus restore quality. This is a simplified approach to producing quality parts, since only two variables are being controlled. (This example uses a thermoplastic; with a thermoset, to reduce cycle time the highest temperature and pressure would be used, etc.)

The next step in the molding-area technique is to use a three-dimensional diagram (Fig. 4-2). By plotting melt temperature vs. injection pressure vs. mold temperature, one obtains a molding volume diagram (MVD), providing more precision control in setting the machine.

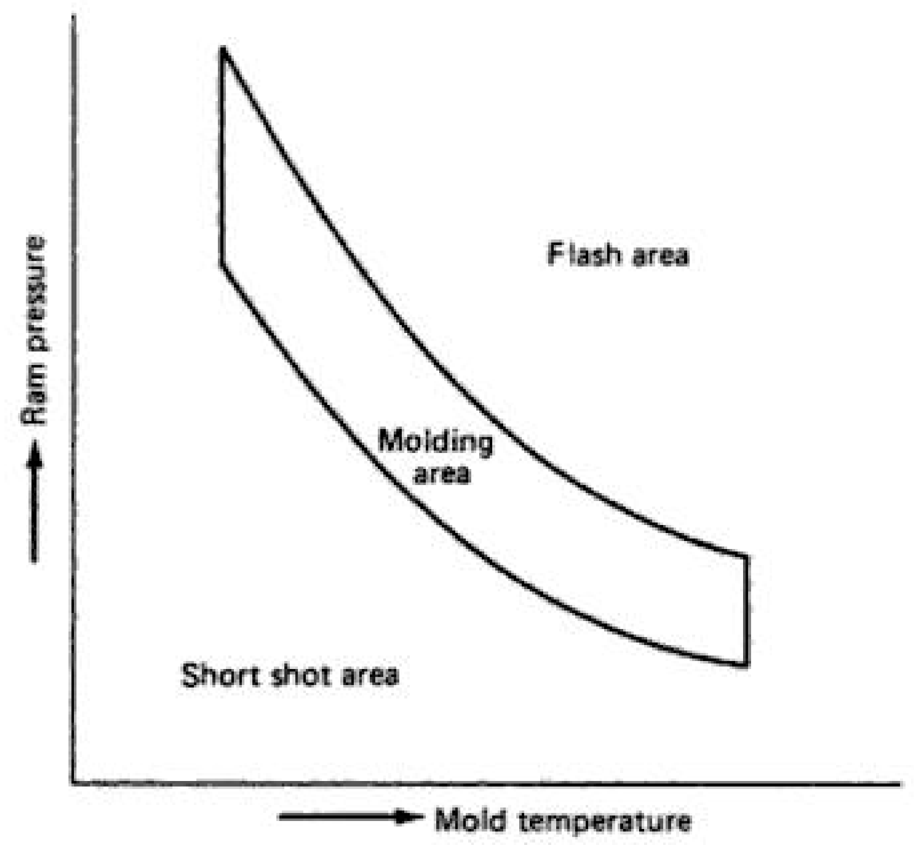


Fig. 4-1 Molding area diagram.

Developing the actual data involves slowly increasing the ram (injection) pressure until a value is obtained at which the mold is just filled out. This is referred to as the minimum fill pressure for that combination of material, mold temperature, and melt temperature. The ram pressure is then increased until the mold flashes. This is logged as the maximum flash pressure. These two pressure values then represent a set of data points for one combination of melt and mold temperatures.

Next, the melt temperature is changed (leaving the mold temperature constant), and a new set of minimum and maximum pressures determined. This is continued until the maximum and minimum melt temperatures are found.

Then the mold temperature is changed, and all the above repeated until the maximum and minimum mold temperatures are found. Once the data are obtained, three-dimensional MVDs are constructed.

MVDs show that the melt temperature for injection molding plastic is an important variable that was not evident in two-dimensional MADs. MVDs are used with all thermosets and thermoplastics. The significance of the MVD approach lies in the fact that one ends up with a dramatic and easily comprehended visual aid to analyzing three of the most important variables for injection molding—namely, injection pressure, mold (or barrel for thermoplastics) temperature, and melt temperature (1, 7, 283).

Using this two- and three-dimensional approach for making molding diagrams, you can analyze injection rate, cavity pressure, etc., and also consider whether to use manual or automatic process controls. As discussed in this chapter and Chap. 9, the use of automatic controls makes it easier to set controls and ensure quality. Of course, some molds produce quality parts just with manual controls; most of the 80,000 injection molding machines in the United States use only manual controls. However, major changes are occurring because the automatic controls can significantly reduce cost and provide zero (or practically zero) defects.

