

Whether one recycles to materials or to energy has to be decided by an economic audit. Recycling is preferable to landfill practice, the costs of which are increasing and where the inherent value of the plastic is lost. Municipal authorities have to consider the economics of recycling operations, taking into account the cost of landfill. Factors to consider are: revenue from recycled materials or produced energy, cost of recycling, savings from nondisposal in landfill, and cost of disposal in landfill of the remaining tonnage after recycling. Although recycling can save energy and resources in the manufacturing process, getting recyclables to market and then processing into products also uses energy and generates waste that must be managed. The use of fuels and the environmental impact of preparing, collecting, sorting, and transporting recyclables should be considered when developing an audit.

Recycling and Lifecycle Analysis

A lifecycle environmental analysis provides information starting from raw materials, through fabricated products, to end of their useful lives. Issues that arise include: recycling of process and scrap materials, release of water pollutants and emission of gaseous and particulate pollutants, disposal of nonrecyclable and hazardous waste, disposition of toxic wastes, and costs.

Recycling Commingled Plastics

Commingled plastics are plastics not sorted by type in a waste system. The unsorted plastics must be combined or blended into one harmonious material.

Recycling Automatically Sorting Plastics

The goal with plastic scrap or waste has always been to speed throughput, improve quality, and add value. This means splitting plastic waste into a much broader network of flows than has previously been possible. The

challenge in automating plastics reclamation lies in integrating separate technologies that require devices for separating, detecting, and aligning. There have been all kinds of approaches; however, the major problem has been (and continues to be) cost to set up the complete operation from collection to output sales. There have been more losers than winners in this field.

Recycling and Common Sense

Before undertaking recycling, incineration, land fill disposal, chemical reclamation, cryogenic gasification, electrokinetic methods, hydrogenation; pyrolysis, or other methods factors such as practicality and economics must be considered. A variety of good cases have been made for recycling with controlled conditions. Good cases can be made for incineration, based strictly on volumetric mass (reduced into insignificant mass with ashes buried under controlled conditions), reclamation, based on energy savings, and so on. Landfill can be beneficial in different ways. Of critical importance is that decisions be based on logic with a full knowledge of facts and costs.

Recycling Limitations

Criteria of logistic technology and properties will determine whether or not it is plausible to reclaim and reuse plastic wastes. These criteria can be assessed economically in a complex way under the aspects of production and economy. Logistic criteria will cover the conditions of accrual according to location and quantity. Technological criteria are the purity and type of plastic, its cleanliness, and its geometry (basic shape and uniformity). Property criteria result from the extent of damage to the material during recycling.

Recycling Facts and Myths

As reported by the knowledgeable and practical people in the waste industry (and

those who sensibly approach the waste problem), it is not possible to recycle everything as some zero-waste advocates claim. Not only is 100% recycling not attainable, but it is not even good for the environment. It has been reported that although the United States recycles an average of about 27 wt% of its trash, in most areas the amount recycled does not exceed 30 to 35% for good reasons. (1) At least 25% of trash is simply not recyclable since it does not make sense to collect valueless items; thus, if communities want to even achieve 50% recycling, about two-thirds of every current recyclable item would need to be recovered. (2) Recycling is also limited in that only a few of about fifty identifiable items are present in significant amounts. Large contributors are cardboard boxes at 13% and newspapers at 6%; most only represent about 1% of trash so that recovering them would create great cost and inconvenience to consumers and waste handlers. (3) To increase recycling rates dramatically, many items would have to be trucked greater distances with more resources needed to clean and process dirty trash, and this would negatively affect the environment.

Recycled plastic items include PET post-consumer soft drink bottles and HDPE bottles. Recycling is a mainstream waste management tool and one that communities should continue to pursue. However, the public and politicians should recognize that high recycling rates could be counterproductive from environmental and economic standpoints (Chap. 17, *Correcting Misperceptions about Plastics*).

Warehousing

Warehouses for raw materials, additives, auxiliary equipment, spare parts, molds, dies, tools, processed plastic parts, etc. comprise a significant requirement of the plastics industry. Warehousing requires proper handling and storage procedures that must be logged economically. Various systems are used successfully. These include the unit warehouse, which makes use of pallets, cages, and similar equipment. Unit warehouses employ a structured organizational scheme

for integrating order-picking and transportation. The system integrates the inward and outward flow (input–output matrix) of goods, the factory administration, process control, quality control, etc. (Chap. 10).

There are various methods of keeping (storing) materials, tools, additives, equipment spare parts, etc. The different products to be stored usually have specific requirements such as temperature, height of loads, handling characteristics, etc. (see Chap. 10, *Material Handling*).

Plastic materials can be received in different forms (pellets, powders, etc.) and different size packages or containers, requiring different methods of storage.

Storage and Condensation

If a plastic is stored in a relatively cold area and then brought into the operating plant, it will often become wet (due to moisture condensation) enough to cause processing problems. Different procedures can be used to eliminate this problem area, such as moving material to an indoor closed storage bin to expose the plastic to the same temperature.

Material Storage

All storage and unloading areas should be kept clean and dry to minimize fire hazard. The store room should be separated from the processing shop by fire-resistant doors. Store materials away from direct sunlight and in properly constructed racks, containers, and/or silos. Usually the use of unheated storage areas with natural ventilation is sufficient. Ensure that the plastic does not stagnate in storage by adopting a strict stock control policy. Adopt a first-in, first-out policy (FIFO). With stock control, if a faulty batch develops, one can find the rest of that batch.

Silo Storage

For processors that can make (truck or rail car) bulk purchases, silos with automatic plastic handling systems, though initially costly, will provide economic paybacks.

They also provide environmental benefits, save floor space particularly when located outside, reduce handling by people, and leave no mess on shop floors as with sacks, gaylords, or big bags, etc. It takes 40,000 lb/month of a single plastic to justifying using a silo.

Processing Different Plastics

The following sections review injection molding of different plastics. They provide different reviews that can be used as guides in processing other plastics. Reviews include molding start-ups to meet different performance capabilities with cause-remedy approaches.

Polyethylenes

Low-density polyethylene (LDPE) is defined as polymerized ethylene having a nominal density of 0.910 to 0.925 g/cu cm. However, medium-density polyethylene (MDPE), with a density of 0.926 to 0.940 g/cu cm, is usually included with LDPE because their processing conditions and properties are quite similar. Therefore, the following information will encompass both low- and medium-density polyethylene unless otherwise stated. Specific polyethylene formulations used for illustration will be selected from the middle of the density ranges covered by LDPE and MDPE.

The injection molding of large, thin-walled items is one of the most difficult challenges in the injection molding of LDPE. Since one of the most commonly encountered items of injection-molded LDPE is a lid, the injection molding of LDPE lids will be described as a fairly typical representation of the injection molding of LDPE.

Injection-molded polyethylene lids are used in a wide variety of closure applications. Many products, such as margarine, cream cheese, whipped topping, ice cream, and sandwich spreads, are packaged in plastic containers (which may be polyethylene) that have polyethylene lids for primary closure. Many other products, such as coffee, peanuts, and shortening, are packed in metal cans that

are used after they are opened to store the unused portion of the contents. Most of these cans are sold with polyethylene overcaps that snap into place and furnish good closure for the cans after removal of the metal tops.

The characteristics demanded in polyethylene lids vary widely. Economy is always important; in nearly every application, it is desirable that the lids be flat and they snap tightly upon the container that they cover.

Some applications demand some degree of clarity so that printed matter on a metal lid can be read through the overcap before the can is sold. Some require resistance to environmental stress cracking, so that the materials that may be in contact with them will not cause them to split. Some require still other characteristics. In addition, the polyethylene lid business has undergone significant technological advances in past years with most of the emphasis on processability or production rate. Extremely fast-cycling machines, stack molds, and larger tonnage presses all have contributed to an increase in the molder's productivity.

This section presents detailed information about the important factors in the injection molding of lids and describes some polyethylene formulations widely used for this purpose.

Screw-type molding machines are preferred to straight-ram machines for molding polyethylene overcaps because they produce more homogeneous melts and permit the use of shorter cycles. They also permit better control of such variables as injection pressure, injection speed, and melt temperature. It is very difficult to mold flat, acceptable lids on a straight-ram machine, unless it is equipped with a screw preplasticator.

The size of the IMM to be used to mold overcaps is intimately related to the diameter of the overcap and number of cavities in the mold. Generally, molds with two to four cavities can be used on molding machines with capacities of 2 or 3 oz and clamping forces of 75 to 150 tons, whereas molds with six or eight cavities frequently require machines of a 5- to 16-oz (0.14 to 0.45 kg) rating with 200 to 400 tons of clamping force available. However, these figures could vary considerably, depending on the size of the overcap.

The clamping force usually necessary in a molding machine for producing an overcap 25 to 30 mils thick is $1\frac{1}{2}$ to 2 tons per square inch of projected area. A single-cavity mold for a 5-in. lid, therefore, would require 28 to 38 tons; a four-cavity mold for the same-size lid, 110 to 150 tons.

Molding Conditions

When setting conditions for molding polyethylene, the objective should be to inject fairly hot material into a cold mold while subjecting the molded part to as little strain as possible. This is usually accomplished by using high injection pressures to ensure quick filling of the mold and very short plunger-forward times to avoid packing the mold.

High melt temperatures are used to permit the plastic to be injected quickly into the mold with minimum strain. High melt temperatures normally give maximum clarity, minimum sunburst, and minimum warpage in the molded parts.

If melt temperatures are too low, molding will be difficult, requiring excessive injection pressures and longer plunger-forward times. This combination of conditions can produce lids with poor clarity and excessive sunburst and warpage.

Melt temperature generally varies from 325 to 550°F (163 to 288°C), depending on the machine used, mold size and construction, and plastic formulation.

Large machines with large material holdup in the cylinder usually operate between 325 and 475°F (163 to 246°C), whereas small machines with little holdup generally operate between 425 and 550°F (218 to 288°C). If the plastic moves through the cylinder rapidly, the cylinder temperatures may have to be set considerably higher than the above temperatures to maintain the desired melt temperature. In a machine operating near its plasticating limits, an indicated temperature of 480°F (249°C) may be required to maintain a melt temperature of 450°F (232°C).

Figure 6-55 shows the relationship between injection molding melt temperatures and the melt index of low-density polyethylene for-

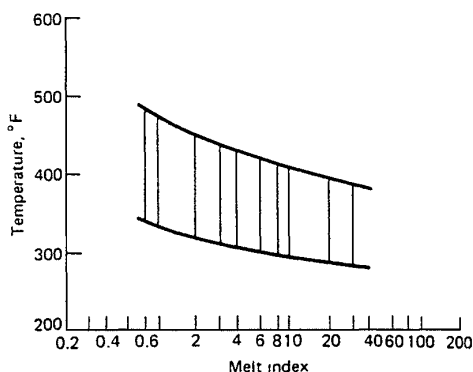


Fig. 6-55 Approximate IM temperature ranges for LDPE.

mulations with a melt index ranging from 0.7 to 40. The optimum mold temperature for lid production seems to be about 400 to 500°F. Temperatures in this range permit short cycles and produce lids with good clarity. Mold temperatures lower than 40 to 50°F can make mold filling difficult, but very clear lids are generally produced while higher mold temperatures result in slow lid cooling, usually causing excessively long cycles.

The most important segments of the lid molding cycle are plunger-forward time and clamp time. Both factors significantly affect shrinkage and toe-in.

The plunger-forward time should be about 0.1 to 0.3 sec longer than the actual mold-filling time. If it is significantly longer than this, the areas around the gates will be packed, and thus they will shrink less than the areas around the outer edges of the lids, so that warpage could result. The plunger-forward time is generally determined by setting all temperatures for molding, decreasing the plunger-forward time in small increments until a short shot results, and then increasing the time about 0.1 to 0.3 sec.

The clamp time should be the absolute minimum setting at which a lid with acceptable flatness, toe-in, and shrinkage can be produced. The clamp time, which must be set after the plunger-forward time is fixed, must sufficiently exceed the plunger-forward time to allow the molten plastic to solidify in the cavities. Since toe-in is desirable but warpage is not, the clamp time must be set for each

mold to give a satisfactory combination of these factors. If the cooling time necessary to produce acceptable lid flatness and shrinkage does not produce acceptable toe-in, the thickness of the lid can be increased so that this portion of the lid will be hotter and shrink more after it has been removed from the cavity. This will increase toe-in.

Since the main objective of lid moving is to fill the mold cavities as rapidly as possible, injection pressure and injection speed should be set as high as possible while still maintaining proper shot-size control. These settings should be at their maximum, if possible.

Proper adjustment of shot size ("starve feeding") is the preferred method for controlling packing when molding lids; if possible, the shot size should be the exact amount of plastic needed to fill the mold cavities. On some small molding machines and even some larger ones equipped with screw preplasticators, shot-size control is sufficiently precise to make this possible. With precise shot-size control, the adjustments described for cycle time, injection pressure, and injection speed should be satisfactory.

Maximum screw speed is usually used so that the time needed to pump material to the front of the screw will not delay the machine cycle. Fast screw speeds generate frictional heat in the plastic and help to produce a homogeneous melt. If temperatures become too high and material degradation results, the screw speed should be reduced. The heat generated in the plastic by the screw rotation is a function of the square of the screw speed; thus, a small reduction in screw speed can result in an appreciable reduction in the heat generated.

Materials

Tenite polyethylene 18BOA (20 melt index, 0.923 g/cu cm) is the Eastman formula used for the production of thin, clear lids. This material is characterized by excellent processability, warpage resistance, and clarity, while exhibiting good toe-in characteristics and stress-crack resistance. A higher-melt-index version of 18BOA is 18DOA

(40 melt index, 0.923 g/cu cm). This material exhibits greater shrinkage and slightly better flow characteristics, but not the toe-in, processability, and stress-crack resistance of 18BOA. Tenite polyethylene 187OA (7 melt index, 0.923 g/cu cm) exhibits exceptional stress-crack resistance. It provides a material with fast cycling characteristics for the lid molder interested in applications requiring high stress-crack resistance.

All three materials have been used extensively in the lid-molding industry in a variety of closure applications and other related items. Because of their consistency, these materials perform especially well in stack molds.

To fully characterize this "family" of high-quality lid-molding materials, an extensive study was performed to evaluate formulas 18BOA, 18DOA, and 187OA over a wide range of melt temperatures and injection pressures to determine lid characteristics at each of these conditions. The materials were evaluated on a 250-ton, two-stage Husky injection molding machine fitted with a three-cavity, 603-lid mold. A four-cavity, 401-lid mold was used in some cases to show the difference in characteristics between large and small lids.

Molding Test Results

Shrinkage Tests were conducted for shrinkage as a function of melt temperature and injection pressure for the three materials. Three basic relationships exist. First, lid shrinkage increases with increasing melt temperature. Second, lid shrinkage increases with increasing injection pressure. The effect is most evident at pressures between 1,000 and 1,400 psi (6.89 and 9.65 MPa). This trend could be attributed to an increase in polymer temperature in the nozzle due to frictional heat generated by the high injection pressures. Third, lid shrinkage increases with increasing melt index. This trend is more evident at low injection pressure than at high pressures. Some deviation from this relationship appeared with formula 1870 at the higher melt temperature [greater than

Table 6-34 Minimum melt temperature at indicated injection pressure

Material	Melt Index	1,000 psi	1,400 psi	1,800 psi
187OA	7	Would not flow	450°F	400°F
18BOA	20	475°F	375°F	350°F
18DOA	40	425°F	350°F	350°F

500°F (260°C)]. This last trend was reversed with the small 401-lid size, with the lowest-melt-index material giving the greatest shrinkage, although only minor differences were observed among the samples. This would indicate that the cavity pressure and frictional heat generated in the material can be adjusted by careful control of the injection pressure, injection speed, and melt temperature to obtain the desired shrinkage. As opposed to the 603-lid results, no difference in shrinkage was observed with changing injection pressure with the smaller 401 lids.

To summarize, the minimum melt temperature at which each material could be molded without causing short shots is given in Table 6-34 for three different injection pressures.

As would be expected, these data indicate that proper mold filling is difficult at low melt temperatures, at low injection pressures, and with low-melt-index materials. This effect apparently lessens with increasing melt index and injection pressure. A greater difference exists in mold-filling capabilities between 187OA and 18BOA than between 18BOA and 18DOA at a given injection pressure and less difference exists among the three materials as the injection pressure increases.

Clarity No difference in the clarity of lids molded at different melt temperatures or different injection pressures was observed. All

three materials formed lids with good clarity at all molding conditions.

Sunburst Tests of lid sunburst effect versus melt temperature for the three materials were conducted. Two basic relationships were found in this evaluation. First, sunburst decreased with increasing melt temperature; second, sunburst decreased with increasing melt index. Injection pressure had no effect on sunburst.

Shot weight Tests of shot weight versus injection pressure and melt temperature for the three materials resulted in three basic relationships. First, shot weight increases with increasing melt index. This effect is more prominent with formulas 18BOA and 18DOA than formulas 187OA and 18BOA in large lids, but the reverse is true with small lids. Second, shot weight increases to a point with decreasing melt temperatures; then, beyond this point, the material becomes too cold to flow properly, and shot weight decreases. Third, shot weight increases with increasing injection pressure. This effect is more prominent at pressures between 1,000 and 1,400 psi (6.89 and 9.65 MPa). In general, the optimum shot weight of the three materials as indicated by this study is as shown in Table 6-35.

Toe-in angle Tests were made between lid toe-in angle and melt temperature for

Table 6-35 Melt temperature at which optimum shot weight is obtained at indicated injection pressure

Material	Melt Index	1,000 psi	1,400 psi	1,800 psi
187OA	7	Would not flow	450°F	425°F
18BOA	20	500°F	425°F	400°F
18DOA	50	425–450°F	350°F	350°F

the three materials. No significant relationship exists between toe-in angle and injection pressure, but as this graph indicates, melt index and melt temperature have definite effects on toe-in angle. For both lid sizes, toe-in angle decreases as the melt index increases. However, the relationship between melt temperature and toe-in depends on lid size—decreasing with increasing melt temperature for the large lids and exhibiting just the opposite effect for small lids. This difference is attributed to a shrinkage phenomenon. Large lids have more total shrinkage across their diameter than small lids, and this has the effect of pulling the top of the lid rim inward around the circumference. This overrides the shrinkage in the skirt part of the lid, causing the toe-in angle to be less, for the 401-lid size.

Warpage Tests were made on the three materials on a standard cycle versus melt temperature. They show that no warpage at all occurred in lids molded from formula 18BOA and 18DOA, whereas those molded from 187OA exhibited slight (but acceptable) warpage at the melt temperature studied. As only formula 187OA exhibited warpage, it is difficult to see any relationship between warpage and injection pressure. However, there is some evidence of decreasing warpage with increasing injection pressure for formula 187OA. The excellent warpage resistance exhibited by 18BOA and 18DOA over the wide range of injection pressures and melt temperatures used in the study indicates that warpage problems previously associated with lid-molding materials have been overcome with these new formulas. In addition, during extensive field trials and the full-scale production usage of these new materials, no warpage problems have been encountered.

Stress-crack resistance Tests were conducted on the stress-crack resistance of the three materials versus melt temperature. No relationship between injection pressure and stress-crack resistance could be observed. However, a significant relationship does exist among stress-crack resistance, melt temperature, and melt index. Stress-crack resistance is directly related to melt temperature

and inversely related to melt index. Formula 187OA (7 melt index) exhibits a stress-crack resistance (time to 50% failures) of greater than 10 min for all melt temperatures at which molding was possible. Relatively lower stress-crack resistance was found in lids molded from 18BOA (20 melt index) at melt temperatures below 450°F (232°C) than those obtained on 187OA lids molded over the same temperature range. At melt temperatures of 450°F and above, time to 50% failures of 18BOA exceeded 10 min. However, analysis of the data indicates that the stress-crack resistance of 18BOA is still slightly lower than that of 187OA, since some lid failures were recorded at melt temperatures above 450°F (232°C) even though time to 50% failures was greater than 10 min. Formula 18DOA (40 melt index) exhibited significantly lower stress-crack resistance than both 187OA and 18BOA. However, at melt temperatures of 525°F (274°C) and above, the time to 50% failures exceeded 10 min.

The apparent data scatter in the curves can be attributed to the test method; any type of stress-crack test exhibits a relatively large standard deviation. However, the curves do serve to point out that stress-crack resistance increases with a decreasing melt index.

Minimum cycle time Data on minimum cycle time (processability) versus melt temperature resulted in three basic relationships. First, cycle time increases with increasing melt temperature. Second, formula 18BOA (20 melt index) appears to exhibit better processability than the other materials. Third, the curves further indicate that the best melt temperature for lid molding from the standpoint of processability would be the point just above where short shots occur. It is interesting to note that this point is similar to the region of maximum melt flow previously mentioned under the shot weight discussions. As would be expected, high injection pressures permit the material to fill the mold at low melt temperatures.

Summary This molding study of Tenite polyethylene formulas 187O, 18BO, and 18DO indicates that the lid characteristics

of shrinkage, shot weight, and low temperature mold-filling capabilities are affected by injection pressure, whereas all the lid characteristics except clarity are affected by changes in melt temperature. The study also indicates the significant effect the melt index has on most of the lid characteristics. In general, it can be concluded that formula 18BOA (20 melt index) should be considered the all-purpose, most versatile material of the three. It is characterized by excellent processability, warpage resistance, and clarity while exhibiting good toe-in and stress-crack resistance. The higher-melt-index material, 18DOA (40 melt index), exhibits higher shrinkage and slightly better low-temperature flow characteristics than 18BOA. However, it does not exhibit the toe-in and stress-crack resistance properties of 18BOA and should be considered only when high shrinkage and/or exceptionally high flow properties are required. Although formula 187O (7 melt index) does not exhibit the flow characteristics and warpage resistance of 18BO, it does exhibit exceptional stress-crack resistance and should be considered in applications where this is the key property.

Polypropylenes

Polypropylene and propylene copolymers are thermoplastic materials having the following characteristics:

- Light weight
- Heat resistance
- Hardness
- Surface gloss
- Stain resistance
- Stiffness
- Ability to form an integral hinge
- Processability
- Chemical resistance
- Stress-crack resistance
- Dimensional stability

These properties make polypropylene and propylene copolymers excellent choices for

molding items such as housewares, appliance parts, automobile parts and accessories, closures, laboratory ware, hospital ware, toys, sporting goods, and miscellaneous items for home and industry.

Polypropylene is typically supplied in either cube-cut or cylindrical $\frac{1}{8}$ -in. (0.32-cm) pellets, the pellet shape depending on the in-plant processing required for producing a particular formulation.

Polypropylene plastic is offered in natural color and a wide range of compounded colors custom-matched to the user's requirements and accurately controlled for uniformity between lots. It can also be colored in the user's plant with either dry colors or color concentrates.

With a nominal as-molded density in basic formulations of 0.902 g/cu cm, polypropylene is lighter than polyethylene and nonpolyolefin plastics and, therefore, produces more parts per pound than these other materials in any given mold. In addition, the high stiffness and excellent processability of polypropylene permit the molding of parts with thin sections that would often be too flexible or unmoldable with other thermoplastics.

Basic formulations of polypropylene are produced in flow rates ranging from less than 1 to 450 to meet a variety of processing and product performance requirements. Variations of basic formulas are available with additives to provide heat stability, weatherability, and the ability to withstand some of the effects of radiation. Some formulas offer improved impact strength, whereas others contain fillers such as talc and calcium carbonate for applications requiring greater stiffness, tensile strength, and heat deflection temperature than provided by general-purpose polypropylene. Processing and performance modifiers, such as antistatic, nucleating, mold release, and slip agents, can be added. Concentrates containing foaming agents designed to be used alone or mixed with other formulas can be supplied. Formulations lawful for use in contact with food under regulations of the U.S. Food and Drug Administration are also manufactured.

In addition to low density and high stiffness, polypropylene has a high softening

point and excellent chemical resistance, stress-crack resistance, electrical properties, and resistance to abrasion. Its availability and wide range of flow rates have promoted its use in a great variety of injection molding applications.

Polypropylene and copolymers are well adapted to molding in any of the commercially available molding machines. For convenience, molding machines will be discussed only as screw-ram and plunger-type machines. These machines differ in the manner in which the plastic pellets are delivered from the feed hopper to the nozzle of the machine. The effect that screw-ram machines have on the plastic is different from that of the plunger machines (Chap. 2).

Cylinder temperatures, injection pressures, and clamp pressures required for successful molding are normally lower for a screw-ram machine than for a plunger machine because the action of the screw results in better homogenization of the material and the development of frictional heat. The frictional heat added by the work of the screw is proportional to the square of the screw speed. If the screw speed is doubled, the heat added is increased by a factor of 4.

Faster molding cycles are generally possible with the screw-ram machines. Polypropylene and copolymers harden relatively fast when injection-molded, and with the lower melt temperature possible with the screw-ram machines, the cycle can be shortened.

The physical properties of items molded from polypropylene and copolymers on a screw-ram machine are generally better than those of identical items molded on a plunger-type machine. Usually, flexural strength, notched impact strength, and low-temperature toughness are increased while shrinkage is reduced. Articles molded in the screw-ram machine contain fewer stresses because the mold cavity can be filled at a lower injection pressure. Reduced molding stresses result in parts with better dimensional stability.

When polypropylene and copolymers are molded in colors, less time is required to change from one color to another when a screw-ram machine is used.

Polypropylene and copolymers behave in much the same way in processing operations, and conclusions drawn concerning one material generally apply to the other as well, except that copolymers appear to be better suited than polypropylene for insulated runner molding on a screw-ram machine.

The use of a preplasticating unit is not essential, but it is advantageous when polypropylene and copolymers are molded in a plunger-type machine. With such a unit, the high heat requirements of polypropylene and copolymers are partially provided before the material enters the cylinder. Therefore, the cylinder can be maintained at a lower temperature than when it is supplying the entire heat input, and the possibility of hot spots is greatly reduced.

Both polypropylene and propylene copolymers have excellent moldability, permitting small parts with a wall thickness of 0.010 in. to be molded satisfactorily. In general, these plastics show sharp decreases in viscosity at their melting point. This allows them to flow in the mold cavities more readily than most other thermoplastics. Their superiority, not immediately apparent in molds that are easily filled, becomes quite obvious in difficult-to-fill molds as a result of this ease of flow. Thin sections can be molded more satisfactorily from polypropylene or copolymers than from almost any other thermoplastic.

The molding of thick sections from general-purpose polypropylene should be avoided if possible because of the formation of a coarse crystalline structure in the article caused by slow cooling of the plastic. Articles with such a structure usually have low impact strength. The toughness of articles molded of impact-modified polypropylene or propylene copolymers is much less dependent on rapid cooling, and these formulations may be better than general-purpose polypropylene for molding thick sections.

When it is necessary to mold an item with a thick section, it is important to locate the thick section near the gate with any reduction in thickness being made in the direction of flow. This makes it possible to maintain effective pressure on the thick sections for a longer time without placing excess pressure

on the thin sections that are farthest from the gate. Gating into thick sections minimizes sink marks and results in less tendency to warping than gating into thin sections.

Another possibility to consider when molding thick sections is the use of a foam concentrate such as Eastman's Tenite polypropylene P2635-08AA. This concentrate has effectively demonstrated, through years of use, its capability for eliminating sinks and voids in heavy-sectioned parts. The specific use of this concentrate is described in an Eastman publication, MB-55, available on request.

Molding Conditions

Table 6-36 gives ranges of conditions for injection molding articles of various thicknesses from polypropylene and copolymers. These are suggested start-up conditions. Final operating conditions may be different from those shown, as they vary with the application, mold design, formula selected, and in-

jection machine used. For molding the same part, plunger machines generally operate at temperatures 30°F (17°C) higher than those for screw-ram machines.

After the mold is constructed, the operating factors that affect the quality, quantity, and cost of the molded product must be determined. Although quality, quantity, and cost are primarily dependent on the quality and type of tooling and machine employed, proper molding techniques and the use of optimum molding conditions have a significant influence. With regard to the quality of injection-molded parts, the most important variables are injection speed, injection pressure, clamping pressure, melt temperature, mold temperature, and cycle time. These variables are discussed in detail below.