Fig. 4-2 Molding volume diagram showing three steps.

Cycle Times

A cycle is the complete repeating sequence of operations in a process or part of a process. One cycle time is the time period, or elapsed time, between a certain point in one cycle and the same point in the next cycle; it is the time to mold a part. As a general guide, regardless of the plastic processed, the average wall thickness (in thousandths of inches) multiplied by 250 equals the cycle time in seconds.

The problem of shortening the cycle time lies principally in assessing all the difficulties of the injection molding process during the design of the part and the mold. Thus what is needed is a device for achieving optimum designs of part and mold. Program systems that provide for computer simulation of the injection molding process are used for this purpose. One should keep abreast of the availability and performance of relevant software so that one can gain in experience. Most important are programs to reduce the cycle time by evaluating the actual process operational settings (see the section on Molding Simulation Programs in Chap. 9).

Molding Pressure Required

The molding pressure is the pressure applied to the molding material in the mold cavity or cavities during injection of the melt from the plasticator. The pressure required is based on the projected area taken at right angles to the applied force (clamp closing direction) plus the cross-sectional areas of those runners that solidify on the mold parting line. The melt pressure required for a specific material is determined from past experience and/or from the material supplier's data sheets.

The force required is calculated by multiplying the projected area by the melt pressure. It is expressed in psi or MPa. The result is the total clamping force required (usually converted to tons). To ensure sufficient pressure in practice, consider multiplying by a processing safety factor (SF) of 1.1. With experience, however, this SF can be reduced or even eliminated (see the section on Molding Thin Walls in Chap. 7).

Products

Plastic products are used in all industries (Chap. 17). They can range from parts weighing an ounce (indeed, grams) to hundreds of pounds. Typical products are reviewed throughout this book. Figure 4-3 is an example of diverse molded and other products used in an electric pressing iron.

Shapes Both shape geometry and design are heavily process-related. As an example, the ability to mold ribs may depend on the thickness and length of the rib, the ability of the melt to flow adequately during processing, the flowability of a plastic reinforced with glass fiber or other reinforcements or fillers, and so on. The ability to produce hollow shapes may depend on the ability to use removable cores or inserts or techniques that include air, fusible, or soluble solids, and even sand (Chap. 15). Hollow parts can be produced using cores that remain in the part, such as foam inserts.

Product obsolescence Tradeoffs exist between coming up with a new design and providing incremental improvements to an existing product. A new design usually avoids constraints imposed by the incremental approach, but it can be costly in time and resources. If one continues the incremental approach too long, the entire concept runs the risk of becoming obsolete.

Processing Plastics

Injection molding machinery provides the capability to process different plastics that require different methods of operation. There are other specifications for IMMs than meeting product size requirements. Machines must also be designed to meet the process

Fig. 4-3 Molded products in an electric pressing iron.

control requirements of the plastic melts. The variables in the machine, plastic melt, and process control must all be managed.

Some information on melt behavior is presented here. See also Chapters 2, 5, 6, and 7 for more processing details.

Basics of Melt Flow

There are variable conditions during molding that influence part performance. Of paramount importance are gate location(s) and controlling the cavity fill rate or pattern. The proper fill helps eliminate part warpage, shrinkage, weld line(s), and other problems or defects (Chap. 8). In the practical world of mold design, there are many instances where tradeoffs must be made in order to achieve a successful overall design. As an example, while a naturally balanced runner system is certainly desirable, it may lead to problems in mold cooling or increased cost due to excessive runner-to-part weight ratios, depending on the production quantity. Software flow analysis guides are available that allow successful designs of runners in which pressure, temperature, rate of flow, etc. are chosen consistently (Chap. 9).

In a typical IMM, the flow of melted plastic into its mold is basically controlled by the injection unit's plasticizing capability and uniformity, control of melt pressure, and screw position. When hot runners are used, their valve gates are involved. Sequential valve gating has become important in some multigate applications. Thus these gates can be opened at different times during injection, increasing control over weld-line location and fill balancing. With an open-loop process, the injection unit is tied to the valve gates from the start of the injection by either the time or the screw position. Once the valve is opened, the flow rate is completely controlled by the injection unit. The so-called dynamic-feed closed-loop system uses variable flow valves. Each valve's position is controlled in response to the pressure requirement downstream of the valves.