Injection speed Normally, high injection speeds are used when molding polypropylene and copolymers because fast filling speed results in a relatively uniform temperature of the material as it fills the cavity. If the filling

Table 6-36 Ranges of IM conditions for Tenite PP and polyallomer compounds

Molding Conditions	Thickness of Section		
	0.063 in. (1.6 mm)	0.125 in. (3.2 mm)	0.25 in. (6.4 mm)
Temperatures			
Rear cylinder, °F	380–420	380–400	380–400
°C	193–216	193–204	193–204
Middle cylinder, °F	400–450	380–420	380–420
°C	204–232	193–216	193–216
Forward cylinder, °F	420–480	400–450	400–420
°C	216–249	204–232	204–216
Nozzle, °F	380–420	380–420	380–420
°C	193–216	193–216	193–216
Melt, °F	400–480	400–450	380–420
°C	204–249	204–232	193–216
Mold coolant, °F	50–80	50–80	50–80
°C	10–27	10–27	10–27
Hydraulic injection pressure			
psi	600–1,500	600–1,500	600–1,500
MPa	4–10	4–10	4–10
Typical cycle time, s			
Plunger forward	5–10	10–15	15–20
Total cycle	15–25	25–35	35–60
Shrinkage, %	1–2	1–2	1–2

rate is slow, particularly in molding thin sections, the first material entering the cavity may cool much more rapidly than the subsequent material, resulting in an incomplete fill, lamination, and possible warpage of the part. This filling problem is present with any thermoplastic, but it is accentuated in molding polypropylene, which has a relatively high crystalline melting temperature and solidifies quickly in the cavity.

It may be necessary to reduce injection speed to control the uniformity of the flow and maintain a good surface finish when parts with thick cross sections are molded with small gates.

Injection pressure The injection pressure should be maintained at the minimum level required to fill the mold. Molding shrinkage may be reduced and sink marks minimized by increasing the injection pressure, but this results in packing the material into the mold cavity. Such packing may cause difficulty in ejecting the piece from the mold and warpage of thin sections.

Normally, the stiffness of a part molded from polypropylene or a copolymer increases slightly as the injection pressure increases, particularly when low melt temperatures are used. Changes in injection pressure do not significantly affect the impact strength of a molded part.

Clamping pressure Clamping pressure is the pressure needed to hold the mold closed against the opposing pressure exerted by the molten plastic under force of the injection and holding pressure.

The pressure transmitted to the mold cavity depends primarily on the type of injection unit used. For example, injection molding machines with any type of preplasticator in which the shooting ram works against molten polymer are very efficient in transmitting applied pressure to the cavity. Screw-ram machines are also very efficient, transmitting up to 90% of the applied ram pressure to the molten polymer in the mold cavity. A plunger-type injection unit, in which the plunger acts against unmelted pellets, is less efficient in transmitting applied pressure to

the mold cavities than screw-ram machines or machines with preplasticators.

Restrictions in the nozzle, runner system, or gates retard the flow of molten polymer and limit the transmission of injection pressure to the cavity. A web gate can be used to good advantage when molding polypropylene and copolymers because it gives a more effective area for transmitting pressure than other gates and will still freeze off when the flow stops.

Melt temperature Processing temperatures for polypropylene vary more with the characteristics of the processing equipment and its accessories (mold, etc.) than they do with the formulation, but in any given processing situation, the optimum temperature may vary somewhat with the flow rate of the material. The best melt temperatures for processing various formulas for Tenite polypropylene will usually fall within the ranges shown in Table 6-37

As the melt temperatures increase, there is a decrease in the stiffness and impact strength of molded polypropylene and copolymers. The decrease in stiffness caused by the increase in the melt temperature is greatest when a high injection pressure is used. Below certain minimum melt temperatures, severe stresses in the molded part can occur with a resultant loss of impact strength.

At normal injection molding temperatures, around 450 to 470°F (232 to 243°C), there is no significant difference in deflection temperature caused by changes in melt temperature. At extremely high temperatures, about 500 to 550°F (260 to 288°C), an increase is noted. High melt temperatures along with long

Table 6-37 Melt temperatures for processing PP

Flow Rate	Melt Temperature for Injection Molding (°F)
4.5	380–450
9.0	370–440
18–30	360–430
50–70	340–410
Talc-filled formulas	380–450
Calcium carbonate–filled formulas	380–450

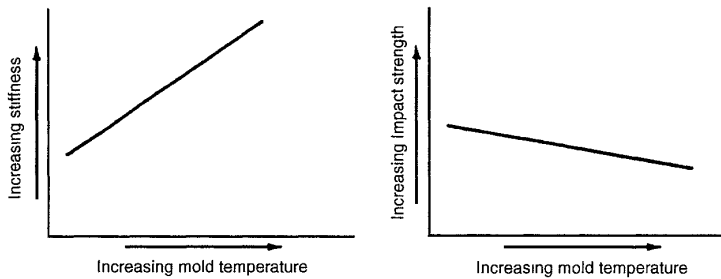


Fig. 6-56 Effects of mold temperature.

residence time at melt temperature may result in increased flow rate (material break-down) and reduced toughness. It is desirable that the shot size utilize one-half or more of the cylinder capacity to limit melt residence time.

Generally, an increase in the cylinder temperature makes it possible to use lower injection pressure and produce a better surface finish, but it also tends to increase drooling from the nozzle, may make flashing a problem, and increases the time for cooling.

Mold temperature Close control of mold temperature is important in molding any thermoplastic, but it has increased significance in the molding of polypropylene and copolymers because of the highly crystalline nature of these plastics.

Mold temperature affects the properties of copolymers less than those of polypropylene, and a relatively tough part can be molded from Tenite polyallomer copolymer with only limited mold cooling. Mold temperatures up to 90°F (32°C) are often satisfactory.

Tenite polyallomer copolymer crystallizes more slowly than polypropylene, and a portion of the crystallinity in the molded part forms after the part is removed from the mold. It is for this reason that the mold temperature has less effect on the properties of polyallomer than those of general-purpose polypropylene.

In molding polypropylene and copolymer parts, it is usually desirable to obtain maximum impact strength rather than maximum stiffness. This indicates that low mold temper-

atures should be used, normally in the range of 32 to 60°F (0 to 32°C). A cold mold cools the material rapidly and causes the formation of a fine crystalline structure.

Some molded parts may require maximum stiffness with impact strength of secondary importance. If this is the case, mold temperatures in the range of 110 to 130°F (43 to 54°C) are desirable. The general trends in stiffness and impact strength as related to mold temperature are shown qualitatively in Fig. 6-56. High mold temperatures result in high shrinkage in the molded part.

In the molding articles of heavy cross sections, where high mold temperatures may be necessary, it may be advantageous to cool the articles in an ice water bath immediately after ejecting them from the mold. This allows the article to be ejected while still hot and thus shortens the cooling portion of the molding cycle. Cooling the parts in ice water also achieves the quick quenching necessary for good impact strength, and it hardens the surface sufficiently to prevent sink marks from forming.

Cycle time Cycle time is largely dependent on section thickness, machine conditions, machine heating capacity, and injection capacity. The overall cycle time can vary from approximately 5 sec for thin articles to 60 sec or more for thick articles.

The ram is in the forward position usually one-fourth to one-third of the total cycle time. If the booster pump is used, it is normally set to cut out when the ram stops moving on the forward stroke of the cycle.

Copolyesters

Copolyesters include an extensive range of amorphous materials with widely differing processing parameters and properties. Probably the most frequently encountered injection-moldable copolyester is Eastman Chemical's Kodar PETG copolyester 6763. This material is a glycol-modified poly (ethylene terephthalate). The modification is made by adding a second glycol, cyclohexanedimethanol (CHDM), during polymerization. The second glycol is added in the proper proportion to produce an amorphous polymer. Kodar PETG copolyester 6763 will not crystallize and thus offers wider processing latitude than conventional crystallizable polyesters. Plasticizers or stabilizers are not required in this polymer.

Kodar PETG copolyester 6763 offers an excellent combination of clarity, stiffness, and toughness. It is lawful for use as an article or component of articles intended for use in contact with food, subject to the provisions of Food Additive Regulations 21 CFR 177.1315 and 21 CFR Part 174, published by the U.S. Food and Drug Administration. Kodar PETG copolyester 6763 is not lawful for use as an article or a component of articles intended for use in contact with carbonated beverages, beer, or containers for food that will be subject to thermal treatment, or under conditions of fill or storage exceeding 120°F.

Typical injection molding applications for PETG include toys, chairs, protective covers, medical device parts, face shields, brush backs, display racks, ice scrapers, containers, and appliance parts.

Molding Conditions

The processing variables that affect the quality of articles molded of PETG 6763 include injection speed, screw speed, back pressure on the screw, injection pressure, clamping pressure, melt temperature, nozzle temperature, mold temperature, and cycle time. The typical conditions for molding PETG 6763 are shown in Table 6-38.

Table 6-38 Typical molding conditions for Kodar PETG 6763 [part thickness = 0.125 in. (3.2 cm)]

Cylinder temperatures, °F (°C)	
Rear	420 (216)
Center	450 (323)
Front	470 (243)
Nozzle	470 (243)
Melt temperature, °F (°C)	480 (249)
Mold temperature, °F (°C)	80 (27)
Injection pressure, psi (MPa)	12,000 (82.7)
Cycle time, s	
Inject	20
Cooling	20
Recycle	2
Overall	42
Screw speed, rpm	60
Injection speed	Slow

The shot size of items to be molded should utilize at least 50% of the machine's plasticating capacity and, preferably, 75 to 80%.

Injection speed Low injection speeds are desirable from the standpoint of part appearance. If splay (visible flow lines generally radiating from the gate) is encountered, it can generally be minimized by reducing the injection speed. If the molding machine is equipped with programmed injection, an initial slow injection rate can be used until some material has entered the cavity; then a more rapid fill rate can be used without causing the splay effect.

Screw speed A screw speed of 30 to 60 rpm is suggested for processing PETG 6763. High screw speeds result in frictional heating, and this has the same effect as increasing the cylinder temperature. If frictional heating is excessive, polymer degradation may occur.

Back pressure on the screw Back pressure is normally not required for molding PETG. However, if large reground particles are present in the feed or color concentrates or dry coloring agents are being used, it may be necessary to use a small amount of back pressure to keep the screw full to plasticate

the material properly and to aid in color dispersion.

Injection pressure Injection pressure is not critical when molding PETG 6763. Relatively high injection pressures are usually required because the material is somewhat viscous at normal molding temperatures.

Melt temperature PETG 6763 can be molded with stock temperatures ranging from 380 to 525°F (193 to 274°C). At the low end of the temperature range, the material is extremely difficult to push into the mold. At the high end of the range, material breakdown can easily occur if long cycles or an oversized machine results in a long dwell time of the material in the heated cylinder. For the most part, temperatures in the range of 420 to 500°F (216 to 260°C) are desirable.

Mold temperature Mold temperature is not critical to the production of acceptable parts from PETG. When fast cycles are desirable, a cold mold can be used. When cavity filling is a problem, a warmer mold can be used. Mold temperatures higher than 130°F (54°C) should be avoided because parts may tend to stick in the cavities.

Purging

PETG 6763 is easily purged from molding machines. Polypropylene, high-density polyethylene, or an acrylic purging compound will readily purge a machine filled with PETG 6763. In general, PETG 6763 can be removed with any material that follows it in the machine.

Shutdown and Start-Up

After the molding machine is purged, normal shutdown procedures should be employed. The screw should be moved to its forward position and the machine operated as an extruder until no more plastic is being extruded. The heat can then be turned off and

the screw stopped. When processing is to be started again, the heater should be turned on and allowed to heat the machine to operating temperature. Then, the injection switch should be activated, even though the screw is already in its forward position. The small motion that results will free the nonreturn valve slip ring, so that it will operate properly. Rotation of the screw can then be begun.

Thermal and Rheological Properties

As PETG 6763 is amorphous, its thermal properties are essentially determined by its glass transition temperature of 178°F (81°C). This copolyester has deflection temperatures of 145°F (63°C) at a fiber stress of 264 psi (1.82 MPa) and 158°F (70°C) at 66 psi (0.45 MPa).

At temperatures encountered in injection molding [450 to 525°F (232 to 274°C)], the viscosity of PETG 6763 decreases rapidly with increasing temperature and at high shear rates.

Drying

The successful injection molding of Kodar PETG copolyester 6763 requires that the pellets be dried before processing, as is the case with all thermoplastic polyesters. PETG 6763 is subject to hydrolysis when it is in the molten state during processing. This hydrolysis results in a decrease in molecular weight that is reflected by a lowering of physical properties, especially toughness. To prevent hydrolysis during the injection molding process, PETG 6763 must be thoroughly dried. Drying the material in a dehumidifying dryer at a temperature of 150°F (66°C) for 4 h is normally sufficient to reduce the moisture content to a level (approximately 0.04%) that will prevent significant hydrolysis in processing equipment operating at 380 to 525°F (193 to 274°C). The dryer temperature should not exceed 150°F (66°C) to prevent the pellets from softening and sticking together in the hopper.

Mechanical Properties

The most outstanding mechanical properties of Kodar PETG copolyester 6763 are high stiffness and good impact strength, particularly at low temperatures. These properties are easily obtainable using the drying and molding conditions given above.

Chemical Resistance

Unstressed tensile bars molded of Kodar PETG copolyester 6763 exhibit good resistance to dilute aqueous solutions of mineral acids, bases, salts, and soaps, and to aliphatic hydrocarbons, alcohols, and a variety of oils. Halogenated hydrocarbons, low-molecular-weight ketones, and aromatic hydrocarbons dissolve or swell the plastic. The chemical resistance of PETG 6763 is the subject of an Eastman publication that is available on request (Publication TR-59).

Weatherability

Kodar PETG copolyester 6763 is not suggested for use in applications requiring outdoor exposure.

Color

Kodar PETG copolyester 6763 may be colored by using color concentrates, dry colors, or liquid colorants. Compounded colors are not available. Color concentrates in a PETG 6763 base to provide material compatibility when mixed are available from Eastman. Most color concentrates are custom-made, but a few standard color concentrates are available from stock. The mixing ratio for PETG 6763 and color concentrate is usually 20:1.

For injection molding PETG 6763 mixed with color concentrate, it is sometimes necessary to use mixing nozzles or Venturi plates to obtain proper color dispersion.

The color concentrates should be kept as dry as the PETG 6763 to minimize hydro-

lytic degradation of the materials during processing.

Polyvinyl Chloride

It is important to understand the molding characteristics of polyvinyl chloride (PVC) and how they relate to the design of processing equipment. Injection molding of flexible vinyl compounds is relatively easy, but special modifications to standard sprue machines are suggested for processing rigid vinyls. Low-shear screws are necessary to avoid overheating the melt. Special surface treatment, to protect machine surfaces against the corrosion PVC can cause, is also available. Plating, high-nickel steels, or stainless steels should be specified in the mold designs. Heavy metals such as copper must be protected because they are adversely affected by PVC, even at levels as low as 2 ppm. Finally, internal mold passageways should be designed without sharp corners or other restrictions where material may stagnate and degrade.

PVC homopolymers have a melting point between 198 and 205°C (388 and 401°F) and begin to decompose rapidly at 200°C (382°F). Here lies the challenge to the processor. Copolymers are somewhat more forgiving. They begin to melt between 140 and 175°C (284 and 347°F) and offer significant processing advantages; decomposition remains at the high level.

PVC is chemically inert, and it is water-, corrosion-, and weather-resistant. It has a high strength-to-weight ratio. It is an electrical and thermal insulator, and it maintains its properties over long periods of time. Perhaps more important than these other considerations, it has demonstrated good price stability in the market.

Rigid PVC compounds in dry blend form have been used for a variety of extrusion applications for quite some time because of favorable economics and processing. The use of dry blends for injection molding rigid PVC products has become increasingly popular. Pelletized rigid PVC compounds were used for the initial commercial production of most

Table 6-39 PVC dry blend formulations

Ingredient	Common Type	Concentration (parts/hundred)
PVC suspension resin	Homopolymer, 0.68–0.74 IV	100.0
Tin stabilizer	Mercaptide, 13–20% tin	1.2–2.0
Processing aid	Methacrylate copolymer	1.5–3.0
Costabilizer/lubricant	Calcium stearate	0.5–2.0
Filler	Calcium carbonate, 1–3 μm	0–5
Pigment/UV stabilizer	Titanium dioxide	1–2
Impact modifier	ABS or MBS polymer	0–5
Lubricant	Paraffin wax or fatty acid amide or fatty acid esters	0.5–1.5

current rigid PVC applications. PVC pipe is an example.

Formulations

As with any rigid PVC formulation, the primary considerations for an injection molding dry blend formulation are cost, ease of processing (molding), and providing the necessary stiffness, impact strength, weatherability, appearance, and other physical properties in the finished part. However, molding from dry blend also requires that other factors be considered. Formulations must be designed to ensure rapid fusion; attempting to inject cold or poorly fused material can result in degradation problems owing to high “melt” viscosity at the high shear rates encountered, as well as poor physical properties in the finished part. Volatile components in the dry blend must be minimized, since there is no pelletizing step to help remove volatiles. Additives must be selected so as to avoid any potential for the segregation of dry blend components during dry blend handling and transfer. For example, ingredients should be selected so that their particle size distributions and bulk densities match fairly closely. Fine particles can be undesirable because they can contribute to housekeeping problems with poorly sealed material transfer systems.

A potential advantage in formulating dry blends as compared to pelletized compounds can be in the use of stabilizer. The required minimum level of this expensive ingredient may be lower in the case of dry blends, since

a pelletized compound has already experienced one “heat history” before the compound reaches the hopper of the injection molder.

A typical starting-point formulation for a PVC pipe-fitting dry blend is shown in Table 6-39. For high-impact applications, the impact modifier concentration should be increased to a level such as 8 to 12 parts per hundred. For applications where optimum weathering resistance is required, the titanium dioxide level should be increased to perhaps 8 to 12 parts per hundred, and the impact modifier used should be an acrylic or EVA type.

The preparation of PVC dry blends for injection molding is similar to that for other dry blend applications. High-intensity mixers should be used. Care should be taken to avoid excessive fluffing or generation of a static electric charge in the cooling blender or dry blend conveying system, since air entrapment in the melt can result during processing. Properly formulated and blended injection molding dry blend can be shipped and handled in either bulk railcar, bulk truck, or 1,000-lb (454-kg) boxes without problems.

Molding Conditions

Rigid PVC in one form or another (i.e., dry blend, pellets, or regrind) has been processed on nearly every conceivable type of reciprocating screw molding machine. These machines have been equipped with numerous types of screws and mold configurations. Successful field evaluations have been conducted

using ABS screws and molds. Shot sizes have ranged from 20% to nearly 100% of rated capacity. Various types of gates, such as submarine gates, have been successfully used.

Shot size Unfortunately, it is not always possible to size the mold with the machine. For maximum productivity and ease of processing, the shot size should be approximately 75% of rated machine capacity. The lower the shot size as a percent of machine capacity, the longer the residence time. This means that degradation is more difficult to control, and quality problems due to greater temperature gradient of the melt off the screw are more apt to occur.

Clamp requirements It is generally recognized that a clamping force of 3 to 4 tons per square inch of projected part area is needed. With less force you run the risk of the mold's parting during the injection cycle. It should be noted that rigid PVC requires a relatively high injection pressure because it is one of the most viscous of all the thermoplastics.

Barrel cooling Few molding machines in the field today that are processing rigid PVC are equipped with barrel cooling. Temperature override, particularly on the front barrel zone, is not uncommon. Therefore, cooling of this zone offers more control and reduces the risk of degradation, thus giving more processing latitude. A liquid (water or oil) cooling system is more efficient; however, a fan is generally adequate.

Hopper design A properly designed hopper can eliminate powder flow (bridging) problems. The optimum angle is 60°; anything less than 45° will lead to problems. The best design is a round cone shape, but a square design is adequate. The primary consideration is the angle of the bottom portion of the hopper.

Screw Design

The common square pitch feed screw (see Fig. 6-57) with a compression ratio of 2:1 and

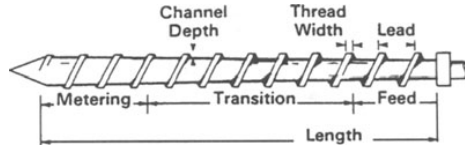


Fig. 6-57 Standard square pitch feed screw.

L/D ratio of 24:1 is used extensively. The shorter L/D of 16:1 is also successfully used, but for dry blend an L/D of 24:1 is preferred. The screw should be chrome-plated and rebuilt or replaced when worn beyond acceptable limits. Often, loss of productivity and quality can be traced to an excessively worn screw. Fig. 6-58 shows a suggested screw design for PVC dry blend, which consists of a barrier screw with a provision for cooling of the screw tip. The barrier screw should provide better melt homogeneity than the square pitch feed screw. The hottest portion of the melt is in the center of the melt stream that flows off the screw tip, so it makes good sense to control the temperature of the tip of the screw (Chap. 3).

There has been considerable debate regarding the best compression ratio (CR) for PVC dry blend. In theory, a CR of 2.3 to 2.4:1 is well suited because the bulk density of the powder is about 37 lb/cu ft and that of the PVC melt about 85 lb/cu ft. The higher CR can cause frictional heat override, but a low CR can be detrimental to the physical properties of the product because of poor fusion. Some fittings producers believe that a low CR (1.5:1) is needed for larger machines (750 tons) and a higher CR (2.0 to 2.4:1) works well for smaller machines (375 tons).

Screw tip The screw tip described in Fig. 6-59 is recommended. Of primary concern is the clearance between the screw tip and nozzle. When the screw is in its full forward position, a clearance of 0.025 to 0.035 in. ensures that a minimum amount of PVC is

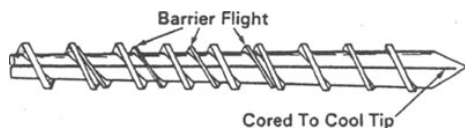


Fig. 6-58 Barrier screw.

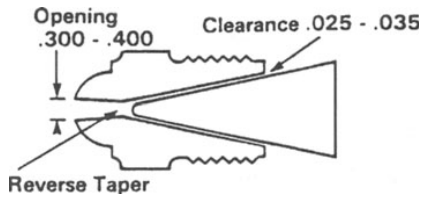


Fig. 6-59 Nozzle and screw tip.

left in the nozzle during each injection cycle. Both the nozzle and screw tip should be chrome-plated.

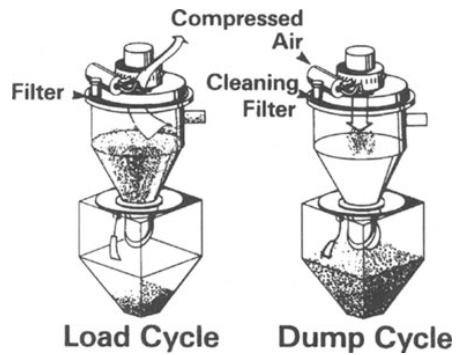


Fig. 6-61 The IMM loader.

Material Handling Equipment

Details on material handling equipment (MHE) are given in Chap. 10.

Plantwide bulk system Figure 6-60 shows a bulk handling system designed specifically for dry blend. Dry blend is obviously more dusty than pellets. However, a closed system such as the one described minimizes house-keeping problems.

Beside the press loader Inexpensive vacuum powder loaders such as the one seen in Fig. 6-61 can be used successfully if the following conditions are met:

- The dry blend should not contain more than 5% of an additive with small particles such as calcium carbonate.
- A PVC resin that has an abundance of fine particles will blind the filter, so particle size must be regulated.

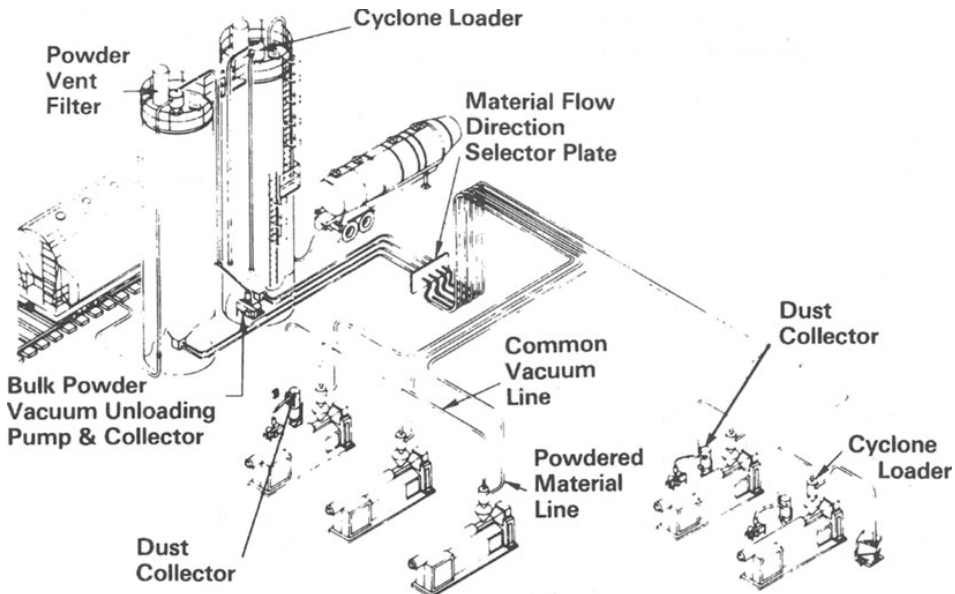


Fig. 6-60 Bulk dry blend transfer system.

Processing Parameters

The conditions shown below can be used as a guide for molding conditions for dry blend. The optimum conditions depend on many factors:

- Dry blend formulation
- Machine size
- Screw design and condition
- Shot size relative to machine capacity
- Mold design

The following suggestions are recommended as a guide for maximizing dry blend performance:

- Maintain the back pressure at a minimum [0 to 100 psi (0 to 0.69 MPa)].
- Run the screw as long as possible for a better melt consistency.
- Keep the injection pressure under 2,000 psi (13.8 MPa), at about 1,200 to 1,600 psi (8.3 to 11.0 MPa).
- Operate with a low injection speed: for large machines (750 tons), 3 to 4 sec/in.; for small machines (375 tons), 1.5 to 2.0 sec/in.
- These and other suggestions are summarized in Table 6-40.

Note The cooling time is the overall factor that governs productivity. The aforementioned molding conditions can be optimized to stay within the normal cycle time so that no loss in productivity occurs.

The recommended molding conditions are also listed in Table 6-40.

Problem Solving

The three most prominent problems that can be experienced when molding with PVC

dry blend are splay, degradation, and blush. (See Chap. 11.)

Splay

(a) The PVC is not sufficiently melted in the metering section of the screw. Thus, air and volatiles are injected into the mold cavities.

(b) The PVC is fused too quickly in the feed section of the screw and can trap unfused particles. Also, the premature melting of the dry blend can act as a barrier (seal) to air and volatiles that need to be forced back through the hopper.

(c) Inadequate venting of the mold exaggerates the problem.

Degradation A discoloration on the inside of the sprue indicates that the melt off the screw is too hot. A discoloration on the outside of the sprue, runner, and part is most likely due to shear degradation.

Blush Blush is generally caused by too large a variation in the melt temperature. In other words, cold and possibly poorly fused material is injected in the mold along with the hotter, more homogeneous melt.

Nylons

Nylons are injection-molded, and there are numerous types of nylons providing different performance characteristics. This review on nylons only concerns nylon 66, a very popular and useful type (108). Three important resin–mold–part interrelations must be considered at the outset by those specifying nylon: First, nylon 66 is a family of

Table 6-40 Recommended molding conditions

Temperature profile (°F)	Screw rpm 20–50
Zone 1 300–330	Injection pressure (psi) 1,200–1,600
Zone 2 320–340	Hold pressure (psi) 800–1,000
Nozzle 320–350	Back pressure (psi) 0–100
Mold temperature 50–100°F	Injection rate
Stock temperature 395–410°F	Large machine (750 tons) 3–4 s/in.
	Small machine (375 tons) 1.5–2.0 s/in.