Mold Filling Hesitation

Here is one of many examples of methods of operating an IMM. To understand the *hesitation effect*, consider the flow patterns throughout injection mold filling. The melt first enters the cavity from the gate, and the flow front reaches the first thin wall section. There is insufficient pressure to fill this thin section, as the melt has an alternative route along the thick section. Melt that just entered the thin section sits there losing heat, until the rest of the mold is filled. When the mold is almost completely filled, the full injection pressure is available to try to fill the thin section. However, the melt in the thin section has frozen, and the thin section is not filled. This problem is caused by the fast–slow–fast (hesitation) filling sequence used. If the melt continues to flow at a nearly steady (uniform) rate, there is no difficulty in filling the thin section. To do so only requires the melt entering the cavity to have the proper temperature, pressure, and rate of injection.

Melt Cushioning

Cushioning the melt means continuing to inject it into the mold cavity under pressure during its shrinkage and until solidification occurs. The purpose is to ensure that, as the stroke is completed and the mold fills, a cushion of melt exists. Usually just a few millimeters (0.04 in.) distance is maintained between the screw or ram tip and the nozzle, which in turn feeds into the cavity or cavities. This action will result in greater compactness and will eliminate or significantly lower the shrinkage of molded products.

Mold Filling Monitoring

Flow-front speed during filling is commonly inferred either from screw position or cavity pressure sensors. The quality of the final molded part, however, is determined by the actual flows of molten plastic into the cavity to pack the melt. The ultrasonic technique is one way of monitoring the filling action. This technology involves the use of ultrasonic transducers and software to verify mold filling patterns and measure flow-front speeds. It permits identifying exactly when mold cavities are filled and switching immediately from injection pressure to packing pressure, saving energy. Ultrasonic beams are emitted from transducers installed on the external surfaces of a steel mold. The beams propagate to the cavity interface. Before the melt arrives at the transducer's position, ultrasonic energy is totally reflected at this interface. After the melt's arrival, part of the beam energy is transmitted into the melt, indicating the arrival. A sensor can monitor the gap caused by the shrinkage of the part away from the mold wall, as well as measure the speed of the gap's development. Ultrasonic waveforms show echoes in the solidifying parts, which can be used to obtain temperature profiles across the melt and to study cooling efficiency.

Sink Marks

Different processing conditions can cause product problems or defects. An example is a sink mark. Sink marks are an indentation on the surface of a molded part that usually occur when there is a significant local change in wall thickness. Examples include ribs, bosses, and undercuts. Sink marks are caused by thermal contraction of the melt during cooling in the mold. Since the volumetric shrinkage of plastics from melt to solid can be about 25% and their compressibility is smaller (perhaps 15%), it is possible to pack out a mold. This action can prevent sink marks during the pressurization phase only. Some compensating flow is necessary to eliminate the sink marks entirely. If it is impossible to use a high enough holding pressure to do so, a lower holding pressure may reduce the marks to an acceptable level.

By analyzing flow as a combination of viscous fluid flow and heat transfer, one can hope to understand what is happening in the mold (Chap. 7). The object is to flow plastic through the thin sections and into the thick sections. With a very slow rate, the pressure drop will be high because of the high heat loss. In the extreme case the plastic can freeze off. With a high holding pressure, there will be a high flow in the pressurization phase and a low flow in the compensating phase. This low compensating-phase flow means that the thin sections will not remain molten long enough for the thick sections such as a boss to be adequately packed out.

Mold Descriptions

Molds are a very important part of the injection molding process, as summarized in Fig. 1-14. There are many different mold designs used to produce all the thousands of different shapes and sizes of products. Examples of a few mold designs are shown in Figs. 4-4 to 4-9.

In the past, when someone purchased an IMM and had made a low estimate of the total cost to set up an operation with its auxiliary equipment, to reduce expenses the mold was skimped. The result most of the time was a disaster, because products did not meet performance requirements or, worse, the cost of molding a quality product went up. The message here is that you get what you pay for.

Molds are of many different designs to meet different product requirements. There are molds that can have common assembly and operating parts so that the tool's cavity or cavities can receive different cavity inserts. Molds can themselves be highly sophisticated and expensive pieces of machinery. They can comprise many parts requiring high-quality metals and precision machining. To take the greatest advantage of these investments, the mold may incorporate many cavities, adding further to its complexity. Many molds have been reengineered as standardized products that can be used with different cavities, runner systems, cooling lines, unscrewing mechanisms, etc.