Table 6-41 Your guide to selecting nylon 66 IM compounds

If You Need	Specify	What It Is
Good stiffness, strength, flow Easier fill-in plunger machines, or faster screw recovery in reciprocating screw machines	General-purpose, unmodified General-purpose, modified	Nylon 66 (melt point: 509°) Lubricated
Easy ejectability from the mold	General-purpose, but with added mold release agent	Lubricated
Greater heat stability in use (to 250°F)	Heat-stabilized grade	Stabilizer retards embrittlement at high use temperatures, best thermal stability but poor electricals
Greater heat stability plus improved ejectability	Heat-stabilized grade with mold release	Same as grade above, but with mold release
Outstanding weather resistance	Weather-stabilized grade	UV-stabilized grade with carbon black
Fast molding, improved color retention on rework, lower mold shrinkage	Color-stabilized, nucleated grade	Rapid crystallization for fast cycles, slightly stiffer than GP nylons, but sacrifices some toughness
Improved ejectability	Color-stabilized, nucleated grade with mold release	Same as grade above, but with mold release
Lower melting, lower mold shrinkage, good flow and color stability	General-purpose nylon copolymer	Copolymer with melt point of 445°F, processes easily and well for heavy sections, but sacrifices stiffness and high-temperature properties
Outstanding impact toughness especially at low temperatures	General-purpose grade	Modified nylon 66 with good moldability (not UL SE Class II)

related resins, not just a single composition. As shown in Table 6-41, various additives or modifiers can be incorporated into nylon 66 that alter its processing-property characteristics. Second, resin selection must be based on both processing and end-use requirements. Thus, it is important to establish carefully the process economics (cycle, number of cavities, heat removal, and mechanical operation of the tool) so that the mold can be built to handle the production goals. Third, overall part design should be scrutinized for redundancy and simplified to require the least complicated mold design. This is a frequently overlooked way to reduce initial mold costs and to improve subsequent mold performance.

Although nylon 66 must be considered a family of resins, all compositions have certain common molding advantages:

- High flow and toughness in thin sections.
- Good weld strength and easy fill of complicated shapes.
- Predictable mold and annealing shrinkages; little tendency for warpage.
- Fast overall cycles. Resins can be molded in cold mold. Ejectability of parts from molds is good; undercuts are readily stripped from cores or cavities.
- Good rework stability. Property losses are minimal on remolding of dry, rework- virgin blends. Processing conditions are unaffected by recycling high levels of regrind.

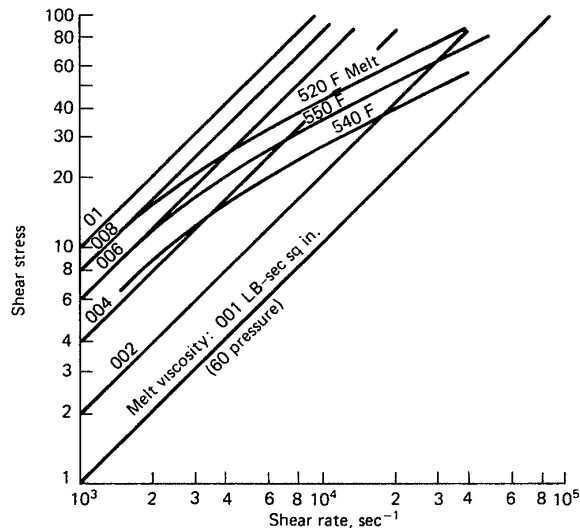


Fig. 6-62 The relationship of shear stress, shear rate, and melt viscosity at indicated melt temperatures (Zytel 101 type 66 nylon).

- Moldability to close tolerances; multicavity tooling presents no unusual difficulties in achieving commercial tolerances.

ties in Fig. 6-62 are typical values at injection pressures used in molding nylon 66.)

Molding Conditions

The flow characteristics of nylon 66 molding grade resins are outstanding. If we consider that these resins exhibit a very sharp crystalline melting point at 509°F (265°C), the melt has good fluidity at temperatures as low as 520°F (271°C) as shown in Fig. 6-62. This figure also shows that the melt deviates from Newtonian behavior at all processing temperatures, meaning that melt viscosity decreases significantly as shear stress (injection pressure) or shear rate (injection speed) is increased. In other words, the melt becomes more fluid as these molding variables increase.

Similarly, the temperature dependence of melt flow (Fig. 6-63), although not greatly different from other engineering resins, also serves to lower viscosity (i.e., improve flow) as the melt temperature is increased. For example, changing the melt temperature by 50°F (28°C) will alter viscosity (flow) by a factor of about 2. (Incidentally, melt viscosi-

How best to fill thin sections It can be argued that any cavity, regardless of dimensions, can be filled when the proper molding

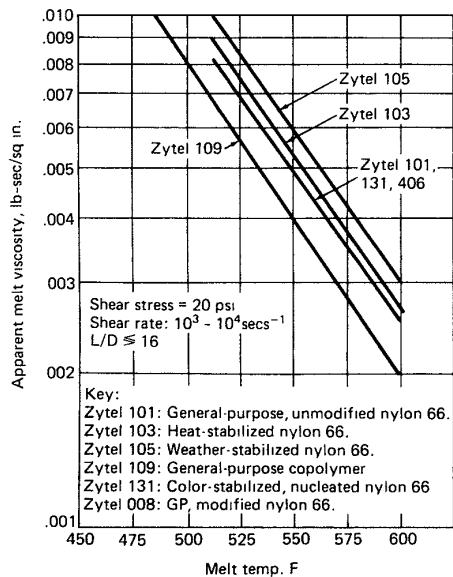


Fig. 6-63 Melt viscosity versus temperature for different nylon 66 molding compounds.

conditions are used. If we assume, for example, that melt solidification in the mold does not occur (if mold temperatures are held at or above the resin's freezing point), any cavity can be filled, provided sufficient injection time is available. From a practical standpoint, however, solidification does occur, and flow will terminate whether the cavity is filled or not. In many cases, this condition results from machine limitations. Thus, in estimating whether any part can be molded, one must first establish its minimum fill requirements (based on the resin's flow and freezing characteristics) and then determine whether this is within the capability of the molding equipment. That is, one must examine the pressure requirements for filling the cavity and the necessary injection rate imposed by solidification of the melt in light of the molding machine's maximum hydraulic oil pressure and pump delivery rate.

Filling a cool cavity with molten nylon, or any thermoplastic for that matter, involves quite complicated fluid flow relationships. As Figs. 6-62 and 6-63 show, the melt viscosity of plastics varies with shear stress, shear rate, and temperature. Accordingly, certain reasonable assumptions must be made to provide a practical guide for estimating fill.

Using a few basic melt-flow equations, we derive Fig. 6-64, which provides useful information, well within engineering reliability, for predicting mold flow and required cavity fill time for nylon 66 (general-purpose nylon, in particular). The data in Fig. 6-64 can be used to predict maximum flow length at specified thickness (or minimum thickness for a specified flow length) and to indicate the time available for filling the cavity of indicated thickness before melt freeze-off prevents additional mold penetration.

The simple, general assumptions we draw are these:

- The cavity can be considered a slab whose volume can be described as length $\times$ width $\times$ thickness.
- Cavity fill time is very fast, so that shear stress and rate are unaffected by melt cooling during the period of filling; that is, flow in the feed channels is isothermal, and melt

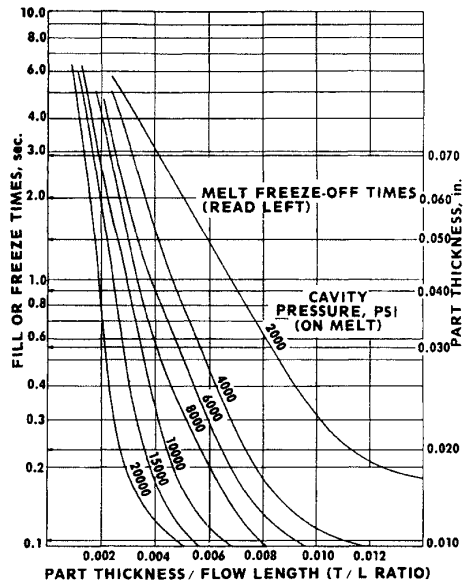


Fig. 6-64 Relationship of fill time, cavity dimensions, and pressure in estimating fill at a melt temperature of $550 \pm 10^\circ\text{F}$ (288°C) and a molding temperature of $120 \pm 20^\circ\text{F}$ (49°C) (with nylon 66 molding compound).

reaches the cavity at the same temperature at which it leaves the nozzle.

- Channel diameters remain constant until the cavity starts to fill.

Figure 6-64 shows generalized curves derived specifically for nylon 66 resins. Based on rheological and thermal data, it is particularly useful for thin sections [$\frac{3}{32}$ in. (0.24 cm) or less]. Knowing the solidification or freezing characteristics of nylon 66, you can compare the actual cavity fill time at various inlet pressures with the allowable fill time before the cavity freezes. (For estimating purposes, pressure drop through the cavity is assumed to be complete and is equal to the actual delivered melt pressure inside the gate.) The penetration or fill time for any cavity, expressed in terms of its thickness/length (t/L) ratio, depends on the available pressure, whereas the maximum allowable time is dependent on freezing of the part of specified thickness. (Part width is not involved except, as discussed in the next section, when volumetric fill rate affects toughness.)

The following examples will illustrate how you can use Fig. 6-64. These are not mere academic problems, but real everyday situations applicable to any molding shop. Bear in mind that the data are valid within $\pm 10\%$ for nylon 66 molding grade resins processed in the range of 520 to 580°F (271 to 304°C) melt temperatures and with mold temperatures of 60 to 180°F (16 to 82°C).

Example 1 What is the maximum flow length that can be attained in a 0.030-in.-thick part, single-gated, with 8,000-psi (55-MPa) cavity pressure available, and what is allowable fill time before solidification occurs?

Look once again at Fig. 6-64 and observe that a 0.030-in.-thick part freezes in 0.55 sec; thus, fill time must be equal to or less than 0.55 sec. An intercept of 0.030-in. (0.076-cm) part thickness (horizontal line) freezing time (0.55 sec) with 8,000-psi (55-MPa) cavity pressure curve yields a t/L ratio of 0.0041 (at the bottom).

Since $t = 0.030$ in. and $t/L = 0.0041$, $L = 0.030$ in./0.0041 = 7.3 in. (18.5 cm) flow (total).

Example 2 The flow length of a 0.020-in.-thick end-gated cavity is specified as 10 in. What is the required cavity pressure to fill, and how rapidly must the part be filled?

A 0.020-in. part will freeze in 0.23 sec, so fill must be accomplished in this time or less. The ratio $t/L = 0.020$ in./10 in. = 0.002 necessitates a cavity pressure of about 22,000 psi (151.6 MPa), which is not feasible on most screw machines. An alternative exists, however. Center-gate the part so that the maximum cavity flow length is 5 in. Although freeze time remains the same, the new $t/L = 0.020$ in./5 in. = 0.004. This new ratio now requires 12,000-psi (82.7-MPa) cavity pressure. Also, if the part thickness could be increased to 0.030 in. for the 10-in. flow case, the t/L would become 0.003. This would allow a fill time of 0.55 sec and an identical 12,000-psi (82.7-MPa) cavity pressure.

This approach to filling cavities can be combined with pressure loss calculations in runners, sprues, and gates to size the necessary "plumbing" of any mold. In Fig. 6-65, pres-

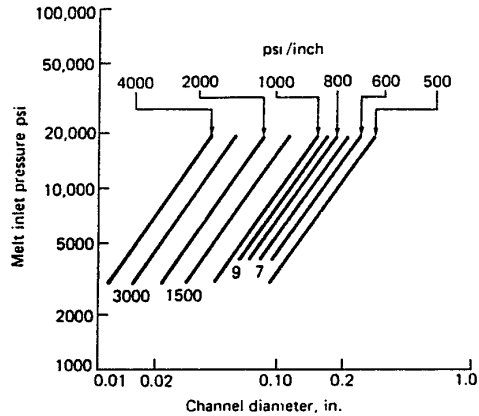


Fig. 6-65 Pressure drops (psi/in. of length) in sprues, round runners, and gates when molding nylon 66.

sure losses for various channel (bore or gate) diameters are plotted versus upstream (entrance) injection pressures.

Example 3 You are given an edge-gated part 0.020 in. (0.051 cm) thick that has its most distant flow point 4 in. (10.2 cm) from the gate; it is to be molded on a reciprocating screw machine capable of a maximum injection pressure of 20,000 psi (137.8 MPa); assume that the total feed runner length is 7 in. and the total pressure drop across the nozzle, sprue, and gate is 3,000 psi. Determine the minimum feed runner diameter necessary to fill the cavity in nylon 66.

Using Fig. 6-64 and working back from the cavity, we obtain:

$$\begin{aligned} \text{thickness/length, } t/L \\ &= 0.020 \text{ in.}/4 \text{ in.} \\ &= 0.005 \end{aligned}$$

$$\begin{aligned} P_c &= \text{cavity fill pressure} \\ &\quad (\text{for 0.020-in.-thick part}) \\ &\quad \text{is 10,000 psi (68.9 MPa)} \end{aligned}$$

$$\begin{aligned} P_{\max} &= 20,000 \text{ (maximum available} \\ &\quad \text{at entrance to nozzle)} \end{aligned}$$

$$\begin{aligned} P_{(\max)} - P_c &= 20,000 - 10,000 \\ &= 10,000 \text{ psi (68.9 MPa)} \\ &\quad \text{(available to fill mold)} \end{aligned}$$

$$\begin{aligned} \Delta P \text{ (nozzle/sprue/gate)} \\ &= 3,000 \text{ psi (20.7 MPa) (typical} \\ &\quad \text{pressure losses given)} \end{aligned}$$

$$\begin{aligned}\Delta P_R &= 10,000 - 3,000 \\ &= 7,000 \text{ psi (48.2 MPa) (available} \\ &\quad \text{to flow melt thru runner)} \\ &\quad \text{runner length} = 7 \text{ in.}\end{aligned}$$

$$\begin{aligned}\frac{\Delta P_R}{\text{in.}} &= \frac{7,000}{7} \\ &= 1,000 \text{ psi/in. (maximum} \\ &\quad \text{allowable pressure drop in} \\ &\quad \text{runner)} \\ &\quad \text{inlet runner pressure} \\ &= 20,000 - 3,000 \\ &= 17,000 \text{ psi (117.1 MPa)}\end{aligned}$$

Using Fig. 6-65, we see that the 1,000-psi/in. (6.9-MPa) pressure loss curve at 17,000-psi inlet pressure intercepts the minimum channel diameter coordinate at 0.135 in. (0.343 cm). Thus, to fill the cavity, the 7-in. feed runner must be at least 0.135 in. (0.343 cm) in diameter (or equivalent area).

Cavity fill rate importance In the preceding section, we have pointedly not concerned ourselves with part width (actually, part volume or weight). As we saw in Fig. 6-64 there are specific minimum fill times for different thicknesses before cavity freeze-off occurs. Thus, the thickness establishes the allowable cavity fill time and establishes the maximum length of flow at various cavity pressures.

Equally significant, we must be concerned with the weight (volume) of the part, and the consequence that this weight must go through the gate in the time necessary to fill the cavity. This, in turn, establishes a volumetric fill rate through the gate. Based on a conservative premise that the fill rate through the gate should not exceed a critical shear rate for the resin (itself a function of melt temperature) to yield maximum part toughness, we can define the size of the gate necessary to fill a part without undue concern for flow-induced brittleness (if we assume adequate cavity venting).

In Fig. 6-66, maximum fill rate (oz/sec/gate) for nylon 66 is shown as a function of gate diameter at several melt temperatures. Note that this is a maximum fill rate and is limiting in that faster fill rates through the opening may melt-fracture the nylon. This phe-

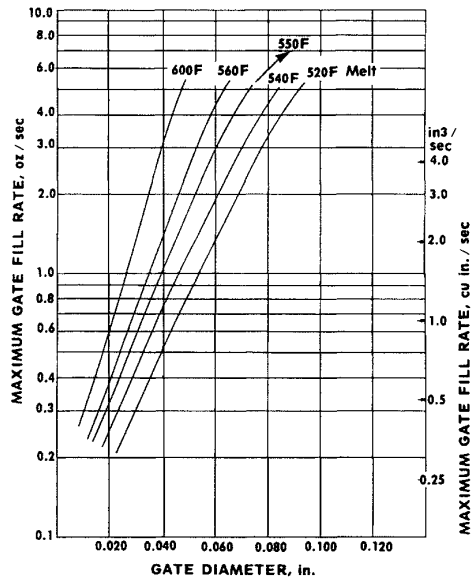


Fig. 6-66 Maximum fill rate through round gates (with nylon 66 molding compound).

nomenon often leads to brittleness, and it is good practice to design molds and operate machines to avoid it.

A practical part design—melt flow consideration is to combine the concepts of Figs. 6-64 through 6-66. In Fig. 6-64, we have specified the allowable fill time (in seconds) for a part having a given thickness. Using Fig. 6-65 and calculating pressure drops in the mold layout, we can arrive at the pressure available to fill the cavity and thus establish the maximum flow length. With Fig. 6-66, knowing the gate size (or assuming that it is equal to part thickness or some arbitrary fraction), we can determine the maximum allowable fill rate (oz/sec) that can be fed through the gate.

Multiplying by the fill time (sec) from Fig. 6-64, we fix the maximum weight (oz) of the part. Since the maximum weight is now known, we can calculate the volume of a solid part (density of nylon 66 at room temperature is 0.66 oz/cu in.). Since volume equals length $\times$ width $\times$ thickness, we can readily obtain the part width and thus have defined the limiting geometry for a tough part in nylon 66.

Let us take an example and solve it step by step.

Assume you have a rectangular part that is 0.040 in. (0.102 cm) thick, molded in a three-plate mold with three gates, 0.030 in. (0.076 cm) in land, and 0.040 in. (0.102 cm) in diameter (subsprues are $\frac{1}{8}$ in. in diameter and 1 in. long). The molding machine is a 20-oz (0.57-kg) 300-ton unit and can deliver 18,000 psi (124 MPa) (maximum) during injection at 5 gal/min; the nozzle has a bore diameter of $\frac{1}{4}$ in. and is 1 in. long; the sprue averages $\frac{5}{16}$ in. in diameter and is 2 in. long; three 5-in.-long feed runners are $\frac{3}{16}$ in. in diameter; you are molding nylon 66 at 550°F (288°C) in a mold at 120°F (49°C). You want to determine how long the part can be and what its maximum possible width and/or weight is.

1. Calculate pressure drops (Fig. 6-65) with machine at maximum pressure, 18,000 psi (124 MPa). Here is what we do step by step:

- (a) Nozzle: at 18,000-psi (124-MPa) injection pressure, nozzle pressure loss is 600 psi/in. $\times$ 1 = 600 psi (4.1 MPa)
- (b) $\frac{5}{16}$ -in.-diameter sprue: inlet pressure = 17,400 psi (120 MPa); $\Delta P_{\text{sprue}} = 500 \text{ psi/in.} \times 2 \text{ in.} = 1,000 \text{ psi}$ (6.9 MPa)
- (c) 5-in.-long feed runners, $\frac{3}{16}$ in. diameter: inlet pressure = 17,400 – 1,000 = 16,400 psi (113 MPa); $\Delta P_{\text{runner}} = 700 \text{ psi/in.} \times 5 \text{ in.} = 3,500 \text{ psi}$ (24.1 MPa)
- (d) $\Delta P_{\text{subsprues}} = (\frac{1}{8} \text{ in. diameter} \times 1 \text{ in. long}): \text{inlet pressure} = 16,400 - 3,500 = 12,900 \text{ psi}$ (88.9 MPa); $\Delta P_{\text{subsprues}} = 900 \text{ psi/in.} \times 1 \text{ in.} = 900 \text{ psi}$ (6.2 MPa)
- (e) $\Delta P_{\text{gate, land}} = 0.030 \text{ in.}: \text{inlet pressure} = 12,900 - 900 = 12,000 \text{ psi}$ (82.7 MPa); $\Delta P_{\text{gate}} = 1,500 \text{ psi/in.} \times 0.03 \cong 50 \text{ psi}$ (0.3 MPa)
- (f) Effective cavity pressure = 12,000 – 50 = 11,950 psi (82.3 MPa) or 6 ton/sq in.

2. From Fig. 6-66 with a 0.040-in.-diameter gate, maximum injection rate/gate is 1.0 oz/sec or 1.5 cu in./sec. With three gates,

4.5 cu in./sec (maximum) can be injected into the cavity without exceeding the critical fill rate for a tough part.

3. Since the machine can displace 5 gal/min or about 20 cu in./sec at 18,000 psi (124 MPa) and the 0.040-in. part must be filled in 0.9 sec, hydraulic oil flow must be throttled by a factor of 4 ($0.9 \times 20/4.5$) from the maximum so as not to melt-fracture resin during cavity fill.

4. Figure 6-64 at 12,000 psi (82.7 MPa) and fill time of 0.9 sec (freeze time for a 0.040-in.-thick part) gives a maximum $t/L = 0.0027$.

5. Since $t/L = 0.0027$ and $t = 0.040 \text{ in.}$ (0.101 cm), $L = 14.8 \text{ in.}$ (37.6 cm).

6. We have established that the part is now 14.8 in. long $\times$ 0.040 in. thick and must be filled in 0.9 sec. Since the maximum combined fill rate (three gates) is 3 oz/sec, it follows that 3×0.9 (or 2.7 oz) is the maximum part weight. The corresponding volume is $2.7/0.66 \cong 4 \text{ cu in.}$

7. The part now can be defined as 14.8 in. $\times$ 0.040 in. $\times$ $w = 4 \text{ cu in.}$ ($w = 6.7$).

8. This hypothetical part could be molded in nylon 66 about $15 \times 0.040 \times 7$ and satisfy the machine and mold requirements for flow and toughness. However, the projected cavity area is approximately $15 \times 7 = 105 \text{ sq in.}$ As the actual cavity pressure required to fill was 12,000 psi (82.7 MPa) or 6 tons/sq in., one would need about a 650-ton clamp to support this force. Obviously, a 300-ton clamp will not do, so in reality we are allowed then a part about 15 in. long $\times$ 3 in. wide in order not to flash the mold. Now the maximum part weight is $15 \times 3 \times 0.040 \text{ in.} = 1.8 \text{ cu in.} \cong 1.2 \text{ oz}$ (0.034 kg), not 2.7 oz (0.077 kg) as originally determined in step 7.

Performance Parameters

Avoid common pitfalls Thin moldings of nylon 66 can exhibit strength differences in their flow and transverse directions. This phenomenon, called property anisotropy, is induced primarily by flow (pressure) orientation of the melt during flow.

Two complicating factors exist. The first, part geometry, is extremely important. Parts of dissimilar shape, yet of the same thickness, will fill in different patterns, and thus differences in flow orientation can arise that may affect one part more than the other.

The second factor, the effect of flow length on orientation, is easier to define. At identical molding conditions, the longer the flow path (per given thickness), the more chance of induced orientation, since higher cavity pressures and injection rates are required. All injection moldings are produced under high-shear conditions, and because cooling times are rapid, only partial recovery or relaxation of the oriented melt molecules can take place before solidification occurs, leaving the part in a strained condition.

This situation acts to reduce the as-molded ductility in the direction of flow, since, in effect, some of the normally available elongation of the material has already been “used up.” The usual ways of reducing flow orientation cause reduction in initial molecular stretching or give more time for stress relaxation.

Typical corrective actions are to increase part thickness to reduce injection pressures required for fill, use hotter molds (which lead to longer cycles and greater stress relaxation), or specify postannealing. However, these remedies can lead to increased costs.

Design Parameters

Parts requiring cavity fill pressures greater than 8,000 psi (55.1 MPa) are likely candidates for anisotropic property behavior, especially in thin sections. Accordingly, a critical flow length (at any thickness) can be calculated for 66 nylons, which is useful in planning gating and part design so as not to exceed this fill pressure requirement. Table 6-42 lists this maximum flow length at three mold temperatures for several section thicknesses.

Welds need not be weak links In the design of complicated shapes, weld lines are often unavoidable. Weld or knit lines are formed

Table 6-42 Critical flow distance for uniform physical properties of nylon 66 molding compound

Nominal Cavity Thickness (in.)	Mold Temperature		
	60°F	120°F	180°F
0.020	3.2	3.4	3.8
0.030	6.8	7.3	8.2
0.040	11.2	12.0	13.4
0.050	16.8	18.0	20.0

when more than one gate is used or wherever a divided stream of plastic joins after flowing around a pin or core. Thin sections are particularly prone to weak welds because of rapid melt solidification.

When welds are formed, they should be sweeping; when unavoidable, butt welds must be vented for maximum strength. In these cases, it is essential that air at the weld escapes before the melt streams unite.

Poor venting at weld points in nylon 66 usually manifests as burning or discoloration (e.g., yellowing). At such spots, the strength of the welds will be inferior to the rest of the part. Obviously, good part and mold design calls for the least number of welds when extreme strength is necessary. The number of gates and internal shutoff cores should be considered an important aspect of the initial part and mold design problem.

The general formula for determining the number of welds is useful to know:

$$N = G - 1 + P$$

- where N = number of weld points
 G = number of gates
 P = number of shutoff cores

Examples of using this formula are shown in Fig. 6-67.

Weld strength can be maximized If we assume that adequate venting exists, conventional techniques to improve weld strength are to:

- Increase melt temperature.
- Increase mold temperature.
- Increase injection pressure.
- Avoid use of external release mold lubricant.

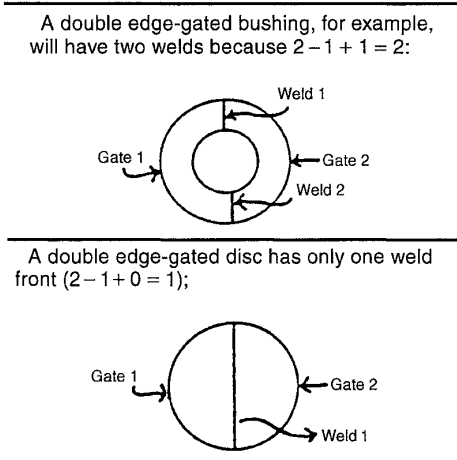


Fig. 6-67 Examples of determining the number of welds.

Often, mold release sprays are pushed into the weld area by the advancing front of molten polymer and prevent good fusion.

With the exception of the last point, the effect of the change is to increase the flow of melt to the junction, that is, to push the melt into the mold faster so that the two (or more) fronts can fuse or unite properly before resin solidification occurs. Typical weld strengths, in tension, range from 50 to 95% of base material strength, although poor weld strength usually shows up as failure in repeated flexure or shear, which is difficult to measure accurately.

To ensure maximum part strength when welds are involved in the design, look at Table 6-43. It assumes that cavity venting is not limiting and that melt at 530°F (277°C) flows into a cold mold at 60°F (16°C).

Table 6-43 Processing design conditions for maximum weld strength in thin sections (nylon 66)

Part Thickness (in.)	Maximum Fill Time (s)	Maximum Part Weight/Gate (oz)
0.020	0.14	0.05
0.030	0.37	0.05
0.040	0.64	0.50
0.050	0.95	1.00
0.060	1.40	2.25
0.070	2.90	13.00

(Note: Higher melt or mold temperatures improve welding.)

The basis for optimum welding is two-thirds of the part-freeze time, as determined from Fig. 6-64. The maximum part weight (per gate) is based on Fig. 6-66 and the assumption that the gate diameter is equal to part thickness. (Smaller gate diameters would further restrict weight.)

Dimensional considerations: A necessary chore The need for the end-user, part designer, and molder to establish and agree on the importance and number of critical dimensions is paramount to profitable molding. Many molds have been built with a certain plastic in mind only to have a poor mold shrinkage estimation or unexpected changes in dimensions after molding force the end-user or molder to try another resin with, usually, lower mold shrinkage to yield parts to print.

Frequently, property compromises are made because (1) it is cheaper than reworking the mold to size, or (2) it is more advantageous to have a part that fits now (for a variety of reasons) than a part that gives better service over the long haul. Also, it is soon realized that employing unusual molding conditions or gate dimensions to alter mold shrinkage after the mold is built generally leads to poor-quality parts.

In a nutshell, then, the use of longer cycles, shrinkage fixtures, or postannealing operations to compensate for bad mold shrinkage estimates can ruin the economics—and that means profits—of molding.

The simple question confronting the mold designer with respect to dimensions can be stated as follows: What size must the cavity be in order to produce a part to size when operating under end-use conditions? To answer this question, it is necessary to consider the dimensional changes in nylon 66, which are brought about by several factors.

Moisture and temperature: Effect on part size If we start from the dimensions of the part under use conditions and work back to mold-cavity size, the first point to consider is the effect of temperature and relative

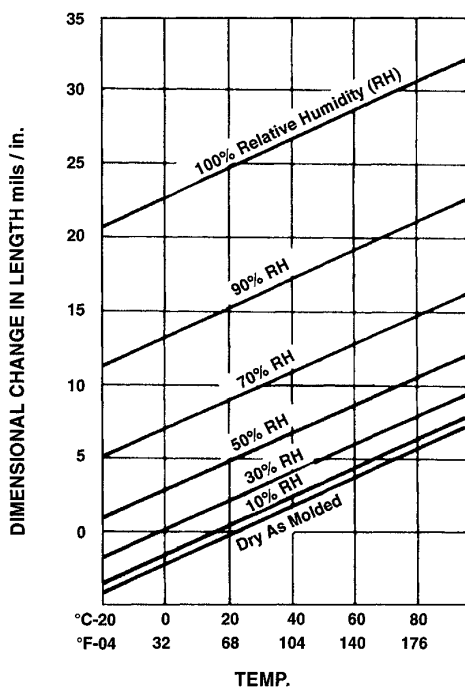


Fig. 6-68 Dimensional changes of GP nylon 66 (Zytel 101) versus temperature at various humidities (annealed samples).

humidity on part size. Nylon, like other plastics and metals, expands as it is heated. It also absorbs moisture from the atmosphere, which results in an increase in part size. These factors are combined in Fig. 6-68, which shows changes in length (mils/in.) of a stress-free test specimen molded in nylon 66. These very predictable changes in the as-molded length represent steady-state values (equilibrium) with a given temperature and relative humidity.

In the typical exposure of a part to an environment of slowly varying humidity, no true moisture equilibrium is reached, but, rather, a balance is established with the average humidity. After initial moisture development has occurred, subsequent variations in relative humidity have little effect on total moisture content and dimensional changes in all but very thin sections. The time to equilibrium is highly dependent on temperature and part thickness (e.g., thin sections absorb water very rapidly at higher tempera-

tures). The combined effect of moisture content and thermal expansion causing dimensional changes in nylon 66 is easily shown. For example, assume that a part of unspecified length will be required to function at 104°F (41°C) and 50% relative humidity. Using Fig. 6-68, we easily determine that this part will grow to be 6.8 mils/in. longer in use than as molded.

Anneal for maximum stability Thus far, we have determined the change in the size of the part resulting from temperature and humidity conditions *after molding*. Another factor affects the size after molding: time.

Depending on part thickness and mold temperature employed during molding, dimensions can decrease with time, especially when parts are exposed to temperatures above 150°F (66°C). This is called postmolding shrinkage.

For the greatest dimensional stability at elevated end-use temperatures, annealing is sometimes employed after molding to relieve molded-in stresses and to establish a uniform level of crystallinity in the part. (*Note:* The level of molded-in stresses in most 66 nylons is generally low because of their high melt fluidity right up to the onset of solidification. This permits relaxation of flow stresses and orientation effects. Nucleated nylons are sometimes prone to have a higher residual stress level.) Parts made in cold molds tend to be most affected because of rapid melt solidification. Flow-induced stresses in thin sections can be “frozen-in,” and quasiamorphous areas, often induced by cold molds, do not fully develop maximum crystallinity.

As-molded crystallinity depends largely on part thickness and mold temperature. The crystallinity of sections $> \frac{3}{16}$ in. (0.48 cm) molded in molds $> 175^\circ\text{F}$ (135°C) does not change greatly with time. However, thin sections molded in cold molds, $< 100^\circ\text{F}$ (38°C), can undergo appreciable postmolding crystallization (especially at elevated temperatures), which results in additional shrinkage. Parts molded under restraint (not free to shrink) may on exposure to temperatures $> 150^\circ\text{F}$ (66°C) shrink in the direction of restraint and expand perpendicular (transverse) to the restraint.

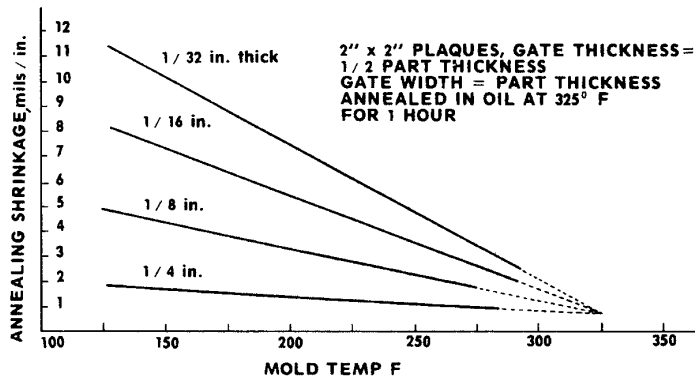


Fig. 6-69 Shrinkage during annealing versus mold temperature for GP nylon 66 (Zytel 101 NC10).

In general, articles molded of nylon 66 used at temperatures less than 130 to 150°F (54 to 66°C) do not require annealing. Conversely, for parts exposed to higher temperatures, especially at low relative humidities in an application requiring stable dimensions, annealing is suggested. [Immersion in oil at 325 to 350°F (163 to 177°C) for 30 min is typical.]

Like moisture and temperature changes, the effect of annealing is very predictable. Fig. 6-69 shows shrinkage during annealing of test specimens of varying thickness molded over a range of mold temperatures. These annealing changes result in contraction of the part. Often, they tend to negate the effect of moisture uptake at elevated temperatures that, as we said, leads to expansion, and, in many cases, total dimensional change after molding is negligible, since the opposing expansion and contraction effects often counterbalance each other.

To illustrate, consider a nylon part about 0.100 in. (0.254 cm) thick, molded with a 125°F (52°C) mold, and subsequently annealed. Then the shrinkage that would occur during annealing would be about 6.5 to 7 mils/in. As we have shown above, total expansion at 104°F (40°C) and 50% relative humidity ultimately causes a 6.8 mil/in. increase in length. The net effect then would be little or no total change from the as-molded dimension.

Estimating mold shrinkage: A critical factor The most critical factor in planning any

injection-molded part is the mold-shrinkage estimate. Molds are sized for a particular resin, usually after the part design is finalized. It is common practice to leave metal for subsequent machining to final dimensions after trial moldings are made. This is costly, time consuming, and not always good metallurgical practice, since many tool steels should be properly heat-treated before use. (Fortunately, EDM techniques allow machining of prehardened steel, which permits certain mold or cavity adjustments after trial shots are made.) Nonetheless, it is desirable to size the mold as closely as possible before use.

Parts injection-molded from thermoplastics are smaller than the cavity in which they were molded. The reason for this size difference is that the cavity is filled with a melt at high temperature that is less dense than the cooler solid. Actually, the difference between the volume of the mold and that of the part is the mold shrinkage. Traditionally, however, the difference between any linear dimension of the cavity and the corresponding linear dimension of the part is called the mold shrinkage of the plastic. Conventionally, this difference is expressed as a ratio of the original cavity dimension and is defined as

$$\text{Mold shrinkage (MS)} = (C - P)/C, \%, \text{ or mils/in.}$$

where

$$\left. \begin{array}{l} C = \text{cavity dimension} \\ P = \text{part dimension} \end{array} \right\} \text{consistent units}$$

The changes in density of a plastic during molding (actually, specific volume) depend largely on the temperature of the melt and the pressure on it. As melt temperature increases, specific volume increases, and as pressure increases, specific volume decreases. At the freezing point, an abrupt decrease in specific volume occurs as the nylon changes from an amorphous liquid to a semicrystalline solid. As the temperature of the solid nylon is further decreased during cooling, the specific volume continues to decrease. Theoretically, the total volumetric change from melt to solid should approximate three times linear mold shrinkage. In the actual molding situation, nonuniform cooling spoils this simplified approach.

In practice, then, final mold shrinkage is determined by the temperature and pressure of the nylon melt in the cavity at the time of gate seal-off and the thickness and crystallinity of the frozen skin. Since the specific volume of a solid material is considerably less than that of any melt, the greater the thickness of the solid layer, the smaller will be the size change as the part comes to room temperature. Minimum shrinkage is obtained when the part is completely solidified when the gate freezes.

The nucleation of nylon raises the temperature at which solidification occurs and thereby hastens freezing of both the part and gate. The usual effect of nucleation is to reduce mold shrinkage, but it also increases the amount of frozen-in flow orientation, which can lead to nonuniform shrinkage in flow and transverse directions and, at times, part warpage. (The transverse shrinkage will be greater.)

Pigmentation can also decrease the mold shrinkage of nylon. The greatest effect is seen with high loadings of TiO_2 and other inorganic pigments and salts that act to nucleate nylon. Organic pigments and dyes do not significantly affect shrinkage.

Part and mold geometry are also very important in determining the mold shrinkage of a given dimension. If the cavity contains undercuts or cores that restrain the free shrinkage of the part, the as-molded shrinkage will be less than for an unrestrained part. The postmolding or aging shrinkage, however, will be greater for a part that is restrained from free shrinkage in the mold because of greater stresses retained within the part.

One may estimate the mold shrinkage of unrestrained parts by using Fig. 6-70. Note

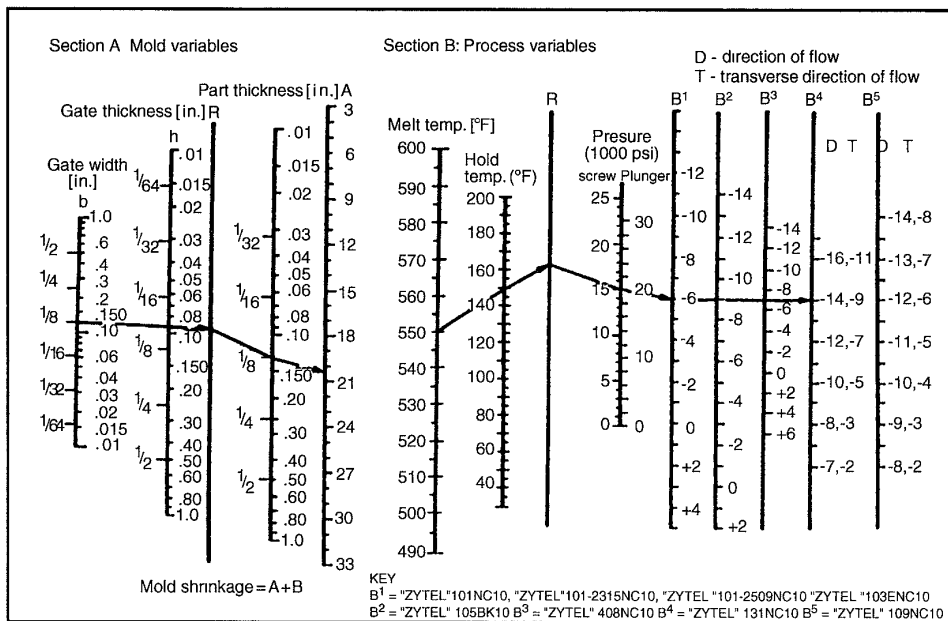


Fig. 6-70 Mold shrinkage nomograph for nylon plastics.

that this nomograph is in two sections: mold variables and process variables. The net effect is additive, except notice that the signs are + in. *A* and - in. *B*. The nomograph is based on data obtained from parts of simple geometry. The injection speed and hold time (dwell under pressure) were adjusted to give maximum part weight with the injection pressure, melt temperature, and mold temperature as variables. For optimum predictability when using the nomograph, the importance of obtaining maximum part weight during molding cannot be overstated. If the cavity is not filled to the limit imposed by the gate seal time, then the measured shrinkage will be greater than that predicted by the nomograph.

Molding Performance Parameters

Use the nomograph For illustrative purposes, we show a typical example in Fig. 6-70 for a part molded in general-purpose nylon (specifically, Zytel 101). Let us look at it:

Mold variables Assume the following:

Gate width = 0.125 in. (0.318 cm)

Gate thickness = 0.090 in. (0.229 cm)

Part thickness = 0.125 in. (0.318 cm)

Connecting scales as shown, one obtains a value of about 20 for *A* (sign is +).

Process variable Assume the following:

Melt temperature = 550°F (288°C)

Mold temperature = 150° (66°C)

Connect points as shown to reference line *R*.

With a screw injection machine, the required melt pressure to fill (for the example) is 15,000 psi (103.4 MPa). (*Note:* Injection gauge pressure on the machine must be converted to equivalent melt pressure; this factor varies with different machine manufacturers.)

Connect reference point (on *R*) with melt pressure and read -6 on scale *B*₁, (for Zytel 101). Mold shrinkage is $A + B = 20 + (-6) = 14$ mils/in.

Had a nylon resin other than Zytel 101 been molded, we would connect the point on *B*₁ horizontally to the specific *B* scale for the resin used. Note that for Zytel 131 (scale *B*₄) and Zytel 109 (scale *B*₅) both resins are nucleated and show a different *B* value, depending on whether measurement is made in the direction of flow or transverse to it.

To illustrate, had we selected Zytel 131 in the preceding example, the *A* value (+20) would be identical. However, the *B* value for flow direction shrinkage would be -14, and the mold shrinkage estimate would be

$$A + B = 20 + (-14) = 6 \text{ mils/in.}$$

If transverse shrinkage were required, then

$$A + B = 20 + (-9) = 11 \text{ mils/in.}$$

Only the nucleated 66 nylons show different flow and transverse shrinkage. The other 66 nylons exhibit the same shrinkage in both directions. Surface lubrication and mold release agents do not affect mold shrinkage.

To summarize key points in this discussion, let us combine Figs. 6-68 through 6-70 and estimate the mold shrinkage that would be necessary to produce a hypothetical part exposed to certain environmental conditions.

Assume that a part is molded in unmodified nylon 66. Part thickness is $\frac{3}{16}$ in., gate thickness 0.100 in., gate width 0.150 in., mold temperature 100°F, melt temperature 540°F (282°C), and injection pressure 12,000 psi (82.7 MPa). The part must be used at 30% relative humidity (RH) at 175°F (80°C). The part is to be annealed after molding for maximum dimensional stability. The problem is the following: Determine the size of the cavity to produce a part dimension (flow direction) of 1.000 in. (2.54 cm) in use.

From Fig. 6-68: Annealed nylon 66 will grow 8 mils/in. in use (30% RH at 174°F).

From Fig. 6-69 (interpolating): For a $\frac{3}{16}$ -in.- (0.48-cm)-thick part molded at 100°F (38°C), the mold will shrink in length during annealing about 4 mils/in.

From Fig. 6-70: If we use the given mold and processing conditions, mold shrinkage is

$$A + B = 22 + (-6) = 16 \text{ mils/in.}$$

Total shrinkage from mold shrinkage and annealing is $16 + 4 = 20$ mils/in. contraction.

Total growth from relative humidity and temperature is 8 mils/in. expansion.

Net shrinkage is $20 - 8 = 12$ mils/in. contraction or 0.012 in./in.

$$MS = (C - P)/C$$

$$0.012 \text{ in./in.} = (C - 1.000 \text{ in.})/C$$

$$C = 1.012 \text{ in. (2.571 cm)}$$

If cavity dimension is sized to 1.012 in., the corresponding annealed part dimension will be 1.000 in. (2.54 cm) at 30% RH and 175°F (80°C).

Mold to close tolerance Nylon 66 possesses a number of processing characteristics that favor fast overall cycles and high production rates. Chief among them is rapid melt solidification or setup in the mold. In addition, rapid crystallization produces rigidity at elevated temperatures necessary for shape retention during part ejection from the mold.

These two factors can be further enhanced by nucleation. Mold release characteristics can be markedly improved by the addition of small amounts of surface-coated release agents.

The excellent flow characteristics of nylon 66 allow for easy mold penetration in thin sections, even in cold molds, without the need for unusually high melt temperatures or injection pressures. Cold molds, in turn, speed up melt solidification and minimize the force required to eject parts from molds.

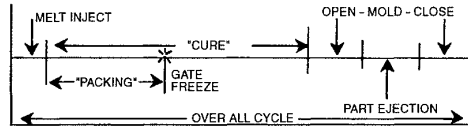


Fig. 6-71 Representation of a typical molding cycle for nylon 66.

Cure time: An important factor In this section, the actual injection of melt (ram-in-motion time) typically takes only a fraction of a second. As Fig. 6-71 demonstrates, most of the cycle involves curing or cooling the polymer, which, until gate freeze-off, can be considered the packing of the cavity.

After gate seal, while the part is cooling until it is stiff enough to be ejected, the screw normally rotates and retracts to produce the next shot. On very fast cycles, the screw sometimes must continue to rotate while the mold is open in order to produce the required melt.

Figures 6-72 and 6-73 give minimum cure times for nylon 66 at various melt and mold temperatures. Data are plotted for two thicknesses: 0.1 and 0.2 in. These times include both time to freeze and time to cool to a temperature where the modulus (stiffness) of the part is suitable for ejection. (Cooling time varies with part thickness approximately as the square of the thickness difference; e.g., if part thickness is reduced by half, cooling is four times faster.)

Cooling times for a nucleated nylon 66 (Zytel 131) are shown in both figures as dotted lines. About 12 to 15% cycle reductions

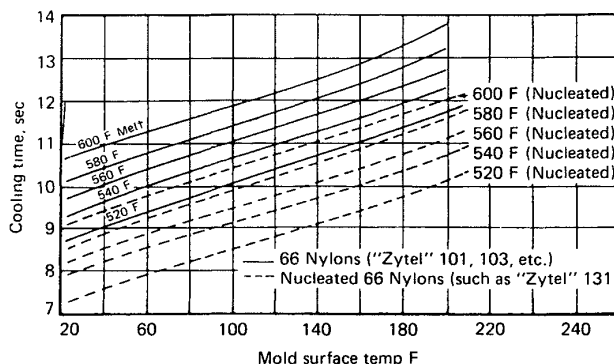


Fig. 6-72 Inmold cooling time for parts 0.1 in. (0.5 cm) thick.

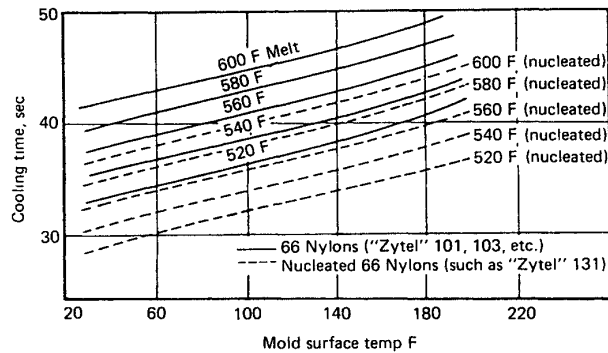


Fig. 6-73 Inmold cooling time for parts 0.2 in. (0.5 cm) thick.

are possible at any thickness using this resin.

Figures 6-72 and 6-73 can also be used to predict the changes in cooling time as melt or mold temperatures are varied. Obviously, the coldest melt and mold temperatures that can be used successfully result in the fastest cooling times and shortest cycles. These figures also indicate the necessity of careful planning for maximum mold cooling when fast cycles are involved.

Mold Release

It can also be seen from Fig. 6-71 that part ejection affects overall cycle. The production cycle can be seriously lengthened if parts hang up and do not fall free from the mold, or if the operator must frequently remove stuck parts.

Mold release agents often help minimize these problems, but be aware that excessive mold release can cause mold vents to plug (leading to part burning) or contribute to surface defects on the molded part. Also, the best mold releases cannot obviate serious mold-design limitations, such as excessive undercuts, too little draft or taper, improperly cooled cores, hot spots, over-packing of sprues, ejector pin penetration, insufficient knockout, etc.

Mold release is particularly affected by injection pressure and mold temperature. Higher injection pressures and mold temperatures usually necessitate higher ejection forces.

Nucleation promotes release The nucleation of nylon 66 also improves part release. For example, you will note in Table 6-44 that the nucleated nylon requires 40% less ejection pressure than the unnucleated nylon. As a result, it experiences less deformation on ejection than the unnucleated nylon when they are molded under identical conditions. (The lower ejection pressure stems from the fact that the nucleated nylon, Zytel 131, sets up faster and offers less drag resistance during part ejection.)

Being stiffer, nucleated compositions also resist pin penetrations. In the practical mold design case, nucleated nylons can be ejected using small-diameter pins, where frequently unnucleated nylons require sleeve, blade, or other types of more costly stripper knockouts, especially on fast cycles. On balance, in molds that are prone to cause part sticking, nucleated nylon 66 will run on faster cycles.

Table 6-44 Mold release characteristics

Typical Ejection Pressures (psi) ^a	Resin
1,900–2,000	Standard nylon 66 molding resins
1,300–1,400	Surface-coated with mold release
1,100–1,200	Nucleated
900–1,000	Nucleated and surface-coated with mold release

^a Based on the mold release of a single-cavity test specimen, using a pressure transducer on a hydraulic ejector mechanism.

Surface-coating nylon 66 resins with about 0.1% aluminum stearate reduces ejection pressure significantly. As shown in Table 6-44, surface-coating a standard nylon 66 molding resin with aluminum stearate reduces ejection pressure about 35%.

Although effective, surface-coating unnucleated nylons does not give a product equivalent to a nucleated nylon in mold release characteristics. However, surface-coating nucleated nylon with about 0.1% aluminum stearate can further reduce ejection pressures by 10 to 15%. Experimental compositions incorporating even more effective internal release agents are under evaluation.

Readily stripped undercuts Although not directly related to fast cycles in the sense of more rapid solidification or easier release, the fact that nylon 66 can be stripped readily from molded-in undercuts should increase production cycles.

A few precautions must be mentioned for you to take full advantage of this characteristic. With few exceptions, hotter mold temperatures permit a greater percentage of undercuts to be stripped. Unfortunately, higher mold temperatures also lengthen cycles, and so a compromise situation always exists. Moreover, nucleated nylon 66 resins and resins with high pigment or particular additive loadings tend to have less ductility (ability to be deformed) than unnucleated resins and often cannot be specified in molds with deep undercuts.

An undercut is a projection or recess usually perpendicular to the angle of draw or mold opening. A stripped undercut may be defined as any portion of the molded piece that is either stretched or compressed while being ejected from the mold.

The principle of molded undercuts, while most often involving an end-use function, is also used in mold design; undercuts for holding the molded part on the proper plate during mold opening, sucker pin, and sprue pullers are just a few examples from a mold builder's standpoint.

The design of a thermoplastic part (and the mold) in which stripping of undercuts is involved must be approached with caution to

prevent part breakage during ejection from the mold. Here are some general guidelines for stripping circular undercuts in thermoplastic materials:

- The undercuts must be free to stretch or compress; that is, the wall of the part opposite the undercut must clear the mold or core before ejection is attempted.
- The undercut should be rounded and well filleted to permit easy slippage of the plastic part over the metal and to minimize stress concentration during part ejection.
- Adequate contact area should be provided between the knock-out and plastic part to prevent pin penetration of the molded part or collapsing of thin-wall sections during the stripping action.
- Figures 6-72 and 6-73 should be referred to for minimum mold cooling times (at indicated thickness) before the ejection of undercuts is attempted.
- Mold release agents do not increase maximum allowable undercuts.

The method of calculating the percent of undercuts, in tension or compression, is shown in Fig. 6-74. The calculation of a maximum allowable undercut is possible if we consider the stripping of an undercut equivalent to an interference fit, or

$$\left(\frac{I}{D}\right) = \left(\frac{E}{S}\right) \times (k)$$

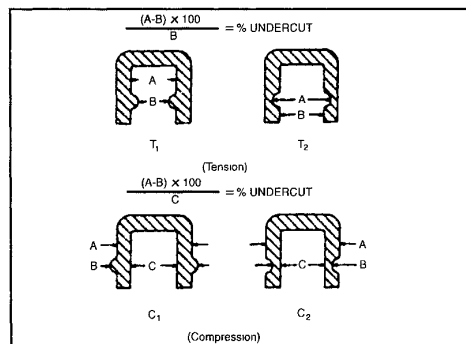


Fig. 6-74 Types of circular undercuts and calculations for maximum allowable undercuts when molding nylon 66 compound.

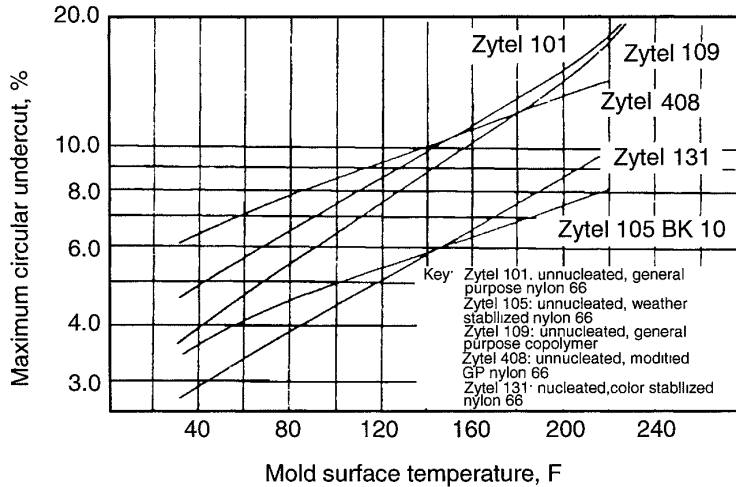


Fig. 6-75 Maximum allowable circular undercuts for different nylon 66 molding compounds.

where:

$I = \text{interference}$ } express ratio as % of
 $D = \text{diameter}$ } original diameter

$S = \text{yield stress}$ }
 $E = \text{modulus}$ } consistent units
 $k = \text{constant}$ }

Figure 6-75 gives maximum allowable circular undercuts in percentages for several nylon 66 molding resins as a function of mold temperature. Undercuts should always be specified as a percentage of the diameter being deformed during ejection rather than as a linear value. For instance, a 0.05-in. (0.127-cm) undercut on a 2-in. (5.08-cm) diameter can be easily stripped in general-purpose nylon 66 (e.g., Zytel 101) in an 80°F (27°C) mold, but a 0.05-in. (0.127-cm) undercut on a 1-in. diameter would require a mold temperature of 180 to 190°F (82 to 88°C).

Close Tolerance: Fast Cycles

Like moldings of any thermoplastic, parts injection-molded from nylon 66 resins are subject to some variation in dimensions from shot to shot. The allowable variations in the dimensions of an injection-molded part are called the tolerances for the part.

Molding tolerances include the total variations in a part dimension that are caused by deviations in the overall molding operations. These deviations may be found in the mold or molding conditions and may be short- or long-term. Good quality-control records are invaluable in determining the source of trouble.

The part or mold designer should be aware of a few general pointers in this regard.

First, tolerances set on any dimension by the designer usually represent a compromise between part function and its cost of manufacture.

Second, an important factor (often overlooked) is that plastic parts can usually operate satisfactorily with wider tolerances than metal parts. It does not pay to specify closer tolerances than necessary.

Third, a part that has many critical dimensions will be more difficult to mold to tolerance than a part with fewer such dimensions. Tight tolerances should not be put on every dimension, particularly those across a parting line, or sections formed by movable cores or sliding cams.

Fourth, minimum tolerances are easiest to achieve in a single-cavity mold. Several sources of variability are introduced when multicavity molds are used (e.g., cavity-to-cavity differences and nonuniformity of

runners and gates leading to the individual cavities). Fine tolerances usually cannot be achieved in molds that have more than one type of cavity.

In general, the greatest variation in part dimensions is introduced by the molding operation itself. Molding variables must be controlled closely if fine tolerances are specified because slight variations in molding conditions can affect part shrinkage. To attain high dimensional reproducibility, it is essential to mold on a fully repetitive cycle.

The ability to maintain close tolerances is dependent on part design, mold design, the injection molding equipment used, and, understandably, the ability of the molder. All areas must be optimized to maintain tight tolerances. (Processing problems that affect molding tolerances are outlined at the end of this chapter.) Without doubt, finer tolerances can be achieved in many cases by resorting to improved control of these problem areas.

Recycling Plastics

It is common practice for injection molders to recycle reject parts, along with sprues and runners (cold-runner systems), through their molding machines. To the molder, this reuse of material frequently means the difference between profit and loss on a job, and to the designer it is often the economic incentive to injection-mold a part.

In a typical mold design, it is an unusual occurrence when the sprues and runners amount to less than 25% of the shot weight. This percentage can occasionally run as high as 75%. It is possible to reuse previously molded nylon 66 without undue sacrifice in physical properties or quality, provided that proper precautions are taken in initial and subsequent moldings and, most important, during interim handling of the reground plastic.

Profitable use of rework demands adherence to three simple precautions:

- Protect regrind from moisture, since all nylons absorb moisture rapidly from the atmosphere. Regrind that is kept covered and reworked promptly (within one-half

hour) will usually not require additional drying.