For over a century it has been easy for those familiar with the engineering (and art) of mold making to obtain the molds they desired. In the past, however, molds were not as complicated as they are now, and in the future

Fig. 4-8 Three views showing flexible insert-type bottle caps made using a simple mold. It permits ejecting parts directly out of the mold without any complex mold movement.

Fig. 4-9 This 96-cavity mold from Husky produces preforms for stretched injection blow molding containers (Chap. 15).

their specification will require even more sophistication. One must either hire qualified persons, who may be difficult to find, or train them in house as described throughout this book. See especially the section on Software and Database Programs.

Mold Basics

The function of a mold is twofold: imparting the desired shape to the plasticized melt and solidifying the injected molded product (cooling for thermoplastics and heating for thermoset plastics). It basically has two sets of components: (1) the cavities and cores and (2) the base in which the cavities and cores are mounted. Figures 4-10 and 4-11 and Table 4-2 show typical layouts and descriptions of products to be molded that include the cavities and cores. Figure 1.11 provides an example of the pressure loading of a plastic melt. Melt moves from injection unit (plasticator), though the mold passageways (sprue, runner, and gate), and into the two cavities.

The mold has two basic parts to contain the cavities and cores. They are the stationary mold half on the side where the plastic is injected, and a moving half on the closing or ejector side of the machine. The separation between the two mold halves is called the parting line. In some cases, the cavity is partly in the stationary and partly in the moving section. The term "mold half" does not mean that the two are dimensionally equal in width.

The size and weight of the molded parts limit the number of cavities in the mold and also determine the machinery capacity required. In the case of large molded parts, such as an auto radiator grille or a one-piece bucket chair, the large exterior dimensions of a single-cavity mold require a correspondingly large clearance between the machine