- Ensure that the regrind contains no degraded nylon. Burned or degraded nylon can form points of weakness when mixed with virgin and subsequently molded into new parts. Because a large quantity of virgin resin can be ruined by the inclusion of a small amount of degraded regrind, material held for long periods of time should be discarded and not reground.
- Prevent contamination of rework from other sources. Good housekeeping procedures and limited exposure of rework to dirty surroundings are keys to prevention of contamination.

In the latter regard, here are a number of easy-to-follow suggestions:

- The area and equipment in which the regrind is produced and handled should be kept as clean as possible.
- Grinders should be kept in close proximity to the molding machine. Sprues, runners, and rejects should be reground as soon as they are removed from the machine; continuous reuse of material (blended with virgin to a fixed proportion) is the best policy.
- Runners, sprues, and parts that contain visible contamination must be discarded.
- Regrind should not be allowed to accumulate in an uncovered container. Whenever possible, eliminate the intermediate storage of regrind.
- In any regrind-handling system, have some means to remove fine particles. Because of a large surface-to-volume ratio, fines absorb moisture very rapidly and present a large surface for the static attraction of dust. Vibrating units equipped with 16- to 20-mesh screens have been found useful for separating fines. Keeping grinder blades sharp, with proper clearance and screen sizes, will also minimize fines.

The ratio of reground nylon 66 that may be blended with virgin will depend on both the quality of the regrind and specifications of the part. If careful regrind handling procedures are followed, high percentages of regrind can be used without difficulty.

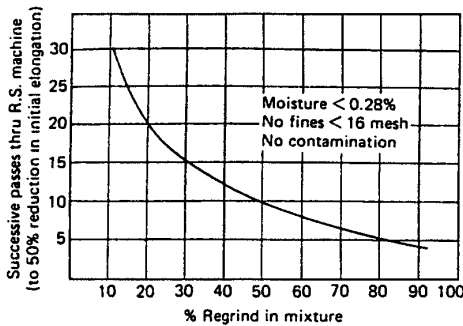


Fig. 6-76 Rework stability of regrind and virgin mixtures.

The amount used should be established by the ratio of the weight of the sprue and runners to the weight of the parts. It is important that the regrind and virgin be mixed before molding and that a constant proportion of regrind be maintained.

Figure 6-76 shows the number of successive passes (in a screw-injection machine operating at normal conditions) that various blends of regrind to virgin can withstand before the as-molded elongation of nylon 66 is reduced in half (this corresponds to a drop from 60 to 30%). It is easily seen that as the percentage of regrind in the blend increases, the number of passes decreases.

Another practical way of looking at rework stability occurs when regrind is immediately fed back to the machine and proportioned to an exact sprue–runner/shot weight ratio. In this system, an equilibrium feed composition will be quickly attained.

For example, if a shot that is 50% sprue and runner is recycled with virgin resin, a condition rapidly exists in which 25% of any shot will have been through the machine one time; 12.5%, two times; 6.25%, three times; 3.12%, four times; etc. Based on experimental data, this composition will have an as-molded percent elongation of 50% (vs. 60% if only virgin resin were used). An 80% regrind/20% virgin blend will yield on immediate recycle an elongation of 35% (vs. 60%), whereas a 20% regrind/80% virgin yields 58% (vs. 60%). Thus, using less than 50% regrind and recycling immediately results in minimal reduction in elongation. Runner

layout should be designed with the weight ratio (to total shot weight) in mind whenever possible.

ABSs (Acrylonitrile-Butadiene-Styrenes)

Like other major plastics (PE, PVC, PS, etc.), there are many grades of ABS available (233). Each grade is tailored to provide a given property balance. This allows the finished product designer considerable freedom in selecting a particular grade to meet all the requirements of processing, end-use demands, and cost effectiveness. However, overall success depends not only on selecting the correct ABS grade but also on being aware of how molding conditions can affect the mechanical properties and appearance of the finished article. In some situations, the effects can be considerable. For example, on a general-purpose ABS grade, by varying four molding parameters over typical commercial practice ranges, the cross-flow Izod impact ranged from a low of 2 (10.7) to a high of 8-ft pounds per inch (42.7 N · m/m). The direction of flow is also important; the Izod broken *with* flow can be as low as 0.5 when the wrong molding conditions are used. Finally, position on the part can also influence a property such as impact; values can be significantly different near the gate compared to 12 in. (30.5 cm) downstream.

In short, it is just as important to pick the correct molding condition as it is to select the right polymer; both are critical in defining the part properties. Tradeoffs are inevitable when dealing with a complex operation such as injection molding. Numerous variables influence the end results, and some variables interact.

Molding Variables and Cause-and-Effect Links

To understand cause-and-effect links, it is helpful to consider the following relationships: *Machine settings* affect *molding variables*, which influence *cause-and-effect variables*, which determine *part properties* to determine *cause-and-effect links*. Let us look

at each of these four elements in more detail. Notice that a distinction is made between machine settings and molding variables.

Machine settings are such things as:

- Cylinder temperature settings
- Screw rpm and back pressure
- Plunger injection speed
- Absence or presence of a cushion
- Hydraulic pressure during injection and hold
- Boost and hold time
- Mold temperature controller settings

Molding variables are more specific parameters than machine settings. They are related to machine settings, but sometimes in a nonobvious way. They include

- Melt temperature in the mold
- Melt front velocity in the mold
- Cavity melt pressure
- Mold surface temperature

The distinction between machine settings and molding variables is a necessary one if we are to avoid mistakes in using cause-and-effect relationships to our advantage. It is molding variables, properly defined and measured, not necessarily machine settings, that can be correlated with part properties. For example, if one increases cylinder temperatures, melt temperatures do not necessarily also increase. Melt temperature is also influenced by screw design, rpm, back pressure, and dwell times. It is much more accurate to measure *melt* temperature and correlate it with properties than to correlate cylinder settings with properties.

Another example concerns injection rate. A ram speed of 1 in./sec (2.54 cm/sec) in a 3-in. (7.6-cm)-diameter cylinder will produce a much faster mold fill rate than in a 2-in. (5.1-cm) unit. It is the local melt front velocity in the mold that directly influences properties. Cavity geometry also affects fill rates; thick sections fill more slowly than thin ones. Single-gated molds have local melt front velocities that are faster than with two gates. Thus, although it is not always easy to measure molding variables directly without special instrumentation, one does need to be aware of what is really being influenced (or not) when a machine condition is changed.

What are the cause-and-effect links that tie molding variables to part properties?

- Orientation
- Polymer degradation
- Free volume, molecular packing, and relaxation
- Cooling stresses

The most influential of these four is polymer orientation, often erroneously called molded-in stress (or strain). Orientation warrants some elaboration; it will be covered in the next section, after a few comments on the other three cause-and-effect links.

Polymer degradation can occur from excessive melt temperatures, or abnormally long time at temperature (i.e., heat history). Very high shear rates can also be a cause. Conditions that create degradation are cylinder, nozzle, and hot-runner heaters set too high and high screw rpm—especially in combination with high screw back pressure. Also look for high melt residence times; shot size too small for the machine capacity; and hangup areas in the barrel end cap, nozzle, tip, and hot-runner system. Excessive shear can result from poor screw design, too much screw flight to barrel clearance, cracked flights, restrictive check rings and nozzles, and undersized runners and gates.

Free volume relates to the spaces surrounding polymer chains that affect the mobility of the chain segments and their ability to relax. Packing pressure and the rate of cooling in the mold can affect relaxation to influence the unannealed heat deflection temperature and elevated temperature dimensional stability.

Stress, commonly called molded-in stress or strain, is a catch-all term frequently misused as being the cause of many molding variable–property problems. Stress is a totally different condition from orientation, yet many wrongly use the terms interchangeably. Stress is caused by either improper mold packing or from the inherently uneven cooling of the part in the mold after fill is completed. Generally, cooling stresses result in the surface of the part being under compressive stress while the core is in tension. It is entirely possible to have a section of a molded part oriented in the flow direction, but in a compressive stress. This illustrates that

residual stress and orientation are fundamentally different concepts. On a molecular level, stress is the result of the short-range deformation of molecules at bonds between atoms.

Molding Variables and Property Responses

With this background on what affects what, and why, we can now summarize some generalizations about molding variable and property responses. As mentioned before, these generalizations have been gleaned from commercial experience and laboratory experiments. They hold true frequently enough to be useful as guidelines for part design, machine operation, and troubleshooting. However, contrary behavior can be observed in a particular isolated case from time to time. Processing technology has not yet advanced to the point where every aspect of what goes on in a machine or mold can be predicted with 100% accuracy.

The following graphs do not have values on the axes; they are *qualitative* responses only. The absolute numbers vary with each grade of ABS. The slopes of the curves and accompanying text do attempt to indicate whether the response is strong or weak. Also, references lead the reader to articles that contain actual data illustrative of how much a property can vary in a given case. Some of the curves are “envelopes” because responses can vary qualitatively, depending on the particular brand or grade of ABS in question. Also, on some graphs, the “normal” operating range for a molding variable is indicated on the horizontal axis by a shaded bar to highlight responses that occur below and above this range.

Appearance Properties

Splay Splay (splash marks or silver streaks) is most often caused by bubbles in the melt coming from moisture, trapped air, and degradation gases. Proper predrying can avoid moisture-related splay. Improper screw design, insufficient screw back pressure, large polymer granules, high screw rpm, and the use of screw decompress can cause splay because of trapped air.

Degradation splay comes from excessive melt temperatures and/or long residence times in the cylinder, high nozzle temperatures, and excessive shear. Too much shear can result from:

- Poor screw designs that cause melt temperature override
- Cracked screw flight or nonreturn valve
- High screw rpm
- Excessive screw back pressure
- Restrictive runners and gates
- Very fast injection rates

Splay can also be packed out to various degrees, depending on the root causes, tool design, and machine conditions. Some machine conditions that enhance packout unfortunately aggravate gas bubble generation during cavity flow. The net results are not always easy to predict. If we assume that the nozzle and mold flow channels are properly designed, faster fill usually yields less splay. (See Fig. 6-77a.) This is so because the time is shortened for bubble growth, and fast fill enhances packout. Elevating melt temperature, although it often can also help packout, almost always results in more splay (Fig. 6-77a). Higher melt temperatures cause more bubble formation since the melt is less viscous and the pressure inside the bubble greater. So, depending on circumstances, at high melt

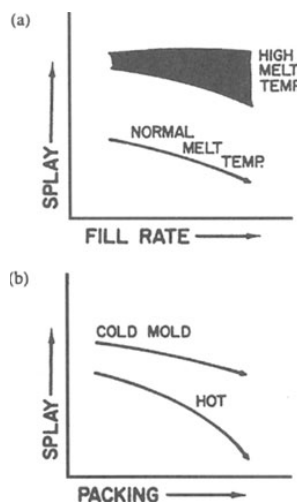


Fig. 6-77 (a) Effect of fill rate on splay. (b) Effect of packing on splay.

temperatures, faster filling can either decrease or increase splay. It will increase if the fast fill pushes the melt temperature too high from shear heating.

Figure 6-77b shows that increased packing can reduce net splay; this is most effective at high mold temperatures. Packing out splay is a “limp along gesture”: It is better to get rid of the root cause of the bubbles so that packout is not required. Packout should not be resorted to on parts to be electroplated or painted, or those that will be exposed to hot water or solvents.

Gloss The melt front that rolls out to define the part surface is inherently lumpy on a microscale because ABS contains two phases, one more deformable than the other. Optimizing gloss depends on pressing this lumpy “virgin” surface against the highly polished mold surface. Although one might expect high melt temperatures always to favor higher gloss, in most cases the opposite is true—especially with a cold mold. (See Fig. 6-78a.) Some ABSs are less sensitive so the response is flatter. It is also possible to have the melt so cold that low gloss will result because packing is hampered. The total response is then a humpback curve.

Mold temperature has a strong effect on gloss. Cold molds [under 140°F (60°C)] reduce achievable gloss and also make gloss more sensitive to the other molding variables. Higher mold temperatures [150 to 180°F (66 to 82°C)] promote gloss and flatten out the melt temperature effect.

Faster filling usually helps gloss, provided that the melt is not oversheared in restrictive runners and gates. The response to fill rate is greatest at low mold temperatures. (See Fig. 6-78b.)

Surprisingly, increasing packing pressure beyond that needed to make a good full part does not always have the strong effect one might expect. The packing pressure effect can be weak and interact with the mold temperature (see Fig. 6-78c). Cases have been noted in which overpacking decreased gloss.

The best gloss is obtained with moderate melt temperature, “upper limit” mold temperature, fast fill, and sufficient but not

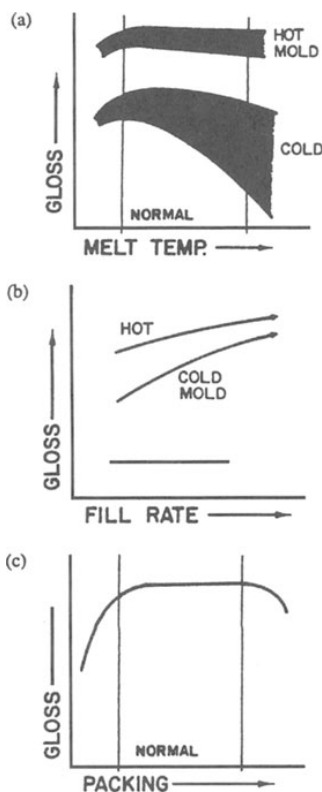


Fig. 6-78 (a) Effect of melt temperature on gloss. (b) Response of gloss to fill rate versus temperature. (c) Effect of packing on gloss.

excessive packing. Since hot molds trade off quick cooling for fast cycles, it is wise not to use higher mold temperature than is needed. By manipulating these four molding conditions, it has been shown that gloss values from 98 to 20% can be achieved on the same grade of ABS—the effects are that pronounced.

Warping

Molded parts can warp under no load conditions at elevated use temperatures for a number of reasons. One should also be aware that warpage is more likely to occur at high humidity (i.e., warping tendencies are greater in hot humid conditions than in hot dry ones). Both molded-in core orientation and cooling stresses can cause parts to warp.

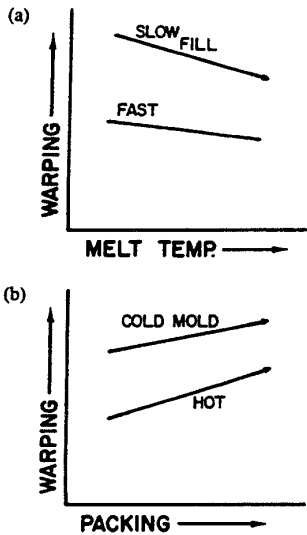


Fig. 6-79 (a) Effects of fill rate and melt temperature on warping. (b) Effect of mold temperature and packing on warping.

Elevating the melt temperature reduces molded-in orientation, thus reducing the tendency to warp. Faster filling also reduces core orientation and consequently also generally reduces warping. The combined responses are shown in Fig. 6-79a.

Colder molds create more warping tendencies in several ways. There is less opportunity for relaxation of orientation, and the more rapid cooling sets up unwanted cooling stresses. Increased packing also creates more stresses, inhibits relaxation, and lowers unannealed heat deflection temperature. (See the section on HDT.) Packing and mold temperature effects are shown in Fig. 6-79b.

To minimize warping, mold at the upper limits of melt temperature, mold temperature, and fill rate. Use only enough packing pressure to obtain a good full part.

Mechanical Properties and Molding Variables

Tensile strength and modulus Tensile modulus is not significantly affected by any of the four molding variables. Tensile *strength* is primarily influenced by orientation; parts are

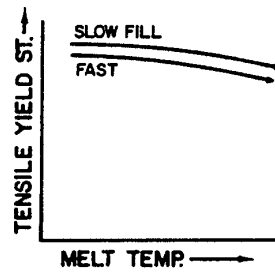


Fig. 6-80 Effects of fill rate and melt temperature on tensile strength.

stronger in the oriented direction. There is also some indication that heat history has a deleterious effect. In contrast to impact properties, tensile property effects are of a lower order. Figure 6-80 shows the important qualitative responses.

Quantitatively, the tensile yield strength at room temperature might drop 5 to 10% of the nominal value over a typical molding condition range as one goes from cold melt—slow fill to hot melt—fast fill. Mold temperature and packing pressure have no significant effect.

Flexural strength and modulus These properties respond to molding variables similarly to tensile properties, so the above-mentioned comments apply.

Flexural creep The limited data available indicate that molding variables have no significant effect on flexural creep.

Heat deflection temperature Studies have shown that unannealed and annealed HDT respond somewhat differently to molding variables. The unannealed HDT (UA-HDT) is affected by packing pressure and mold temperature. No effect due to melt temperature or fill rate has been noted. Attempts to correlate UA-HDT with orientation or cooling stresses have been unsuccessful. This is interesting in view of the well-known fact that annealing normally increases the HDT value by as much as 40°F (22°C).

Figure 6-81a shows that overpacking the mold can result in a loss of 10 to 15°F (6 to 8°C) in UA-HDT. Also, cold molds

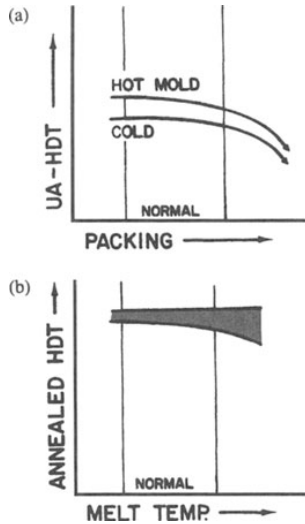


Fig. 6-81 (a) Packing and mold temperature effects on UA-HDT. (b) Effect of melt temperature on annealed HDT.

[80°F (27°C)] can reduce UA-HDT by 10°F. High packing and fast cooling inhibit molecular motion and hinder the preferred ordering of polymer molecules.

The annealed HDT, in contrast, is *not* influenced by packing pressure, mold temperature, or fill rate. Some data have been accumulated showing that as the melt temperature is increased, the annealed HDT is reduced, perhaps by 10°F (Fig. 6-81b). This effect is not always consistent and might depend on the exact ABS grade in question.

Izod impact

Notched Izod impact is strongly influenced by orientation, and the molding variable responses reflect this. Since orientation is directional, it is necessary to be specific about the direction of break relative to the flow direction. Orientation can be beneficial when Izod is being broken *across* the flow (bAf). However, this same orientation weakens the part when broken *with* flow (bWf). It is possible for the bAf value to be two to five times greater than the bWf value. Some applications benefit by having as much impact in

one direction as possible; the other direction is unimportant. Other applications require uniform impact (i.e., no directional preference). Molding variables can be manipulated to achieve either result to some degree.

Melt temperature affects Izod impact through two possible mechanisms. Elevating melt temperature within the recommended range decreases the core orientation that strongly influences this property. This will cause bAf Izod to decrease while the bWf value increases. (See Fig. 6-82a.)

Not only do excessive melt temperatures yield even less orientation, they can also degrade the polymer. This reduces both bAf and bWf Izod impact. This is why the curves in Fig. 6-82a have a downward break above the recommended melt temperature range.

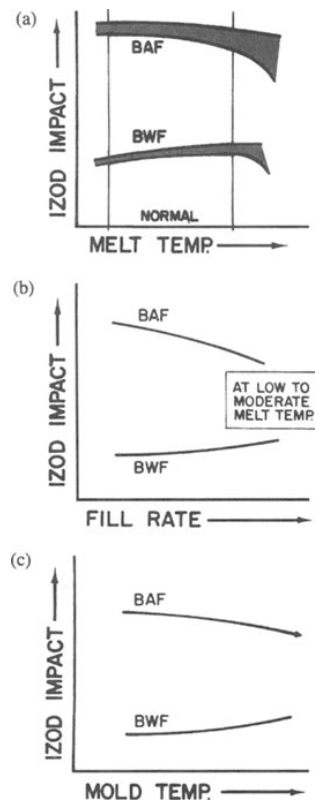


Fig. 6-82 (a) Effect of melt temperature on Izod impact. (b) Effect of fill rate on Izod impact at low to moderate melt temperature. (c) Effect of mold temperature on Izod impact.

Depending on their structure and stability, ABSs differ in their strength of response to melt temperature. Abusing the melt can cause several-fold reduction in Izod bAf. The bWf generally responds less strongly; it can be improved about 50% by increasing the melt temperature within the recommended range.

Faster filling decreases core orientation; consequently, the response is to reduce bAf Izod impact and increase bWf. At low melt temperatures, the fill rate effect can be 15 to 50% or more. At high melt temperatures, the fill rate effect diminishes considerably because melt relaxation tends to erase any fill-induced orientation. (See Fig. 6-82b.) Increasing the mold temperature also has the effect of reducing the difference between the bAf and bWf values by promoting slow cooling and improving melt relaxation. The mold temperature effect [i.e., 80 vs. 180°F (27 vs. 82°C) mold] is not quite so pronounced as the fill rate effect. The mold temperature effect is strongest at low *melt* temperatures and slow fill rates. (See Fig. 6-82c.) Packing pressure does not have a strong or consistent effect on Izod impact.

Weld line strength Weld lines, formed by the rejoining or colliding of two melt streams, are typically weaker than nonweld areas for several reasons. There is a sharp notch at the weld that acts as a stress concentrator. Trapped air between the fronts can interfere with proper knitting. Orientation in the weld area occurs at right angles to the principal flow direction and comes from the elongational stretching of the melt front. This orientation is also thought to contribute to the weakness of the weld. It is important to avoid trapped air at the weld, so proper mold venting is imperative. Information on the effects of molding variables is not abundant, but what does exist gives us the following general guidelines.

Increasing both melt and mold temperature will frequently improve weld line strength. (See Fig. 6-83a.) Higher melt temperatures promote molecular knitting and entanglement at the weld and also yield less net orientation. Consequently, one can try

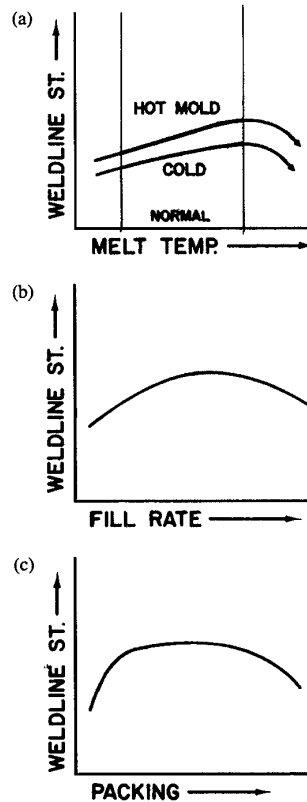


Fig. 6-83 (a) Effects of melt and mold temperature on weld line strength. (b) Effect of fill rate on weld line strength. (c) Effect of packing on weld line strength.

elevating melt temperature within the recommended limits. Excessive melt temperatures will degrade the polymer causing a general weakness, including weakness at the weld. For this reason, the melt temperature curves in Fig. 6-83a turn over above the recommended limit. Mold temperature elevation also helps because it promotes slow cooling, there is more time for packing out the weld notch and allowing the molecules to entangle, and more of the orientation relaxes away. However, in most cases, the mold temperature effect, though positive, is not so pronounced as the melt temperature effect. Fill rate and packing pressure effects can be complex because of competing behavior and interactions. Because of these tradeoffs,

changing the variables can some-times have no net effect, or they might go through a maximum. Exactly what happens can also depend on the particular grade of ABS, part design, and melt and mold temperature levels.

Increasing the fill rate, on the one hand, can promote knitting via the same mechanism as elevating the melt temperature. Fast fill will generate some heat, as well as minimize mold cooling during flow. On the other hand, fast fill can create more undesirable frontal orientation and aggravate venting problems, thus causing weld line weakness. (See Fig. 6-83b.)

Insufficient packing obviously can create more prominent and weaker welds. However, overpacking can also contribute to weaker welds by two mechanisms. Overpacking creates a sharper notch, which simply increases the stress concentration under service conditions. Also, overpacking hampers melt relaxation and molecular entanglement (knitting). Figure 6-83c summarizes the probable situation.

There is an optimum packing pressure and fill rate that will depend on particulars relevant to each part design. When troubleshooting, one can try going in both directions on these two variables and carefully noting the property response. Neither response is expected to be as strong as with melt or mold temperature changes. Also, it should be realized that while manipulating these variables can improve welds to some degree, it is not likely that they can produce weld lines as strong as nonweld areas.

Missile impact The response of falling dart impact (FDI) to molding variables can be significantly different in some respects when compared to bAf Izod impact. In the case of bAf impact, molded-in core orientation *increases* the impact. By contrast, orientation is almost always harmful to FDI because there will be weakness in the cross-flow direction. The FDI test causes biaxial deformation, and the part will be no stronger than the weakest direction—the high strength in the flow direction is of no help.

Generally, the rule is to manipulate molding variables to minimize orientation with-

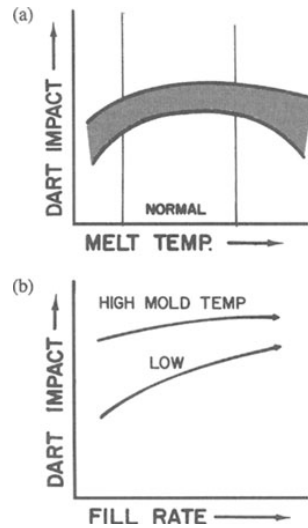


Fig. 6-84 (a) Effect of melt temperature on FDI. (b) Effect of fill rate on FDI at low and high mold temperatures.

out causing degradation. This means elevating melt temperature within the acceptable range. The heat stability of individual ABS grades will vary; some can tolerate increased melt temperature more than others before degradation takes away the gains made from decreased orientation. As a result of all these factors, the response is shown as an envelope (Fig. 6-84a).

An elevated mold temperature promotes the relaxation of orientation and usually interacts significantly with fill rate. Changing fill rates has the most effect at low mold temperature (Fig. 6-84b). Quite often, packing pressure has no effect on FDI. When an effect due to elevating packing pressure has been noted, it has almost always been detrimental. This has been especially true in combination with low melt and low mold temperature and slow fill. Experiments and commercial practice have uncovered situations where overpacking has reduced FDI to half the optimum value. Overpacking increases net orientation and could possibly upset the cooling stress balance to put the surface in tension, rather than the usual compression. Both these conditions would be expected to reduce FDI.

Molding for Electroplating

Appearance, plate adhesion, and dimensional stability are all key quality factors when molding for electroplating. From a molding variable optimization standpoint, plating represents one of the most challenging cases because of tradeoffs and competing factors. For example, some molding variable settings that optimize plate adhesion are not the best choice for suppressing splay or part warping tendencies. Usually, parameters are selected that give the best plate adhesion and thermal cycle performance. It is from this aspect that the following discussion is structured.

If we assume that the preplating and plating steps are properly carried out, the adhesion of the plate to the ABS is mainly determined by the strength of a thin layer of ABS just underneath the plate. Low adhesion and plate blistering seldom involve clean separation of the plate from the ABS. Rather, there is a delamination of ABS from itself in the boundary layer. The boundary layer is conditioned by the orientation coming from the melt front. To optimize the strength of this critical layer, it is desirable to minimize the orientation there. As shown in Fig. 6-85a,

the two key variables are melt temperature and fill rate. Slow fill rates should be used to minimize surface orientation and promote a strong ABS boundary layer for the plate to lock into. However, here is a good example of one of the aforementioned compromises. One might also want to minimize part warpage, since twisting or bending of the plated part could build up stresses that would pop or crack the plate. As mentioned earlier, warpage is minimized by filling fast, since it puts orientation on the surface rather than in the core. Fortunately, there is a reasonable way out of the situation. High melt temperatures favor relaxation of orientation, especially core orientation coming from slow fill. Thus, one should use the high end of the melt temperature range without going so far as to degrade the polymer, causing splay or poor part appearance. The proper selection of fill rate and melt temperature can increase plate adhesion by 50% or more.

Mold temperature and packing pressure have a lesser effect. High mold temperatures will help to reduce orientation, especially core orientation coming from the required slow fill. Packing pressure should be sufficient only to obtain a full, good-looking part. Overpacking retains unwanted orientation and can build up unfavorable stresses. The mold temperature and packing responses are shown in Fig. 6-85b.

Property Variation with Position
Mold Geometry

The key molding variables of melt temperature, melt pressure, and fill rate are seldom the same point to point in the cavity. The first two particularly vary in the flow direction. The local velocity can vary in the flow direction even in a simple part, and in the cross-flow direction as well as in complex ones. Local velocity is also affected by local thickness. Even mold surface temperature is seldom the same at each point in the cavity. Since these parameters vary point to point in the mold, their influence on properties does likewise. Indeed properties such

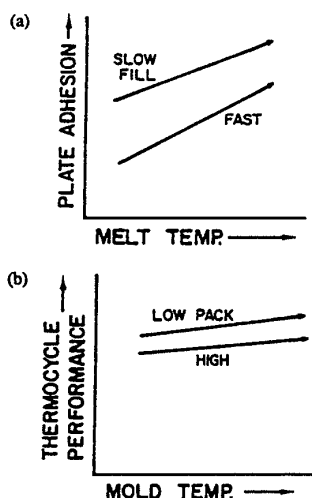


Fig. 6-85 (a) Effect of melt temperature and fill rate on plate adhesion. (b) Effect of packing and mold temperature on thermocycle performances.

as impact and electroplate adhesion do vary across and down the part flow path.

Summary

Many property versus position effects and possibilities can exist. A few key examples will make the point that the processor needs to be aware of this phenomenon.

Orientation is usually greatest at the gate end of the part and gradually lessens toward the end of the flow path. As a result, Izod impact bAf will be higher at the gate end but lower at the dead end. Falling dart impact, because it suffers from uneven orientation, is less at the gate and higher at the end of flow.

On a 4-in. (10.2-cm) wide slab, over a 15-in. (38.1-cm) flow length from the gate, the Izod impact bAf dropped by half while the FDI *increased* fourfold! This example illustrates another point: Molding variables, whether machine- or position-induced, can cause one property to increase while another falls off. Injection molding process control is full of such tradeoffs. Even seemingly minor perturbances on the mold surface, such as knock-out pins, part coding numbers, or embossing, can produce surface orientation anomalies. These can affect properties that are sensitive to surface orientation; a good example is electroplate adhesion. It has been shown that scribing lines 0.005 in. (0.013 cm) deep in one mold surface crosswise to flow can reduce surface orientation on the noncorresponding part surface. With this technique, one can locally improve plate adhesion.

Polycarbonates

Commercial grade polycarbonate is a linear polyester of carbonic acid in which the carbonate groups recur in the polymer chain. This engineering thermoplastic is based on bisphenol A and has an aromatic structure. A product of the reaction of the sodium salt of bisphenol A with phosgene, its rigid aromatic rings coupled to the methylated carbon atom provide the polymer with its engineering properties. Although the linear polyesters may contain aliphatic, aliphatic-aromatic, or

aromatic constituents, it is the aromatic type that is best recognized as polycarbonate. It is this structure that is responsible for the high softening temperature, broad temperature usage, rigidity complemented by toughness, resistance to creep, and other important properties.

Polycarbonate is basically an amorphous polymer and therefore transparent. Although there are some grades of lower-molecular-weight polycarbonate that can be specially processed into a semicrystalline state, it is the amorphous polymer that is of the greatest commercial interest.

Although most basic grades of polycarbonate are linear polymers, polycarbonate can be produced with a limited degree of short chain branching that dramatically affects the low shear viscosity of the melt. The branched grades are generally used for extrusion although they have shown some application to injection molding where mold design and its effect on melt rheology have been taken into consideration.

Polycarbonates that are suitable for injection molding generally fall into the average molecular weight range of 26,000 to 35,000. Molecular weights higher than the upper limit of this range tend to be difficult to process because of high melt viscosity. Basic-grade polycarbonate is typically available in three molecular weight grades: low, medium, and high. Since the viscosity increases as molecular weight does, the molding application may dictate grade selection.

Drying

Similar to other polyesters, polycarbonate is hygroscopic and will absorb moisture from its surroundings. This characteristic often proves detrimental to the physical properties of the material when processing at high moisture levels. The result is a chemical reaction between the polymer and water that reduces the molecular weight of polycarbonate. As discussed later, this can have profound effects.

To ensure retention of engineering properties, moisture should not exceed 0.01% in

Table 6-45 Properties of 100% PC regrind

Material: Property	Regrind History			
	Virgin	1st	2nd	3rd
High molecular weight: Natural				
Melt flow rate (g/10 min)	4.6	4.9	5.0	4.9
3.2 mm izod notched impact (J/m)	956	945	935	950
Yellowness index	2.8	4.8	7.3	10.1
Low molecular weight: Natural				
Melt flow rate (g/10 min)	15.2	15.2	16.2	16.0
3.2 mm izod notched impact (J/m)	820	880	810	820
Yellowness index	1.8	3.5	5.1	6.6
Flame-retardant: Natural				
Melt flow rate (g/10 min)	11.7	12.2	13.0	14.9
3.2 mm izod notched impact (J/m)	110	105	95	100
Yellowness index	3.8	5.0	6.8	8.5

the pellets. Since the equilibrium moisture content at 23°F (−5°C) and 50% relative humidity is 0.18%, drying in desiccant hopper dryers or forced convection ovens will be necessary. Although equilibrium moisture levels may be low, the polymer retains the water tenaciously as drying is diffusion-controlled. Hence, delivery air must be supplied from the desiccant unit to the hopper at −18°C dewpoint and 120°C. Drying may be accomplished in shallow trays using forced convection ovens operated at 120°C and with a fresh air makeup of 10%. In this case, pellet depth should be limited to 1½ in. In either case, oven or desiccant hopper dryer, hot air contact time with the pellets should be 4 h.

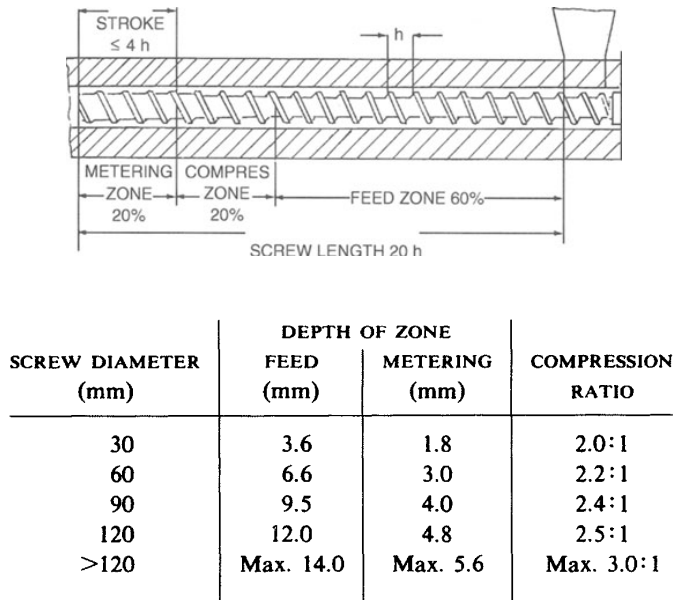
Recycle and Virgin Proportions

Regrind usage is a concern for any injection molder with an eye on profit. Maximum utilization must be made of every pound of resin, particularly when engineering thermoplastics are involved. Scrap generated in the injection molding of polycarbonate may be regrind and blended with virgin material and used successfully if certain precautions are observed.

The proportion of regrind blended with virgin resin will be influenced primarily by the shear and thermal histories of the melt.

Long residence times in the barrel in combination with high melt temperatures may result in an increase in melt flow rate and subsequent change in physical properties. The sensitivity of these properties to processing also depends on the grade of polymer. Table 6-45 compares physical properties according to regrind history for three different polycarbonate grades: two natural grades of different molecular weight and a flame-retardant grade. In comparing the change in melt flow rate, natural grades appear less sensitive to change than the flame-retardant or specialty type. In natural grades, higher melt flow rate material is slightly more sensitive to melt flow rate change than material with a lower melt flow rate. The most notable change in property occurs in the yellowness index, which is observed in all three grades. As pigmentation and other additives are introduced, physical properties would be expected to be influenced even more by regrind history.

In regard to retention of mechanical properties, the highest probability for successful regrind use will be found with high-molecular-weight natural polymer. In this case, color may be the discriminating factor. In certain applications, the use of 100% one-time regrind may be acceptable, whereas a recycle stream of 25 to 30% regrind could prove detrimental to physical properties because of the regrind history distribution of the stream.



SCREW PITCH

$H = 1.0 D$ for Screw Diameter < 80 mm

$H = 0.9 D$ for Screw Diameter > 80 mm

Fig. 6-86 Typical screw design for IM PC.

The general recommendation of 20% regrind loading has been found to be suitable in most cases.

In certain applications, regrind usage is discouraged. High-quality optics demand stringent color and transmission standards that can be met by special grades of polycarbonate. Regrind blending of these grades, however, risks the loss of their excellent optical properties.

Processing

The injection molding of polycarbonate does require some special capabilities of the processing equipment. Because of its high viscosity, polycarbonate is usually processed at a high temperature to obtain a less viscous melt. This requires barrel temperature capability of up to 350°C. Even at such reduced viscosity levels, a high-molecular-weight polycarbonate will require higher injection forces than lower-molecular-weight

resin to fill certain part geometries. Therefore, injection molding equipment suited to processing polycarbonate should be capable of at least 138-MPa injection pressures.

Suggested screw designs for polycarbonate are illustrated in Fig. 6-86. (See also Chap. 3). Here a metering-type screw is depicted. A generous feed length should be allotted to solids transport and melting. A rapid transition in the compression zone is not recommended, owing to the viscous nature of polycarbonate. Such a sudden compression could result in overloading of the screw or drive motor if melting were incomplete when the plastic entered this zone. In such a case, the high modulus of the pellets would create a sufficient resistance to deformation to cause degradation of the polymer and seizure of the screw. The screw pitch recommended for screws of diameter less than 80 mm is 1.0 D (0.9 D for a diameter greater than 80 mm).

Minimum screw L/D is 15:1, and as indicated in Fig. 6-86, the compression ratio should be 2:1 for small screws, increasing to

2.5:1 to 3:1 for the larger diameters. The increase in the compression ratio for larger diameters enhances back mixing of the melt, which tends to offset the reduced efficiency of a deeper feed section.

A shutoff valve, normally required, should provide good flow characteristics.

Hydrolysis

When problems with performance or cosmetic features of polycarbonate are recognized after molding, the chances are very good that the cause was improper drying prior to molding. For this reason, drying should be given the highest degree of consideration when approaching the molding of polycarbonate. As will be discussed later, other process factors are of concern, but few are as important as drying.

Often, the effects of inadequate drying emerge as visual defects in the molded part. The most common evidence in natural resins is the presence of silver streaks on the surface. If the moisture level is high enough, small bubbles may be seen in the body of the part. This is a result of the vaporization of retained water and/or the generation of a gaseous degradation by-product, carbon dioxide. Visual identification of a "wet" polymer is, of course, subject to the limit of solubility of the gases in the resin, which is controlled by injection pressure and part geometry. In light of this, the visual detection of moisture levels in excess of 0.06% moisture has been possible in some moldings.

Rheology

Selecting the proper molecular weight of polycarbonate will depend not only on the performance requirement but also on the degree of difficulty in filling the cavity. Figure 6-87 describes the cavity-filling capability in terms of the flow length versus part thickness relationship for polycarbonate. At a given part thickness, a lower-molecular-weight polymer will have a longer flow length than a higher-molecular-weight polymer. The difference becomes even more

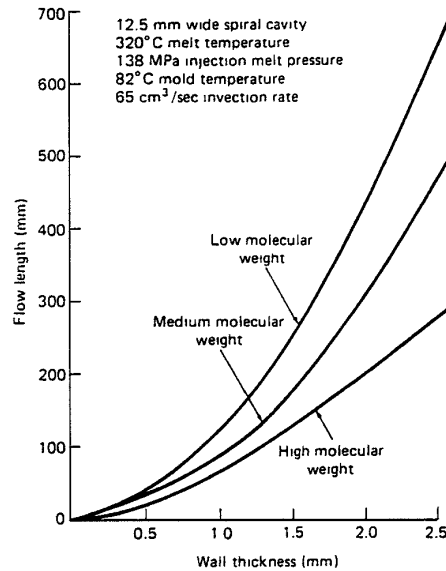


Fig. 6-87 Spiral flow comparison of PC typical of the three molecular weight ranges.

acute as part thickness increases. These data were obtained at constant molding conditions. In order to assess the flowability of the polymer, one must consider the effect of the main processing variables.

Heat Transfer

Although melt temperatures may be high (280 to 340°C) for the injection molding of polycarbonate to reduce viscosity, the high glass transition temperature of 150°C promotes short cooling times. In addition, the thermal diffusivity of polycarbonate is high in comparison to other polymers found in injection molding applications. Table 6-46 illustrates the thermal diffusivity of a number of polymers including polycarbonate. The defining relation for one-dimensional unsteady-state heat transfer is as follows (6):

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}, \quad \alpha = \frac{k}{\rho C_p}$$

where T = temperature

t = time

x = thickness

α = the thermal diffusivity

Table 6-46 Comparison of thermal diffusivities of various plastics

Polymer	Thermal Diffusivity ($\times 10^{-4}$ sq cm/s)
Polycarbonate	10.03
PBT	9.21
Nylon 6, glass-reinforced	8.86
CAB foam	8.48
Polystyrene	7.73
ABS	7.43
SAN	7.30
Nylon 6, unreinforced	6.94
Polypropylene	5.88

For a fixed part geometry, the cooling rate of the polymer is completely defined by α . The larger the value of α , the higher the cooling rate. High glass transition temperature and large thermal diffusivity allow for the fast cycling of parts injection-molded of polycarbonate.

Figure 6-88 illustrates typical cooling times as a function of wall thickness for specific

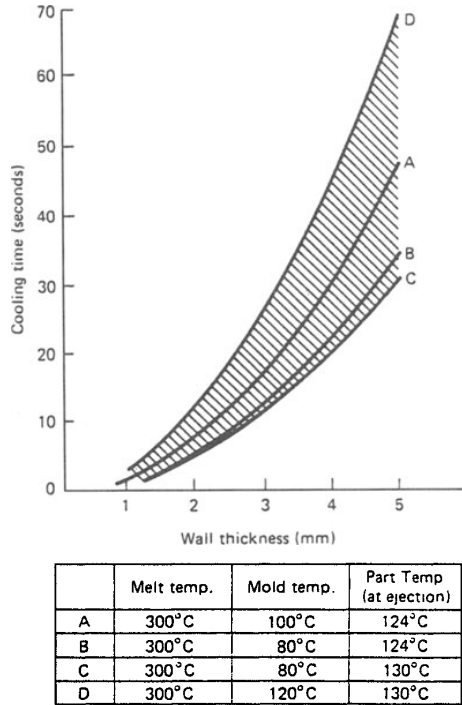


Fig. 6-88 Cooling time versus wall thickness for polycarbonate.

melt, mold, and part temperatures. Cooling time increases with the square of the thickness for any given temperature condition. At a given thickness, low mold temperature and high part temperature at ejection reduce cooling time. In addition, at a given thickness, since cooling time is proportional to the logarithm of the temperature conditions a linear change in mold or part temperature does not promote a corresponding linear change in cooling time.

The cooling curves were generated by the following relation:

$$t = \frac{x^2}{\alpha \pi^2} \ln \left[\frac{8}{\pi^2} \left(\frac{T_m - \bar{T}_w}{\bar{T}_p - \bar{T}_w} \right) \right]$$

where

$$\bar{T}_w = 0.5 \left(\frac{b_w T_w + b_m T_m}{b_w + b_m} + T_w \right)$$

In the above relations, the following definitions apply:

- t = cooling time (sec)
- x = part thickness (cm)
- α = thermal diffusivity of polymer (sq cm/sec)
- T_m = melt temperature (°C)
- $\bar{T}_w$ = average mold wall temperature during injection cycle (°C)
- $\bar{T}_p$ = average part temperature (°C)
- b_w = thermal penetration number of mold (J/sq cm-sec^{1/2}-°C)
- b_m = thermal penetration number of polymer (J/sq cm-sec^{1/2}-°C)

The cooling equations apply to other polymers, as well as polycarbonate, and may be useful in estimating cooling cycle times.

Residual Stress

The performance of parts injection-molded of polycarbonate will depend not only on the grade (melt flow rate and presence of additive) of material but also on part design, environment, and processing conditions. The failure of a polycarbonate article can often be traced to high residual or “frozen-in” stresses in the part. These stresses result from nonuniform cooling of the part while in the mold. Residual stress may also be

promoted through overpacking of the mold cavity during injection hold. Thermally induced stresses occur when a given region cools more rapidly than its surroundings. Since shrinkage is temperature dependent, cooler regions shrink in advance of hotter areas, giving rise to a nonuniform stress distribution.

Annealing

Annealing can be employed to reduce the effects of residual stress, but this procedure is not recommended as an alternative to changes in effective processing variables such as mold temperature and injection hold pressure.

Annealing relieves molded-in stress but may result in a decrease in notched Izod impact strength and an increase in the brittle impact transition temperature. Figures 6-89 and 6-90 illustrate such changes when annealing is applied to the residually stressed, simple plate geometry described above. When the notched impact test adequately describes in-use behavior, the effects of annealing specimens can be anticipated; annealing increases the elastic modulus, initiates crazing after shorter periods of time at a given stress level, and can decrease ultimate elongation to as low as 10%. Thus, annealing a polycarbonate part generally cannot be recommended if the article is exposed to continuous loading of significant magnitude in practical use.

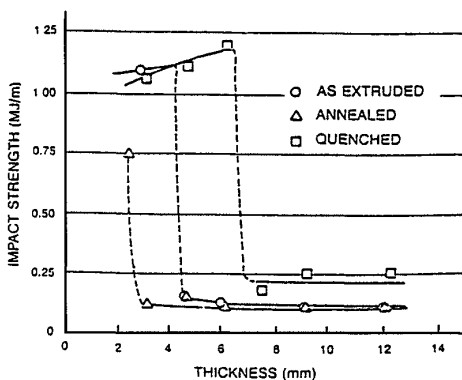


Fig. 6-89 Notched impact strength of PC as influenced by thermal treatment after processing.

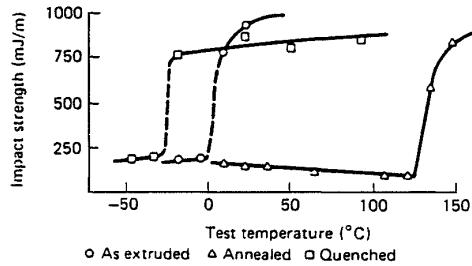


Fig. 6-90 Ductile-brittle transition of PC as influenced by thermal treatment after processing.

Injection Molding Thermosets

Different types of plastics are injection-molded. They range from commodity and engineering thermoplastics to reinforced thermoplastics and thermosets. As reviewed in different parts of this book, over 90% by weight of plastics processed through injection machines are thermoplastics. (See particularly Chap. 3 and the section, "Molds for TS Plastics," in Chap. 4.) There are similarities and also distinct differences in processing TPs and TSs. As reviewed at the beginning of this chapter, the curing characteristics of TSs require higher heat in the mold to complete the cross-linking (curing) of the TSs.

Thermoset injection molding uses a screw or plunger to feed the plastic through a heated barrel [usually at 120 to 275°F (49 to 135°C)] to decrease its viscosity. This melt is injected into a heated mold [usually 300 to 480°F (149 to 249°C)] (Chap. 2). Once the plastic fills the mold, it is held under pressure while chemical cross-linking occurs to make it hard. The hardened or cured part can be ejected from the mold while at an elevated temperature. Once this plastic hardens, it can not be remelted. However, the scrap can be granulated and used as filler material in plastic compounds. Figures 6-91 to 6-93 are examples of TS injection molding machines.

Most TSs are available in a granulated pellet or flake shape and can be fed from a gravity hopper into the screw injection unit. With TS polyester bulk molding compound (BMC), a stuffer ram feeder is used to move it into the plasticator. BMC is usually a TS polyester plastic mixed with strand glass fiber reinforcements that are usually $\frac{1}{4}$ to $\frac{1}{2}$ in.

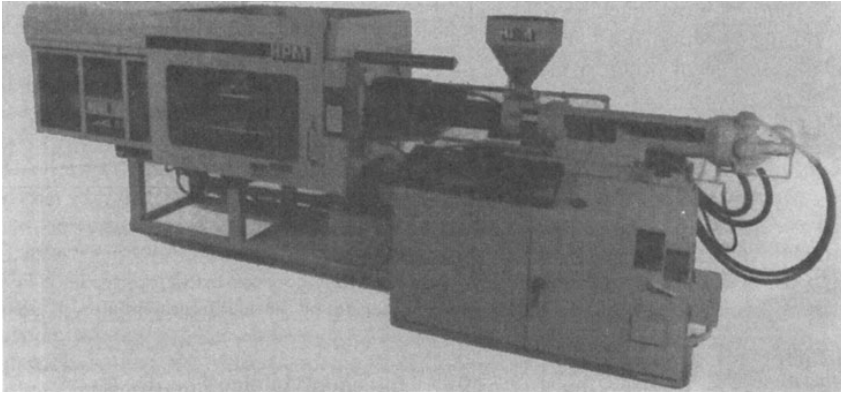


Fig. 6-91 HPM 300-ton clamp reciprocating screw injection molding machine for thermoset plastic processing.

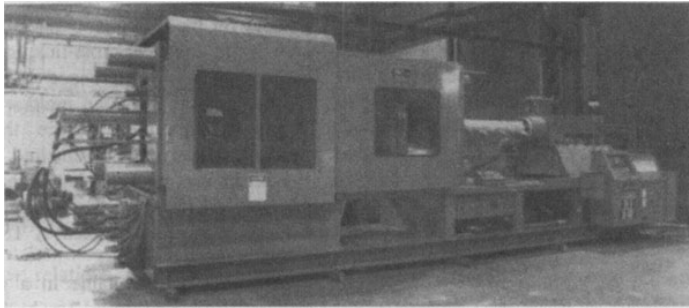


Fig. 6-92 Hull's 600-ton hydraulic clamp with reciprocating screw for thermoset plastic processing.

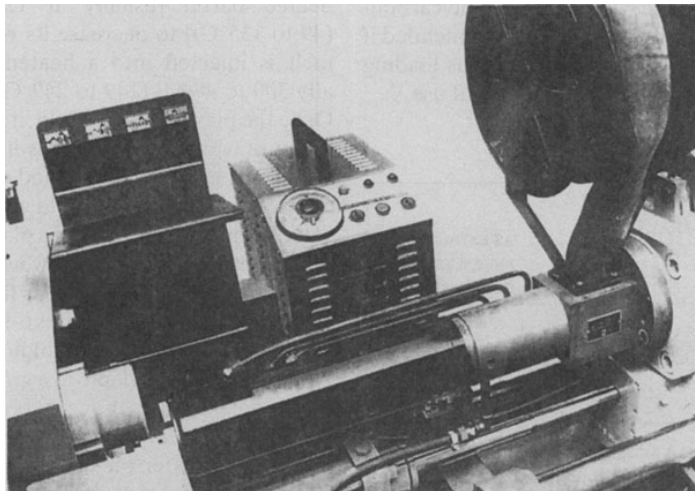


Fig. 6-93 Negri Bossi 12-80-ton FA molding machine equipped for injection molding of TS elastomers. Note the special barrel provided with a jacket that allows circulation of the conditioning fluid (heating and cooling control), and note on the right-hand side the support with its reel holding the band of elastomer to feed the barrel.

(0.6 to 1.3 cm) in length, fillers, and other additives into a viscous compound that resembles bread dough. Its preparation occurs with a sigma blade mixer. The compound is delivered to the processor in the form of a ball, a slab, or an extruded “log.”

The primary plastics used for injection molding (in order of their volume of use) are phenolic, polyester BMC, melamine, epoxy, urea, vinyl ester, and diallyl phthalate (DAP). Most of the thermoset materials contain high volumes of fillers (up to 70% by weight) to reduce their cost or increase performance, by reducing shrinkage, and increase strength or special properties. Common fillers include glass fibers, mineral fibers, clay, wood fibers, and carbon black. These fillers can be very abrasive and create high viscosity, which must be overcome by the process equipment (Table 6-11).

Process

TPs and TSs both exhibit a decreasing viscosity as they are heated. However, TSs increase in viscosity with time and temperature because of the chemical reaction of cross-linking. The combination of these effects results in a U-shaped viscosity versus time and temperature curve (Fig. 6-6). It is the aim of the TS injection molding process to operate the filling of the mold in the minimum viscosity region since the pressure needed to form the material to the mold shape is lowest. This also lessens damage to the fibers in the polymer.

The injection molding process uses a screw to move the material through a barrel heated with water or oil circulating through a jacket around the barrel (Fig. 6-94). Screws are designed for each type of material with slight

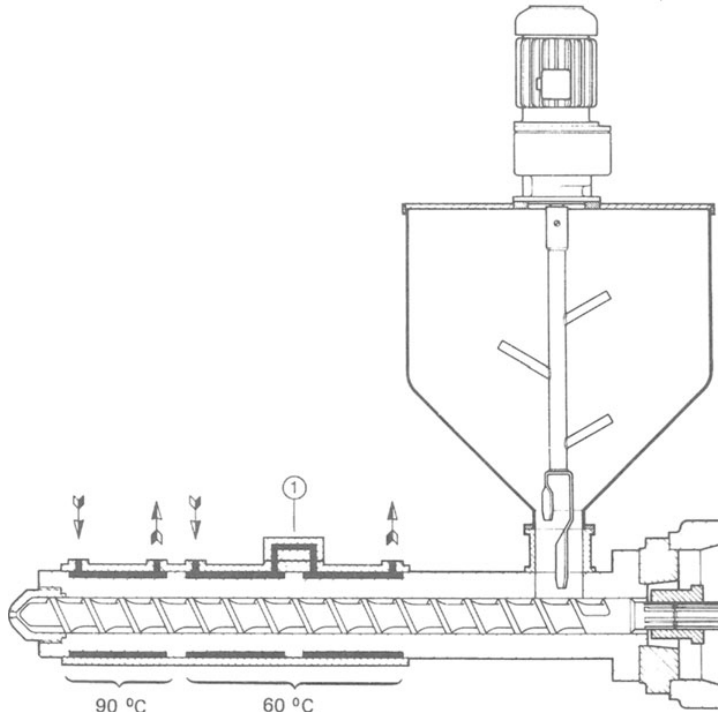


Fig. 6-94 Schematic of a Negri Bossi plasticizing barrel for thermoset plastics, heated by fluid circulation in two independent zones. By removing the manifold indicated by 1, the barrel can be heated in three zones.

compression to remove air and to heat the material to a low viscosity. Most thermoset materials are very fluid at this point so they do not require a compression ratio in the screw.

The injection of material into the mold is done by stopping the screw rotation and hydraulically driving it forward at high speed to force the plasticated, low-viscosity material into the mold (similar to TPs). This fast flow can call for material pressures to 30,000 psi (207 MPa) with cavity filling in 0.5 sec. The high velocity of material imparts more frictional heat to speed the chemical reaction once the cavity is filled.

Once the cavity is filled, injection pressure is reduced to a holding pressure of about 5,000 to 10,000 psi (34 to 69 MPa). This secondary hold pressure is retained on the material for about 5 to 10 sec, after which the pressure is released and plasticating begins for the next shot.

The material is held in the hot mold until it is rigid and then the clamp opens and the part is ejected. The part may be slightly uncured and somewhat flexible at ejection, with final curing happening in the 1 or 2 min after ejection from the retained heat in the part. The total cycle for injection-molded thermoset parts ranges from 10 to 120 sec, depending on the part thickness and material type.

There are many variations and special techniques used to improve part quality and consistency. Since some thermoset polymers generate gases as they are heated, a “breathing” cycle is often used after the mold is partly filled. In this step, the mold opens slightly to allow gases to escape and then is quickly closed and the remainder of the charge injected.

Injection compression (coining) molding will give higher strength, better dimensional control, and improved surface appearance. This is done by using a mold with a telescoping cavity and core so that the mold can be left open $\frac{1}{8}$ to $\frac{1}{2}$ in. (0.3 to 1.3 cm) during injection, followed by rapid compression as the mold is closed (Chap. 15 reviews coining).

BMC made from glass fiber, fillers, and unsaturated polyester resin can be injection-molded by adding special equipment to the

machine. A piston stuffer is attached to the barrel to force-feed it. Then it can be processed in two ways. One is with a conventional reciprocating screw to auger the material forward while mixing and heating. This requires a check valve on the end of the screw to prevent reverse flow over the screw flights since the viscosity is very low. The other process uses a plunger or piston to force the material into the mold cavity. The plunger is commonly used with materials that have glass fiber contents over 22% by weight, since less damage is caused to the fiber and higher strengths can be obtained.