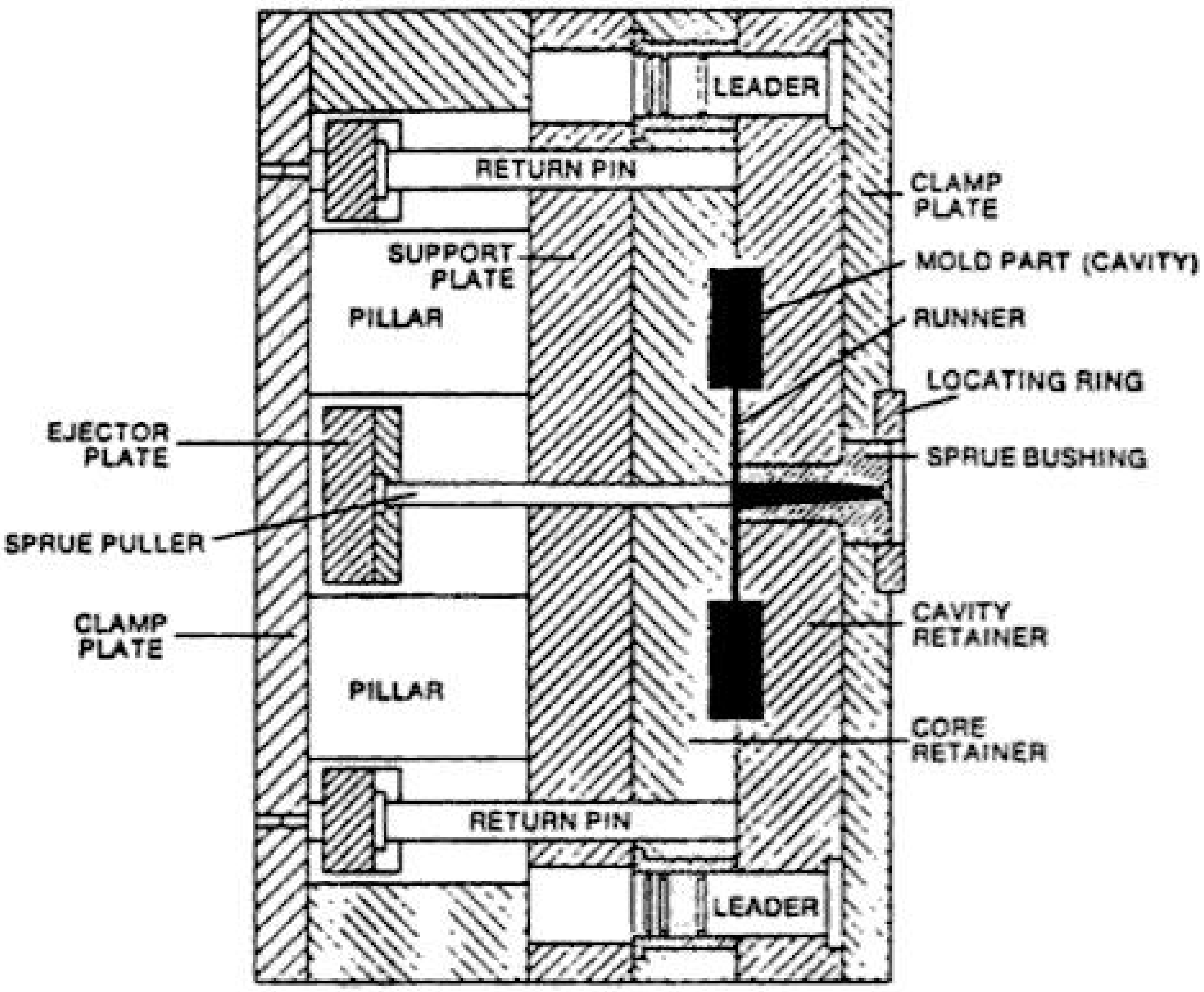


Fig. 4-10 General configuration of a mold.

tie-rods. In turn, the machine tie-rod clearances limit the number of cavities that can be installed in a multicavity mold.

It is important to design a mold that will safely absorb the forces of clamping, injection, and ejection. Furthermore, the flow conditions of the plastic path must be adequately proportioned in order to obtain uniformity of product quality in cycle after cycle. Finally, effective heat absorption from the plastic by the mold has to be incorporated for a controlled rate of solidification prior to removal from the molds.

The mold designer should become thoroughly familiar with the processing information on the plastic material for which the mold is being built. (See Chap. 6 for information on material processing.)

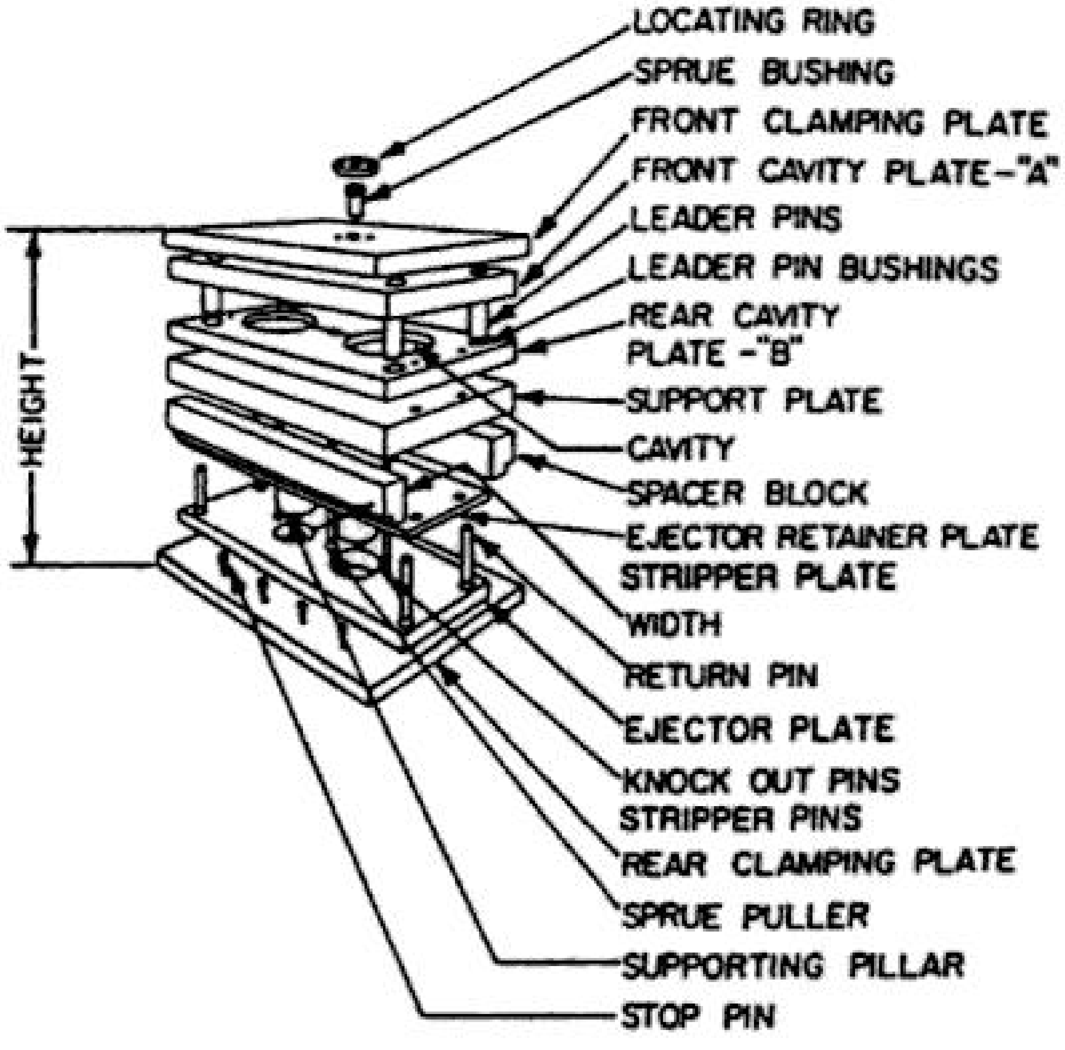


Fig. 4-11 Exploded view of a mold base.

Table 4-2 Functions of the injection mold

Mold Component	Function Performed
Mold base	Hold cavity or cavities in fixed, correct position relative to machine nozzle.
Guide pins	Maintain proper alignment of two halves of mold.
Sprue bushing (sprue)	Provide means of entry into mold interior.
Runners	Convey molten plastic from sprue to cavities.
Gates	Control flow into cavities.
Cavity (female) and force (male)	Control size, shape, and surface texture of molded article.
Water channels	Control temperature of mold surfaces, to chill plastic to rigid state.
Side (actuated by cams, gears, or hydraulic cylinders)	Form side holes, slots, undercuts, threaded sections.
Vents	Allow escape of trapped air and gas.
Ejector mechanism (pins, blades, stripper plate)	Eject rigid molded article from cavity or force.
Ejector return pins	Return ejector pins to retracted position as mold closes for next cycle.

The mold determines the size, shape, dimensions, finish, and often the physical properties of the final product. It is filled through a central feed channel, called the sprue. The sprue, which is located in the sprue bushing, is tapered to facilitate mold release. In single-cavity molds, the sprue usually feeds the polymer directly into the mold cavity, whereas in multicavity molds it feeds the polymer melt to a runner system (cold or hot), which leads into each mold cavity through a gate.

The mold is aligned with the injection cylinder by means of a ring in the stationary mold half, into which the cylinder nozzle seats. The locating ring surrounds the sprue bushing and is used for locating the mold in the press platen concentrically with the machine nozzle. The opening into which the ring fits is made to a tolerance of −0.000 and +0.002 in. (−0.000 and +0.005 cm). The ring itself is made 0.010 in. (0.025 cm) smaller than the opening, providing a clearance of 0.005 in. (0.013 cm) per side. A clearance above this amount may cause misalignment with the nozzle, which in turn would entrap part of the sprue, causing the sprue to stick on the wrong side. The sprue bushing on the locating ring end has a spherical radius of $\frac{1}{2}$ or $\frac{3}{4}$ in. (1.27 or 1.91 cm) to fit the machine nozzle radius. The hole through the length of the sprue has a $\frac{1}{2}$ in./ft taper of $1°11\frac{1}{2}''$ on each side. This hole must have a good reamed and polished finish to prevent sprue sticking.

The parting line is formed by cavity plates A and B. Cavity plate A retains the cavity inserts and supports the leader pins, which maintain the alignment of cavity halves during operation. These guide pins are preferably mounted in the stationary mold half to ensure that the molded product(s) will fall out of the mold during ejection without being fouled. One of the four leader pins is offset by about $\frac{3}{16}$ in. (0.48 cm) to eliminate the chance of improper assembly of the two halves.

The alignment of mold halves is usually accomplished using leader pins. Many moldmakers use tolerances of ±0.0008 to ±0.0013 in. (±0.0020 to ±0.0033 cm) from side pin to bushing. Tighter tolerances of ±0.0004 to ±0.0008 in. (±0.0010 to ±0.0020 cm) provide more accurate alignment and less wear. On ejector systems, a minimum of four leader pins and bushings are used to prevent cocking of the plate, which reduces wear and prevents seizing.