Hot- and Cold-Runner Molding

In Chap. 4, runner systems and runners for TS plastics were discussed. The standard injection cold-runner molds for TSs are very similar to the standard injection hot-runner molds for TPs. Because one cannot grind and recycle the TS cold-runner system like the TP hot-runner system, there is always interest in reducing the amount of TS required to mold parts. Thus, the cold runner can be used so that the runner system does not solidify. However, TSscrap (runner, etc) can be granulated and used as filler in TSs and TPs.

Toward this end, molds may be designed to maintain thermoset material in a plastic state in the runner without ejecting it from the mold. This cold-runner technique is not too different from hot-runner thermoplastic mold designs, except that heated water is used to maintain a “runner” temperature of between 150 and 210°F (66 and 99°C) and cartridge heaters are employed to maintain proper cavity and force temperatures for curing. This type of mold is known as a cold-runner thermoset mold, or sometimes a “warm-runner” mold (Fig. 6-95). Parts may be separated from the runners right at the part surface; or short subrunners may be ejected with the parts, leaving most of the runner material in the warm manifold, to be used in the next shot.

A multicavity standard (hot-runner) injection mold for small thermoset parts may have 50 to 150% of the shot size in runner or waste

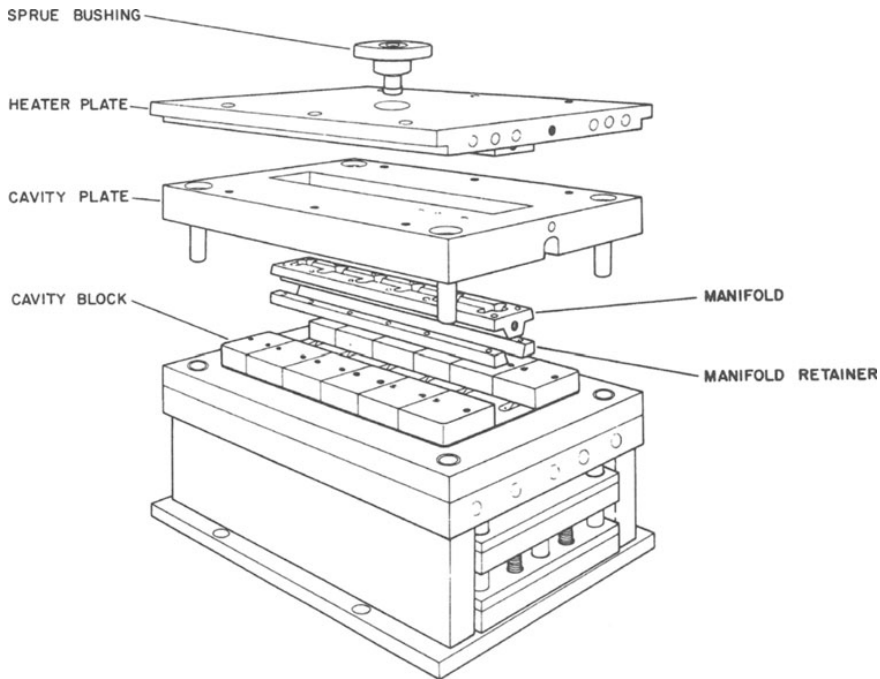


Fig. 6-95 Expanded view of a cold-runner manifold for TS plastic injection molding.

material. By using a cold-runner mold, this waste can be reduced to as little as 10% of the shot.

Material Stuffer

To process TS materials that are “dough-like” in handling, different techniques are used to move this type of material into the injection molding machine. Some machines use a single reciprocating screw system and others a two-stage screw plasticating system (Chap. 2). Regardless of the machine used, stuffers are generally required.

As an example, there are a number of injection molding machines specifically designed to handle thermoset polyester operations. All require stuffing cylinders because of the physical characteristics of the material. Most FRP is puttylike (BMC) or a fiberlike coated material, neither of which flows freely through normal hopper systems (Fig. 6-96).

On some machines, the material or compound is forced from the stuffer cylinder from

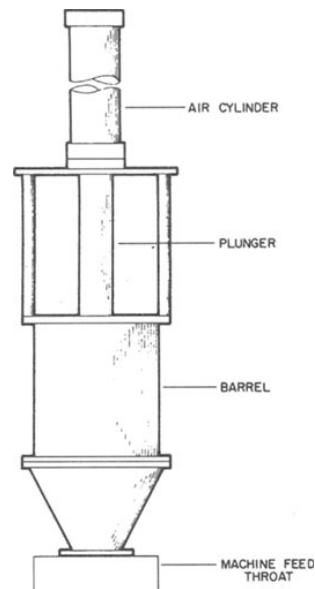


Fig. 6-96 Schematic of a material stuffer for BMC materials.

the top or side into the rear of a conventional screw injection cylinder. The screw acts only as a conveyor that moves the material to the front of the cylinder instead of providing a plasticating function. Then, the screw acts as a plunger. It does not turn as it pushes the material into the mold.

On other machines, a plunger instead of a screw pushes the material into the mold. This type densifies material as it pushes it into the mold cavities.

Screws and plungers can be interchanged within the same machine frame, requiring only changes in electricals.

Another type is the coaxial plunger machine. Material is dropped into a stuffer cylinder inline with a smaller cylinder that pushes the material into the mold. Advantages claimed for this structure include the short distance that the material has to flow. Angles and corners around which the material must move have been eliminated.

Energy Considerations

Injection molding is an energy-intensive process, since the central operation is the conversion of the feedstock from the solid phase to a physically and thermally homogeneous melt followed by a forming operation and subsequent resolidification of the polymer. The phase change from solid to melt requires an input of thermal energy from two main sources: the heated barrel and the drive mechanism; a second energy input is then required for the forming process; finally, energy must be removed in the resolidification process (7).

A certain minimum energy input is inevitable and determined by the thermodynamic properties of the polymer being processed. This minimum energy can be defined as

$$E_{\min} = M \int_{T_s}^{T_M} C_p \cdot dT + \int_0^{t_i} p \cdot \dot{v} dt$$

where C_p = specific heat

M = mass of shot

T_M = required melt temperature

T = temperature

$\dot{v}$ = volumetric injection rate

and other symbols are as previously defined.

The first term on the right-hand side of the equation is the energy required for shot preparation, and the second is the energy required for forming. Typically, in practice, the energy required for shot preparation is perhaps an order of magnitude greater than that required for forming.

An overall process efficiency for injection molding can therefore be defined as

$$\eta = E_{\min}/E_A$$

where E_A = actual total energy supplied per cycle

On this basis, typical efficiencies of machines now in use range from 10 to 25%. Efficiencies of this order indicate significant energy losses in practice. However, since injection molding machines are required to provide useful motion, such as clamp opening and closing, product ejection, sprue break, etc., a certain expenditure of energy is necessary beyond the theoretical minimum for shot preparation and forming. A major design objective, therefore, is to produce required motions with minimum energy expenditure. In contrast to injection molding, process efficiency for commercial single-screw extruders typically range from 35 to 75%.

Since shot preparation involves the larger component of the theoretical minimum process energy, it is useful to define a plasticating efficiency as

$$\eta_p = \left(\int_{T_s}^{T_M} C_p \cdot dT \right) / E_p$$

where E_p = actual plasticating energy supplied per cycle

The plasticating efficiency of standard injection units under typical molding conditions has been observed in the range of 25 to 50%. However, significantly higher efficiency is possible with injection units designed to minimize energy losses and equipped with high-performance screws.

An energy balance approach is particularly useful in the study of injection unit performance. This approach can be used to determine the magnitude of energy losses at different points in the system, for example,

feed throat cooling losses, drive motor return line losses, inherent back pressure losses, mechanical friction losses, thermal losses from the barrel, and drive train losses. In particular, the application of the energy balance approach to each barrel zone provides particularly useful information concerning screw performance.

Barrel insulation has considerable potential for minimizing thermal losses, but the insulation should not be used unless screw design is adequate. If, because of incorrect screw design, areas of the barrel experience a net heat transfer from the polymers, the temperature of the barrel in those areas will increase until an equilibrium is achieved in which thermal conduction to neighboring barrel zones is equal to the heat transfer from the polymer. This heat can produce undesirable effects in plasticating and, in particular, may lead to thermal degradation of the polymer.

In more general terms, particular care should be taken in selecting mechanical components that will operate at high efficiency in the given application. This is particularly true in the case of the drive mechanism. An oversized drive train will tend to operate at lower efficiency than an optimally sized one, since higher fixed losses are inevitable. Experimental observations indicate that the efficiency of a typical hydraulic drive system can drop from 80% in a high loading condition to 50% in a low load condition.

High-performance screw designs offer significant energy-saving potential in addition to improved product quality. Often, improved melt mixing affects product quality more than the average temperature of the final melt, making it possible to save energy by reducing melt temperature. This provides the additional advantage that mold cooling time can be reduced, thereby increasing productivity and also reducing the contribution of fixed losses, such as thermal convective losses, to overall energy losses.

Summary

In this section further information applicable to the performance of plastic mate-

rials has been presented. Figure 6-97 is a nomograph that shows how to determine a filler loading compound's weight, a calculation normally determined by a computer program. Since most plastic products only have to survive in a temperature environment that a human can tolerate, practically all plastics meet this requirement (Fig. 6-98). The more heat resistant plastics are shown in Figs. 6-99 and 6-100. Note where red oak is located in Fig. 6-99.

Terminology

Ablative plastic A material that absorbs heat, while part of it is being consumed by heat, through a decomposition process that takes place near the surface exposed to the heat. An example is a carbon fiber-phenolic reinforced plastic that is exposed to a temperature of 1,650°C (3,000°F); it is the surface material used on a rocket or space vehicle to enable reentry into the earth's atmosphere from outer space.

ABS nylon alloy Thermoplastic alloy of ABS and nylon (PA) with properties similar to ABS but with higher elongation at yield.

Accelerator Also called promoter or co-catalyst. A chemical substance that accelerates chemical, photochemical, biochemical, etc. reaction during processing, such as cross-linking or degradation of plastics. Action is triggered and/or sustained by another substance, such as a curing agent or catalyst, or environmental condition, such as heat, radiation, or presence of a microorganism. An accelerator can be used to hasten a chemical reaction with a catalyzed TP or TS plastic. It can be used to reduce the time required for a TS plastic to cure or harden and is often used in room temperature cures. During processing, it undergoes a chemical change.

Activator Compounding material used in small proportions to increase the effectiveness of an accelerator. Both organic and inorganic types may be used. The majority require both zinc oxide and a fatty acid

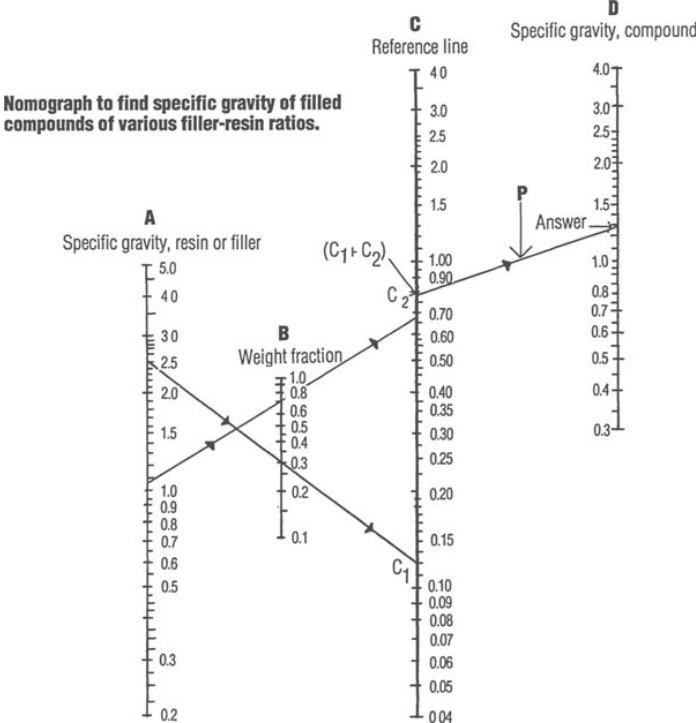


Fig. 6-97 Nomograph.

such as stearic acid to develop optimum final properties. They are usually added at the start of compounding. This action eliminates the potential difficulty in dispersing them evenly throughout the mixed compound.

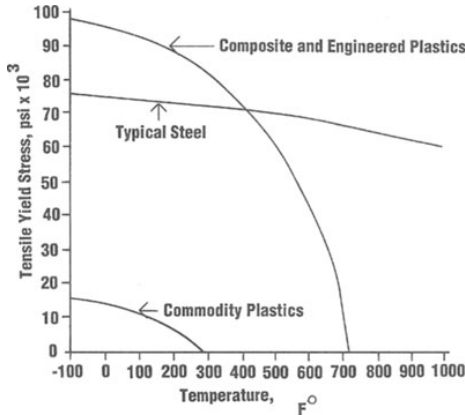


Fig. 6-98 Guide to maximum tensile stress versus temperature.

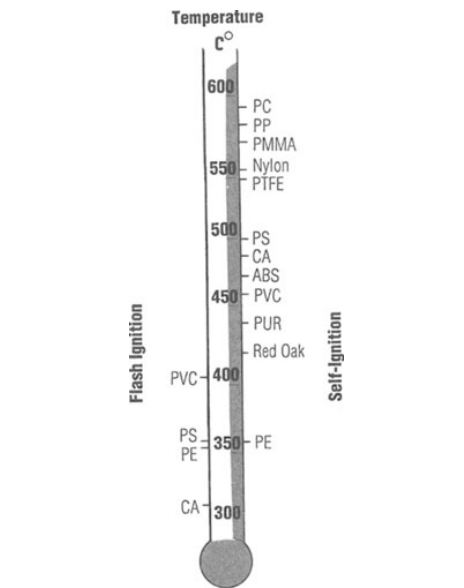


Fig. 6-99 Flash ignition and self-ignition points for various plastics and red oak.

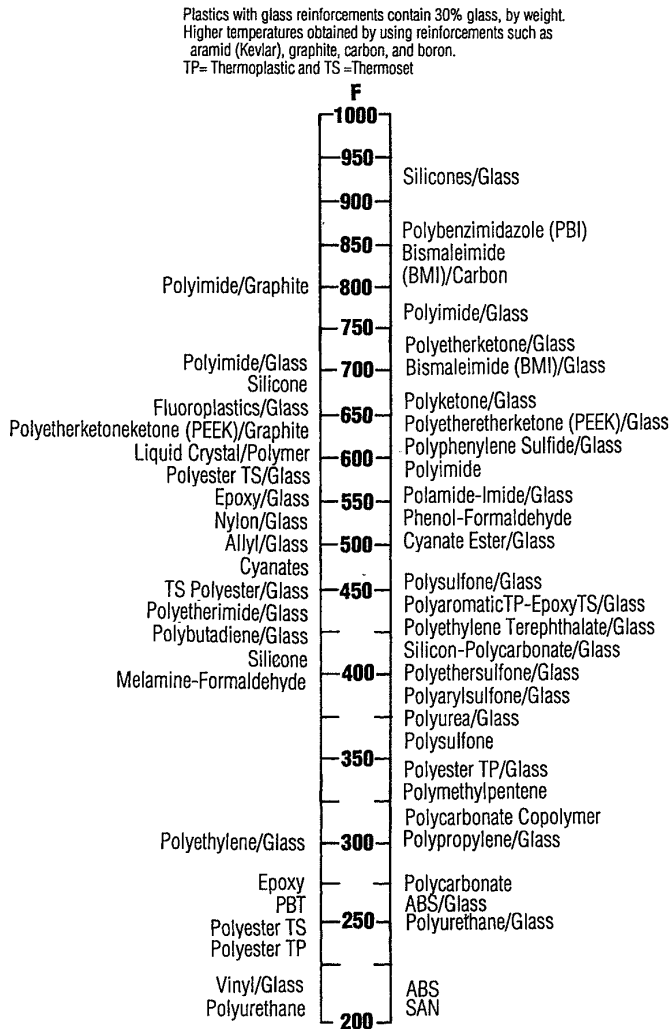


Fig. 6-100 Guide to heat resistance performance based on heat deflection temperature test (ASTM D 648 at 264 psi).

Aluminum foil A solid sheet of an appropriate Al alloy, cold rolled very thin, varying from a minimum thickness of about 0.0017 in. (0.0432 mm) to a maximum of about 0.0059 in. (0.1499 mm). Aluminum foil can be molded (internal or externally) to provide a barrier or decorative effect. In the Al industry, thickness of at least 0.006 in. (0.1524 mm) is sheet material (sheet). After (oil) cold rolling, the foil is annealed to restore its workability. From the standpoint of packaging as well as other ap-

plications, one of its most important characteristics is its impermeability to water vapor or gases. Bare foil 1.5 mil (0.0015 in. or 0.038 mm) and thicker is completely impermeable and used in plastic coating and packaging process systems

Anticaking agent Additive used primarily in certain finely divided compounds that tend to be hygroscopic to prevent or inhibit agglomeration and thus maintain a free-flowing condition of the material.

Antioxidant agent (AOA) Also called aging retardants. AOAs are of major importance because they extend the plastic's (that are affected by oxygen) useful temperature range and service life during processing and/or product use. The variety of AOAs available and their specific uses are extensive. They retard oxidation during processing heat, atmospheric oxidation, and/or the degrading effects of oxidation. Certain plastics, such as PE, are susceptible to degradation that starts when free radicals are released after exposure to heat, UV radiation, and mechanical shear, or in the presence of reactive impurities such as catalyst residues. There are also nonstaining antioxidants. Antiozonant agents can control oxidative degradation by ozone.

Antistatic agent Also called antistat. Used to minimise static electricity in plastics. Such agents are of two types: (a) metallic devices, which come in contact with the plastics and conduct the charge to earth and (b) chemical additives, which, mixed with the compound prior or during processing, give a reasonable degree of protection to the finished product. They function either by being inherently conductive or by absorbing moisture from the air to release the static charge.

Asbestos A commercial term applied to fibrous varieties of several silicate minerals such as amosite and crocidolite (not the name of a distinct mineral species). These extremely fine fibers are useful as fillers and/or reinforcements in plastics. Characteristics include withstanding wear and high temperatures, chemical resistance, and strengths with high modulus of elasticity. When not properly handled or used, like other fibrous materials, they can be hazardous.

Aspect ratio The ratio of length to diameter of a material such as a fiber or rod; also the ratio of the major to minor axis lengths of a material such as a particle. These ratios can be used in determining the effect of dispersed additive fibers and/or particles on the viscosity of a fluid or melt and in turn on the performance of the compound based on L/D

ratios. In reinforced plastics, fiber L/D will have a direct influence on the compounded plastic performance.

Atomic weight The relative mass of an atom of any element based on a scale in which a specific carbon atom (carbon-12) is assigned a mass value of 12.

Barrier Any material or device that limits passage through itself of solids, liquids, semisolids, gases, forms of energy (such as UV light), and/or other material. Limitation can be by physical or chemical means.

Barrier layer A separate layer of material, such as a plastic, whose presence is intended to stop or hinder the passage of another material.

Barrier via chemical modification Chemical modification of the plastic surface during or after fabrication permits controlled permeation behavior in certain parts.

Batch processing, computer Application of computer data analysis techniques to the classification, assimilation, and interpretation of subjects such as plastic and chemical information. Basically batch processing is a method in which a computer program or set of related programs must be completed before going on to the next operation. Its major purpose is to correlate data in such a way that trends or patterns become apparent.

Biodegradable A material that has the proven capability to decompose in the most common environment where it is disposed within a time period such as one year, through natural biological processes, into nontoxic carbonaceous soil, water, or carbon dioxide.

Biodegradable and waste Biodegradable plastics have existed for over a century and methods to cause degradation have been studied. Certain products have been specifically designed to degrade: to eliminate waste, cause explosives to perform (by sunlight, rainwater, etc.; principally used by the military), to make medical products (sutures, implants, controlled release formulations of

drugs, etc.), etc. However, the main emphasis for over a century has been on producing reliable, high performance and long-life plastics.

Bulk factor Term used to describe the volume occupied by a specific weight of material to be processed. It is also the ratio of volume of a raw material to the volume of the fabricated part or waste before and after compaction.

Bulking agent A material or chemical added to another chemical that increases the quantity of the mixture required without changing the chemical activity of the total.

Bulk storage Tanks or silos large enough to accept bulk shipments of individual substances.

Compatibilizer agent Substance blended with dissimilar plastics, including recycled plastics. If natural compatibility is missing, a plastic can be chemically modified, such as by grafting, to improve reactivity with another plastic, or a third agent can be added to do the blending. Two-component and multi-component mixtures are used. The most common agents are block or graft copolymers and polymer co-solvents.

Composite A combination of two or more materials with properties that the components do not have by themselves. Included are reinforced plastics (1).

Compound An intimate mixture of a plastic(s) with all the materials necessary (such as additives) required to fabricate a product.

Compound, dry blend Also called powder blend. A free-flowing dry compound containing all necessary additives prepared without fluxing or the addition of a solvent.

Compression set The residual deformation of a material after removal of the compressive stress or load.

Fines The pieces that are substantially smaller than the bulk of the regrind that fall

through the granulator screen. Fines are bigger than dust but smaller than regrind. Too many fines can cause feeding and processing problems.

Longs Oversized raw material that can result from loose or broken granulating screens.

Melt index A term used that indicates how much plastic melt can be pushed through a set orifice with various conditions controlled. It represents the “flowability” of a material. Higher values indicate easier flow (Chapt. 12).

Plastics From the Greek word “to form,” a class of materials capable of being formed into all kinds of (simple to extremely complex) shapes. Practically all plastics at some stage in their manufacture or fabrication can be formed into various shapes that can range from being extremely flexible (rubbery or elastomeric) to extremely hard (high performance properties).

Post-consumer Identifies plastic products generated by a business or consumer that have served their intended purpose and that have been separated or diverted from solid waste for the purposes of collection, recycling, and disposition.

Processing agent An aid, agent, or media used in the manufacture, preparation, and treatment of a material or article to improve its processing and/or properties.

Promoter A chemical, itself a weak catalyst, that greatly increases the activity of a given catalyst.

Release agent Substance applied to molds (also called adherent), to prevent or reduce its adhesion to another surface.

Shelf life Also called storage life or working life. Time during which any material retains its storage stability under specific temperature and environmental conditions so that it remains suitable for fabrication. This term should not be confused with pot life.

Stabilizer Agents or materials present in or added into practically all plastics to improve their performance. Stabilizers serve to inhibit chemical reactions that bring about undesirable chemical degradation. An example is in vinyls and polyolefins, where stabilizers are added to maintain properties at or near their initial values during storage, during fabrication of parts, and during service life of the parts. Some stabilizers impede or retard degradation, usually caused by heat or UV radiation. Stabilizers are used in some plastics, particularly elastomer, to also assist in maintaining the physical and chemical properties during processing and in service. There are three major groups: metallic (barium stearate, cadmium stearate, etc.), organo metallic (dibutyl tin dilaurate, etc.), and organic (epoxies, etc.).

Stabilizer, internal An agent incorporated in a plastic during polymerization as opposed to a stabilizer added during compounding.

Strengthening plastic mechanism With some exceptions, strengthening of plastics is the work of the polymer chemist. But exceptions exist. Polyamide-imide and phenolic can be increased in strength by a postmolding thermal treatment (such as heat treating steel or even heat treating plastics). Also, certain additives are used; however, major improvements occur when stretch-orienting plastic products, fabricating reinforced plastics, etc.

Strength of material Refers to the structural engineering analysis of a part to determine its strength properties.

Strength ratio The hypothetical ratio of the strength of a product to the strength it would have in the absence of weakening defects.

Strength service factor A factor used to reduce a strength value to obtain an engineering design stress. The factor may vary depending on the service condition, the hazard, the

length of service desired, and the properties required of the product. This factor is part of a safety factor.

Synergism Arrangement or mixture of materials in which the total resulting performance is greater than the sum of the effects taken independently such as with alloying or blending.

Thixotropic A characteristic of material undergoing flow deformation in which viscosity increases drastically when the force inducing the flow is removed. The material is gel-like at rest but fluid when agitated such as during molding. Thixotropic materials lose viscosity under stress.

Viscosity, reactive processing Effective viscosity of a material undergoing reactive processing. The design of conventional (non-reactive) plastic processing equipment is complicated by the non-Newtonian nature of plastic melt viscosity. When attempting to design equipment to process reactive fluids, one is faced with an even more formidable task: accounting for changes in viscosities with conversions, temperature, and molecular weight, as well as nonuniformities within equipment. Difficulties can be experienced when attempting to mix or pump polymerized fluids with rapidly rising viscosities that accompany the reaction. To understand the associated flow phenomena, it is necessary to deal with the relationship between extent of reaction and viscosity. Reaction viscosity is much more sensitive to concentration and molecular weight than to temperature and shear rate.

Water vapor transmission (WVT) The rate of water vapor flow, under steady specified conditions, through a unit area of material, between its two parallel surfaces and normal to the surfaces. Metric unit of measurement is $1 \text{ g}/24 \text{ h} \cdot \text{m}^2$. Also, perm is a unit of measurement of water vapor permanence where a metric perm is $1 \text{ g}/24 \text{ h} \cdot \text{m}^2 \cdot \text{mmHg}$, or in U.S. units $1 \text{ g}/\text{h} \cdot \text{ft}^2 \cdot \text{in. Hg}$.

Process Control

Process Control Basics

Injection molding control involves many facets of both machine operation and the behavior of plastic, most importantly their interaction. Principally the processing pressure and temperature versus time determine the quality of the molded product. The design of the control system has to incorporate the logical sequence of all these basic functions, including injection speed (which is pressure dependent), clamping and opening the mold, opening and closing of actuating devices, barrel temperature profile, melt temperature, mold temperature, cavity pressure, holding pressure, and so on (Figs. 7-1 and 7-2). These controls are essential to produce molded quality products. Quality features include mechanical properties, dimensional accuracy, absence of distortion, and surface quality (Chap. 4).

Developing a process control (PC) flow diagram requires a combination of experience of the process and a logical approach to meet the objective that has specific target requirements. Process controls range from very simple and standard types (Fig. 7-3) to those more sophisticated (Fig. 7-4). An example of a very convenient and simplified approach for process control is to establish molding process windows as reviewed in Chap. 4 (Molding Process Windows; Figs. 4.1 and 4.2). Figure 7-4 highlights one aspect of PC involv-

ing cavity pressure distribution, which is used to eliminate short shots and flash resulting from low and high cavity pressure values. Statistical process control is used to establish acceptable limits thereby resulting in less scrap, etc. (Chap. 13).

As injection molding becomes more complex, molders require greater accuracy and increased variations in the types of cycles that could be adapted to their machines. These include variations in core pull sequences, different ejection sequences, and changes in the timing of high-pressure application after clamp close in combination with injection, screw rpm, back pressure during melting, etc. This section is a summary of the subject.

Different types of machine process controls can be used to meet the requirements, based on the molder's operating needs. Control systems available can monitor (alarm buzzes or lights flash on deviation), feedback (deviation sets up corrective action), and program the controller (minicomputers interrelate "all" machine functions and "all" melt process variables). Knowledge of your machine and its operating needs is a prerequisite to developing an intelligent process control program.