Mating with plate A is plate B, which holds the opposite half of the cavity or the core and contains the leader-pin bushings for guiding the leader pins. The core establishes the inside configuration of a part. Plate B has its own backup or support plate. The B backup plate is frequently supported by pillars against the U-shaped structure known as the ejector housing. The housing, consisting of the rear clamping plate and spacer blocks, is bolted to the B backup plate, either as separate parts or as a welded unit. This U-shaped structure provides the space for the ejector plate to perform the ejection stroke, also known as the stripper stroke. The ejector plate, ejector retainer, and pins are supported by the return pins. When in an unactivated position, the ejection plate rests on stop pins. When the ejection system has to be heavy because of required large ejection forces, additional supporting means are provided by mounting more leader pins in the rear clamping plate and the bushing in the ejector plate.

The overall height of the mold should correspond to the open space in between the machine platens. In the moving mold half, spacers are used to create space for the ejector system, which consists of two ejector plates with ejector pins. The open space should be such as to permit the ejector pins to complete their ejection stroke. Note that the mold height, or die height, in the usual horizontal operating machine is the horizontal dimension of the mold. When the mold is removed and placed upright on a workbench, its mold height is vertical.

All the mold plates (excluding the ejector parts) and spacer blocks are ground to a thickness tolerance of ±0.001 in. Conceivably, a combination of tolerances could build up to cause an unevenness at the four corners. If great enough, such a condition would damage a platen when under full ram pressure. It is advisable to check the uniformity of all four corners prior to preparing the base to receive cavities.

Both mold halves are provided with cooling channels filled with coolant to carry away the heat delivered to the mold by the hot thermoplastic polymer melt. For thermosets, electric heaters are located in the mold.

When the mold opens, molding and sprue are carried on the moving mold half; subsequently, the central ejector is activated, causing the ejector plates to move forward, so that the ejector pins push the article out of the mold. Ejector pins have a tendency to produce a very slight flash line, which in some areas of a part may be objectionable; therefore, their location and the amount of recess formed by them in the part should be agreed on with the product designer.

In the smallest injection molding machines, the mold may be completely demountable, and while being filled is held in a simple vise. This can be vertically or horizontally acting to suit the cylinder; some cylinders are downstroking and some horizontally acting. With a horizontally acting cylinder and vertical clamp, the runners and sprue bushing are in the same plane; and often, because the pressures involved are not very great, the hardened sprue bushing is replaced by a simple runner cut into one or both halves of the mold.

With the larger horizontal clamping machines, thought should always be given to whether a horizontal or a vertical flash line is either possible or desirable. In Fig. 4-12 a vertical flash line is shown, whereas Figs. 4-10 and 4-11 depict the more common horizontal flash line. With a mold having a vertical flash line, sometimes called a positive mold, it can be seen that material cannot escape from

Vertical flash line

Fig. 4-12 Mold designed with a vertical flash line, typical of a compression mold (also called a positive mold system), where the aligned male and female mold parts meet.

production on a strict order basis, whereby manufacturers produce molds according to exact defined parameters submitted by customers, to more of a partnership basis. A moldmaker now becomes involved in a project from the beginning, acting more as a consultant who supports a client throughout all stages of a project.

Taking this into consideration, we see that a moldmaker is not only requested to produce molds, but also has to design the parts according to the requirements of a customer. Furthermore, a moldmaker, in addition to his or her specific technical knowledge, must be acquainted with various plastics and the relevant injection molding technologies that will be used. Usually, the moldmaker has to undertake detailed discussions with the customer and material supplier to decide on the most relevant parameters with regard to tolerances, etc., prior to starting the design process.

An additional need in recent years, to be competitive in the international market where new products have to be presented on shorter time scales, has made the use of computers indispensable. The application of computer systems such as CAD, CAM, or CAE in the mold industry nowadays is a basic requirement. More and more companies are requiring the transfer of design and geometry data by the use of these systems. To work profitably for customers in many areas, it is necessary to install a complete network that directly links computer-generated design data to the numerically controlled production metal-cutting machinery. The CAD system should have two- and three-dimensional capabilities to advance all relevant design activities.

A powerful computer system enables one to react quickly to clients' requirements, especially in terms of changes in design and savings in time and money. Specific software automatically produces the data for CNC programming and forms the connection between design and production departments. The CAM portion of a computer-automated system converts design data into numerical control data used by CNC machines, which will mill and/or erode the shapes onto the parts.

Inevitably, the use of computer systems requires the adjustment of mechanical equipment according to the rapidly progressive CNC technology. It becomes an integral part of the system.

Mold Types

There are many different types of molds, designed to meet many different product requirements (1, 7, 179, 256). Industry generally identifies six basic types for use with thermoplastics. These types are (1) the cold-runner two-plate mold; (2) the cold-runner three-plate mold; (3) the hot-runner mold; (4) the insulated hot-runner mold; (5) the hot-manifold mold; and (6) the stacked mold. Figures 4-13 and 4-14 illustrate these six basic types of injection molds.

A two-plate mold consists of two plates with the cavity and cores mounted in either plate. The plates are fastened to the press platens, and the moving half of the mold usually contains the ejector mechanism and runner system. All basic designs for injection molds have this design concept. A two-plate mold is the most logical type of tool to use for parts that require large gates. This cold-runner system results in the sprue, runners, and gates solidifying with the cavity plastic material.

The three-plate mold is made up of three plates: (1) the stationary or runner plate, which is attached to the stationary platen and usually contains the sprue and half of the runner; (2) the middle or cavity plate, which contains half of the runner and gate and is allowed to float when the mold is open; and (3) the movable or force plate, which contains the molded part and ejector system for the removal of the molded part (Fig. 4-15). When the press starts to open, the middle plate and movable plate move together, thus releasing the sprue runner system and degating the molded part. This type of cold-runner mold design makes it possible to segregate the runner system and the part when the mold opens. The die design makes it possible to use center-pinpoint gating.

Fig. 4-13 Types of molds, illustrating cold-runner two-plate, cold-runner three-plate, and hot-runner mold for thermoplastics.

In the hot-runner mold, the runners are kept hot in order to keep the molten plastic in a fluid state at all times. In effect, this is a "runnerless" molding process and is sometimes called that. In such molds, the runner is contained in a plate of its own. Hot-runner molds are similar to three-plate injection molds, except that the runner section of the mold is not opened during the molding cycle. The heated runner plate is insulated from the rest of the cooled mold. The remainder of the mold is a standard two-plate die.

Runnerless molding has several advantages over conventional cold-runner-type molding. There are no molded side products (gates, runners, or sprues) to be disposed of or reused, and there is no separating of the gate from the part. The cycle time is only as long as is required for the molded part to be cooled and ejected from the mold. In this system, a uniform melt temperature can be attained from the injection cylinder to the mold cavities. Shot size capacity and clamp tonnage required in the injection molding machine are decreased by the size of the sprue and runners.

The insulated hot-runner mold is a variation of the hot-runner mold (Figs. 4-16 and 4-17). In this type of molding, the outer surface of the material in the runner acts as an insulator for the molten material to pass through. In the insulated mold, the molding

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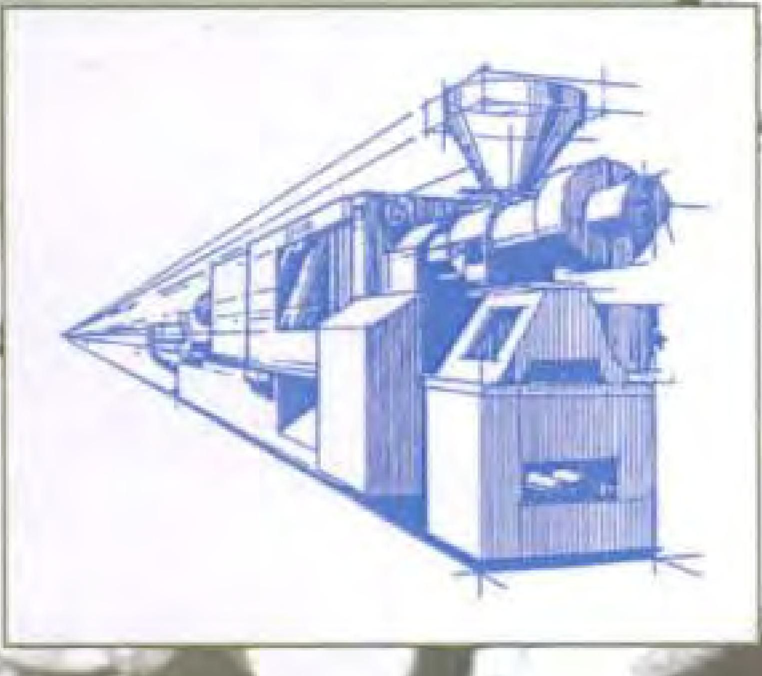

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