There are controls of an open-loop type. These merely set a mechanical or electrical device to some operating temperature, pressure, time, or travel. They will continue to operate at their setpoints, even though

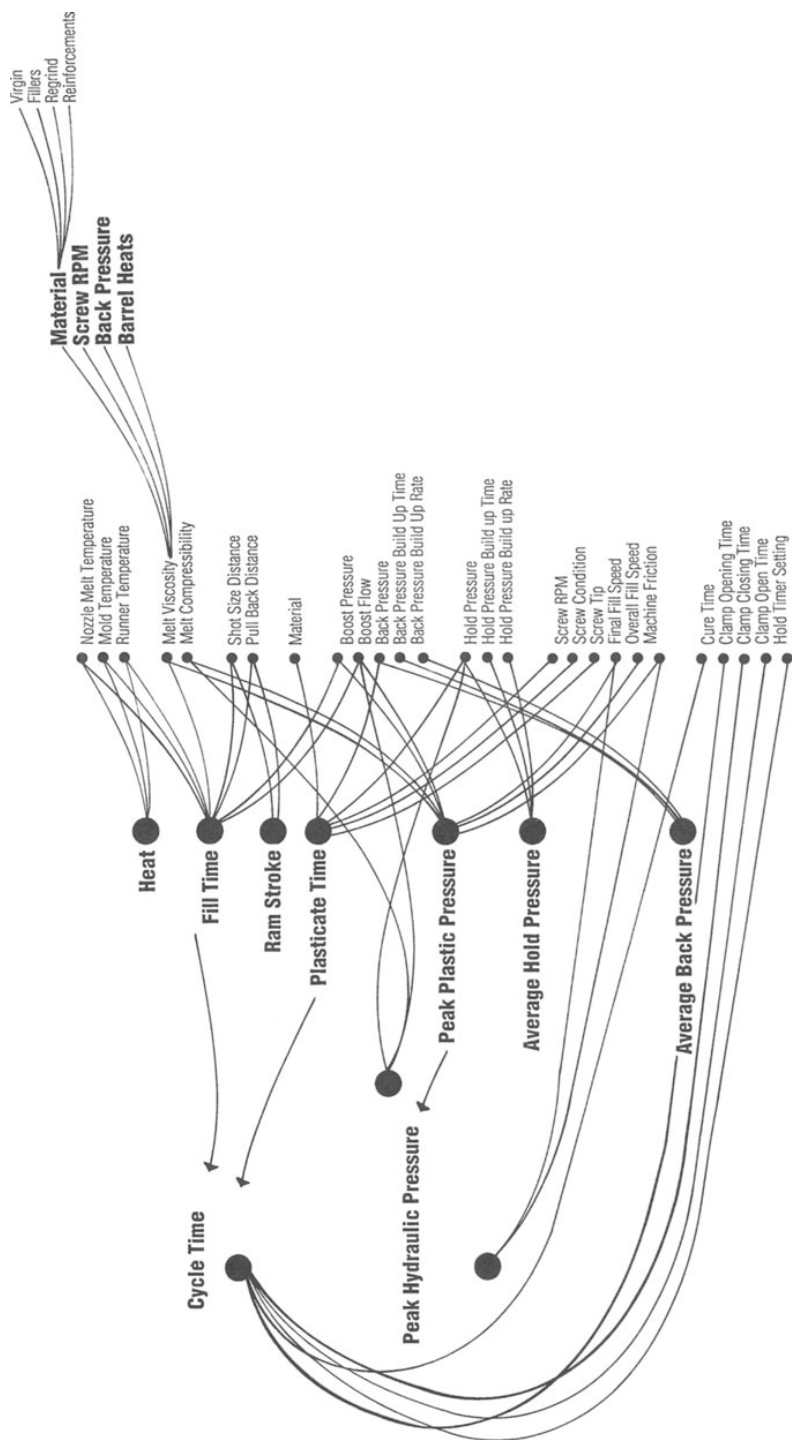


Fig. 7-1 Example of injection molding machine controls.

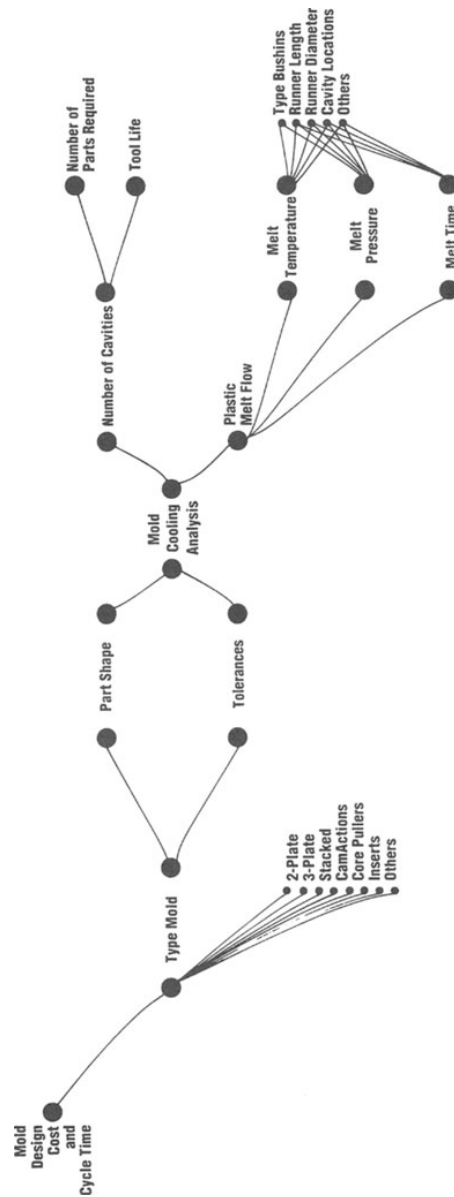


Fig. 7-2 Example of process controls involving molds.

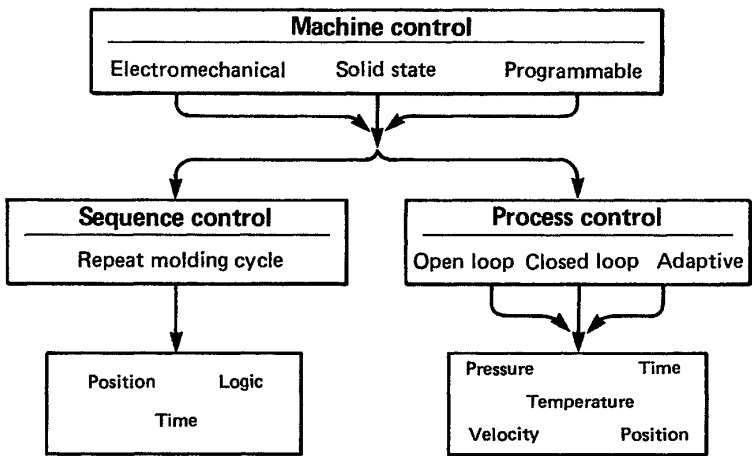


Fig. 7-3 Simplified overview of process control for IMMs.

the settings are no longer suitable for making quality parts. During molding, the total process is subject to a variety of hard to observe disturbances that are not compensated for by open-loop controls. Process control closes the loop between some process parameter and an appropriate machine control device to eliminate the effect of process disturbances.

With controls properly installed and applied, the performance of the plastics in the machine can be controlled within limits to produce zero-defect parts meeting performance requirements at the lowest molding cost. The limits have to be set on the basis of testing and evaluation of molded parts. See Figs. 7-5 to 7-7 for the basic analysis of

effects of specific injection molding machine and plastic material variables. The next important aspect to analyze is the effect of interfacing the different variables as shown in Fig. 7-8.

With a little effort practically all molding machines are capable of providing useful melts that go into molds and produce salable products. Certain machines provide tighter operational controls (thanks to modern process controls, which continually advance the state of the art in processing) that permit production of quality products with less effort at the least cost. The interrelationship between a plastic and machine performance is summarized in Fig. 7-1.

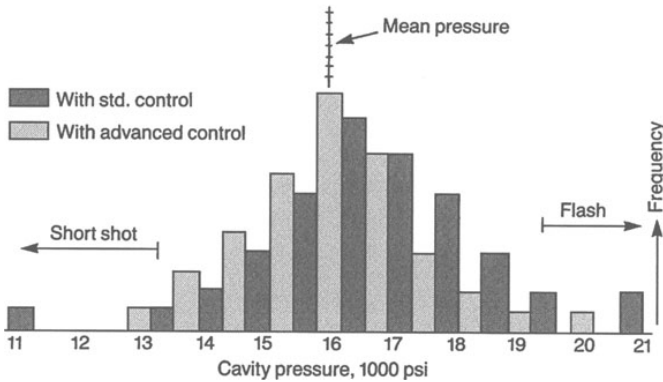


Fig. 7-4 Advanced process control includes tighter cavity pressure control.

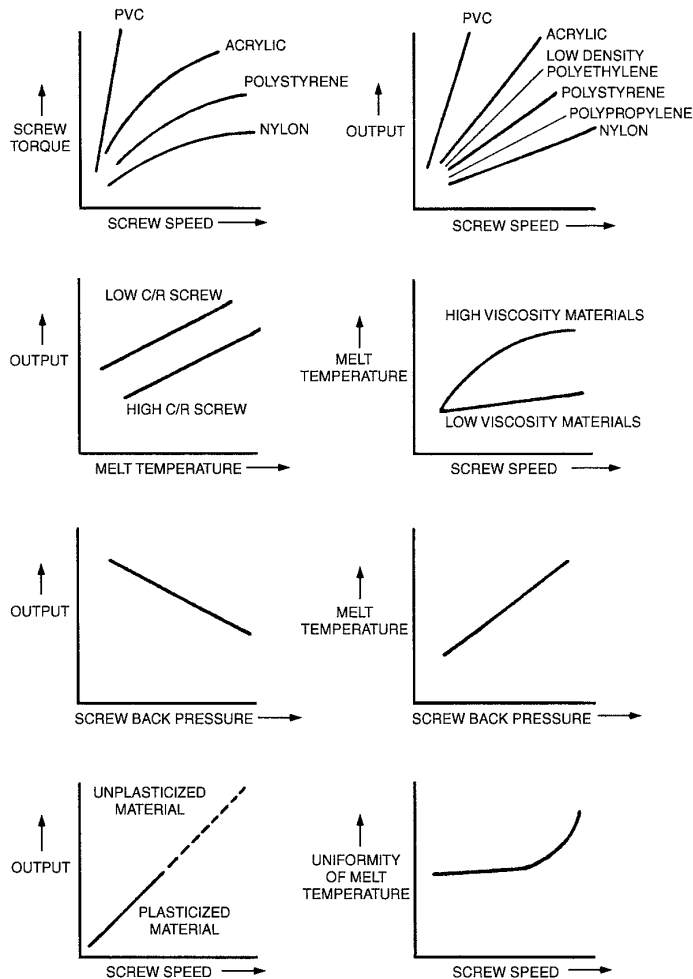


Fig. 7-5 Effects of IMM and plastics material variables.

To reduce molding cycle time (Figs. 7-1 and 7-2) and produce quality-controlled or useful parts requires more precise control in the injection molding operation. At higher production rates, excessive scrap and rejects become less desirable than ever, and molders find themselves trying to reduce these levels. With more automation, molding optimization is further complicated by automated operations that move the products directly from the molding machine to the assembly stations. Effective process control, therefore, is essential to maintain the benefits of modern process technology.

Purchasing a more sophisticated process control system is not a foolproof solution to molding-quality problems. Solving part-reject problems requires a full understanding of the real cause, which may not be as obvious as it first appears. The conventional place to start troubleshooting a problem is the melt temperature and pressure. But often, the problem is a lot more subtle; it may involve mold design, faulty control devices, and other machine components.

Problems in mold design can cause pressure and temperature differences between cavities. Sometimes, factors not directly

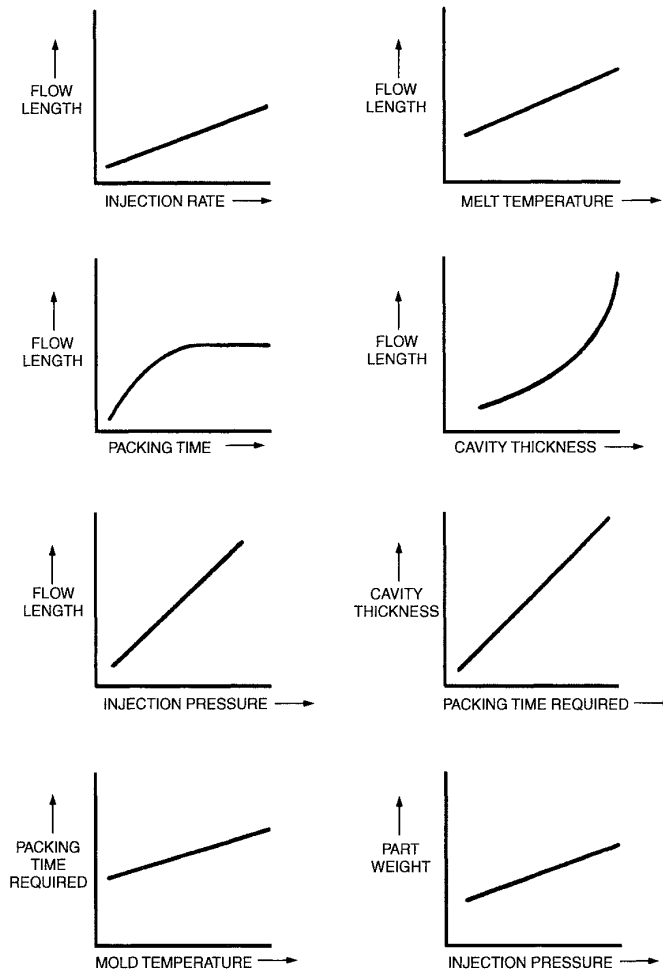


Fig. 7-6 Effects of IMM settings on various properties such as flow length.

related to the process may be influencing quality, such as an operator making random adjustments of control devices and the rate that plastic moves into the screw. Process control systems usually cannot compensate for such extraneous conditions.

Studies have shown that compared to the most efficient plastics molding machine of the 1970s, a new microprocessor-controlled machine can save well over \$1,000 a year in energy alone while being more productive. That figure would be much higher if we were to base our comparison on some of the mechanical relics that are still widely used.

Development of the microprocessor is proceeding along lines similar to those followed by the reciprocating screw. The screw plasticator was first added to machines originally designed for plungers. However, it soon became apparent that the reciprocating screw would be much more effective if it were used on a machine designed specifically to accommodate it.

In like manner, it does little good to have timers that read in hundredths of seconds if the machine itself does not have servomechanisms that match the microprocessor's precision. The machinery must be as good as the

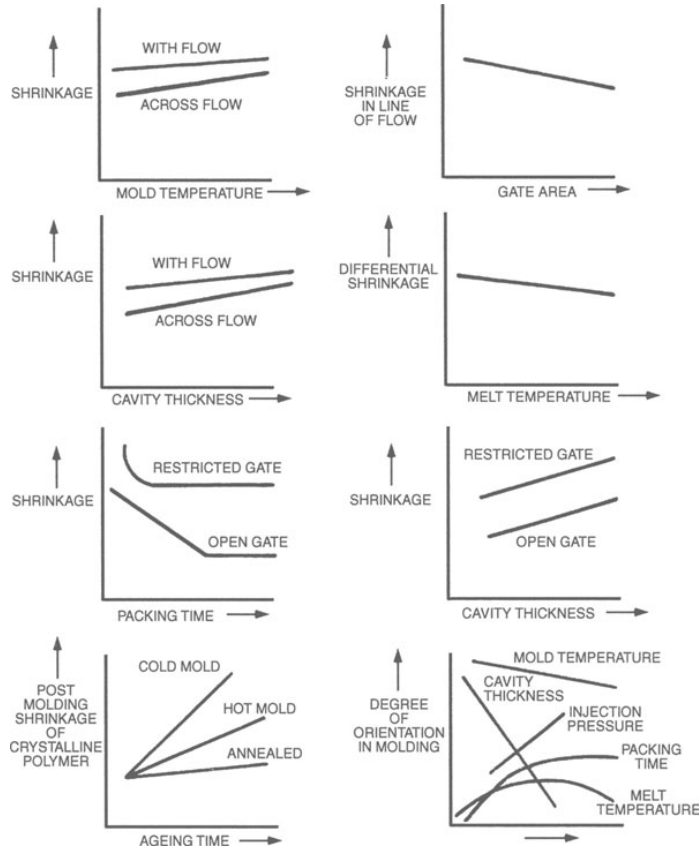


Fig. 7-7 Machine settings and mold cavity dimensions affect plastic properties such as shrinkage.

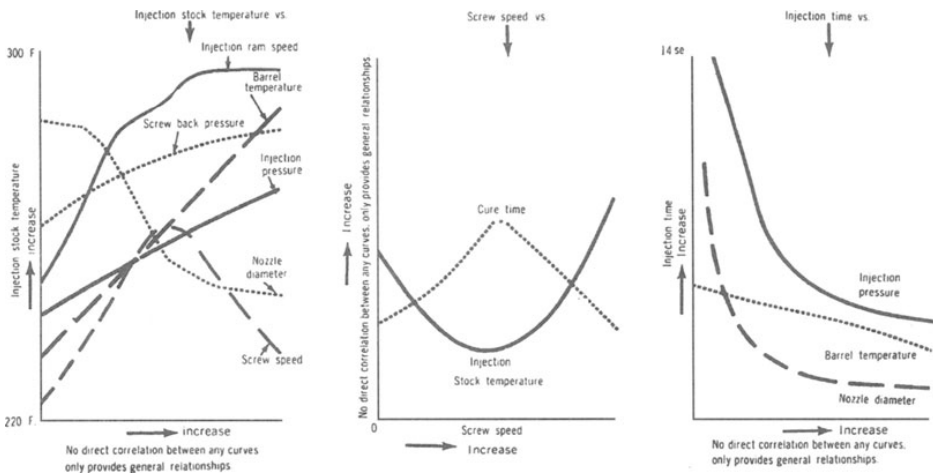


Fig. 7-8 (Left) Injection stock temperature versus injection speed. (Center) Injection time versus injection pressure. (Right) Screw speed versus TP cooling time.

control device, or there is little sense in having a microprocessor.

Developing Melt and Flow Control

The mechanism for melting is described in Chap. 3 on screw design.

The addition of back pressure is a means of creating more workload on the screw by restricting its ability to pump the plastic. In the process, it increases melt temperature and uses more drive energy. Its benefit is to increase working of the plastic to improve color blending and melt quality. The proper heat profile does these things as well. Therefore, consider using no back pressure until the heat profile is obtained and then add only that back pressure necessary. The rate of fill of the mold is determined by many factors, such as viscosity of the melt, gate size, the machine's capabilities, mold temperature, etc.

The computerized molding machine increases productivity. It does this in several ways. First, it enables the molder to fine-tune all the relationships that exist in both the clamp and injection end of the machine. At a digital control panel, the setup technician can scroll through all the machine functions, cutting off a tenth of a second here, three-tenths of a second there, throughout the entire job.

Furthermore, once the optimum settings have been determined for a particular mold, they can be repeated simply by entering them in the control each time the job is run. An exacting setup job need only be performed once during the life of a mold.

However, cycle time is not the sole determinant of productivity. Fast cycle times may easily be negated by high rejection rates. The computer's ability to fine-tune the machine to a given mold also results in the highest-quality part and lowest rejection rate. Part quality is also enhanced through the use of computer-driven process control devices.

The microcomputer is far more dedicated than the human worker. It can continually make adjustments within the machine and make it perform more efficiently. Energy consumption is an important concern of the molder. The microcomputer is by far the best energy-saving tool known to modern in-

dustry. (Details on computer simulation are given in Chap. 9.)

During molding, the need exists for a good-quality melt at the lowest possible temperature. The hotter the melt is on injection, the longer the mold must be held closed to cool the part. This action affects cycle time. It also affects part quality and energy use. The proper heat profile will not only reduce cycle time but will save energy as well. If a reduced amount of heat is transmitted to the plastic through the heater bands, the energy required to remove the heat from the mold will be reduced as well.

Inspection

Inspection variations are often the most critical and most overlooked aspect of the tolerance of a fabricated part. Designers and processors base their development decisions on inspection readings, but they rarely determine the tolerances associated with these readings. The inspection variations may themselves be greater than the tolerances for the characteristics being measured, but without having a study of the inspection method capability this can go unnoticed.

Inspection tolerance can be divided into two major components: the accuracy variability of the instruction and the repeatability of the measuring method. The calibration and accuracy of the instrument are documented and certified by its manufacturer, and it is periodically checked. Understanding the overall inspection process is extremely useful in selecting the proper method for measuring a specific dimension. When all the inspection methods available provide an acceptable level of accuracy, the most economical method should be used (Chap. 12).

Computer Process Data Acquisition

The central data acquisition in the injection molding plant can contribute to creating the basis for more rational production, process optimization, and quality assurance. Essential to the useful operation of a central computer concept is the careful selection of the computer system and program software

package, as well as *suitable training for the system user* (Chaps. 9 and 13).

Fabricators of injection molding parts increasingly see themselves confronted with rising manufacturing costs, in addition to higher demands regarding quality and flexibility of parts. This concerns demands for maintaining and documenting the specified quality features, as well as the requirement for highly punctual delivery. Therefore, requests for productivity increases needs to take into account the following:

1. The utilization of the machines can be improved by more accurate production planning on the basis of more up-to-date information (factory data).
2. Production downtimes due to faults can often be reduced to a few causes. Well-maintained molds and machines are just as much a prerequisite as the knowledge of significant patterns of faults.
3. Unavoidable retooling can be accelerated by the use of preheating stations, quick tool-change devices, and automatic mold changers.
4. The process sequence itself should be constantly optimized with regard to the part quality, cycle time, and fault frequency. By constant monitoring of the machine and statistical evaluation, disadvantageous effects on the manufacturing sequence can be recognized and eliminated.

5. Effective quality testing assesses several quality-determining factors during production (part weight, length dimensions, etc). Further information regarding production quality and the essential parameters affecting quality can be gained from correlation models.

Most of these measures are only rational if the production manager can rely on exact information about the actual state of the production factors. Since the majority of new injection molding machines are equipped with microprocessor controls by the manufacturer, the required information can be retrieved via an interface and shown at the terminal.

In principle, all product or production data can be allocated to one of the following

groups. By *setting data*, we mean all setpoint values that are required to manufacture a certain part on a certain machine with a certain mold. By the term *operating data*, we refer to all data that yield direct information about the organization of the current production. They are, thus, the basis for production planning and control, as well as invoicing and calculation.

Rational production data acquisition gives production managers the opportunity of informing themselves about the current state of production at any time. The actual values of the process parameters that are significant for injection molding are described as *process data*, such as melt, cylinder, mold temperatures, injection time and viscosity, etc. For certain reasons, such as mold wear, material exchanges, etc., it may be that *correction data* for machine setting are necessary.

If the *actual values* deviate greatly from the mean values, and at the same time the scattering increases, it can be assumed that the machine will no longer reproduce the specified basic setting to meet part requirements.

Many machinery manufacturers now offer through their microprocessor controls the possibility of registering complex processing parameters, such as the integral of the mold internal pressure or the injection work. These parameters can also be used as control parameters for process control. Some controls already include closed-loop control programs that, for example, influence the changeover to holding pressure on a certain change of the integral value. Although these processes have long been proven in practice, the actual problem lies in determining the settings.

The mathematical relationship among the integral value, holding pressure correction, and their effect on the molding is of no interest at all for the adjustment of such a process control. It is fully adequate for the narrow range of validity of this control model to determine the relationships empirically, and thus to give a rough quantitative description. One can derive relationships from the comparison of the essential actual values (Chaps. 7, 9, and 13) with the dimensions of the molding (quality data) with the aid of a computer.

Control Flow Diagrams

Basic process control can be compared to preparing a martini (or preparing a special fruit drink). It requires a graphic description of the process “road map” to get from one position to another. The process to prepare a batch of martinis requires formulation (ingredient ratio), raw materials (gin, vermouth, ice, and olives), equipment (graduated measure, mixer/stirrer, and glasses). A flow diagram is desired that must incorporate all aspects of the process highlighting gaps, contradictions, and skeleton on which to build further documentation. Manufacturing equipment requires utilities, space, capacity, and a work crew.

For any parameter that has a numerical value, there must be a reliable determination procedure or “test method.” Test methods can be of definite variety, very simple to complex, inaccurate to high accuracy, and unreliable to very reliable. Work done on any process or its output is only as good as the test methods. Test methods consist of procedures, equipment, calibration and standardization, traceability, and precision and accuracy. Figure 7-9 summarizes how to make

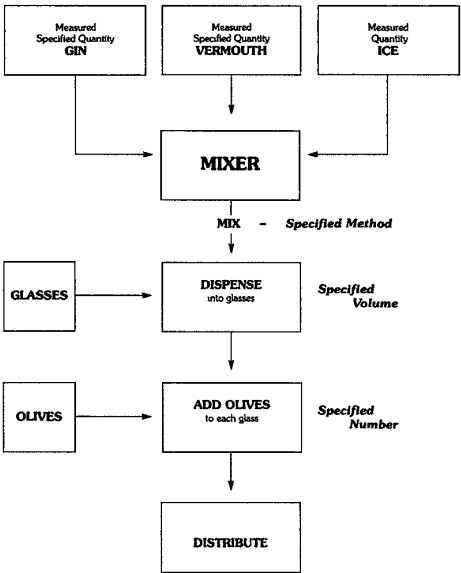


Fig. 7-9 Process flow concept.

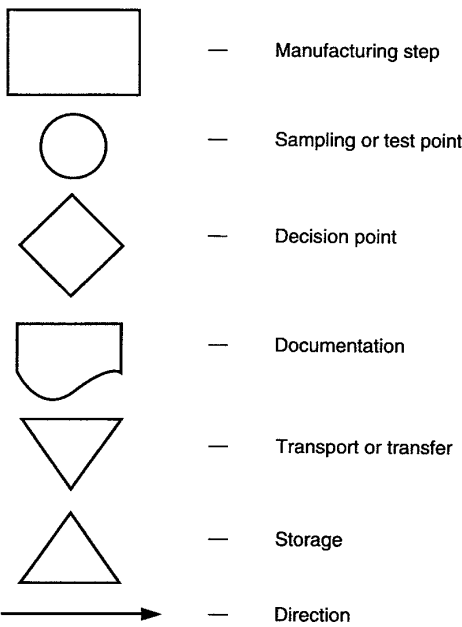


Fig. 7-10 Typical set of symbols.

a martini; it involves materials, quantities, equipment, and a process step. The “finished product” description follows the customer’s description—namely, a glass containing a chilled mixture of gin and vermouth with one or two olives. The customer is either satisfied or dissatisfied.

The preparation of a flow diagram concerns no absolute technique, wide variety of personal choice, and standardization of layout, symbols (Fig. 7-10), and terminology. Figure 7-11 is the production flow pattern that will meet large-scale martini production, for ready-mixed, bottled martinis, just like mother used to make.

Fishbone Diagram

Next, analyze the process using the “fishbone” diagram (Fig. 7-12). A capability study is to be run on identifying how much you know about the process that is influenced by the raw materials process parameters. Often, answers are not available on factors such as enough time, enough money or equipment needed for production, acceptable product

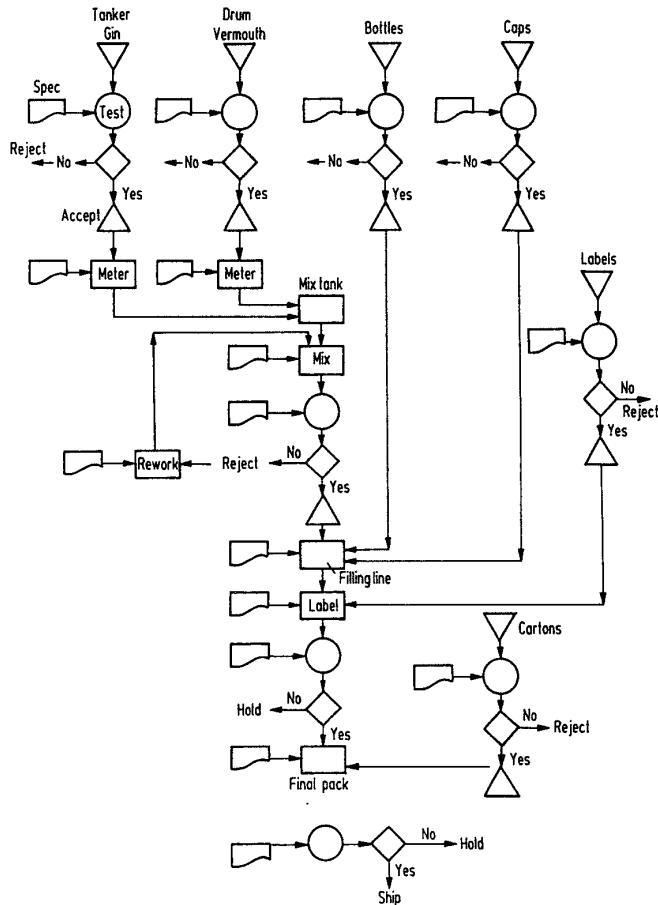


Fig. 7-11 Production process flow diagram.

produced, if standard costs were not met, why defective parts were produced, was it important that process parameters be shifted,

and/or what influence did a raw material source have on the process. To analyze the process requires identifying key parameters and determining parameter limits.

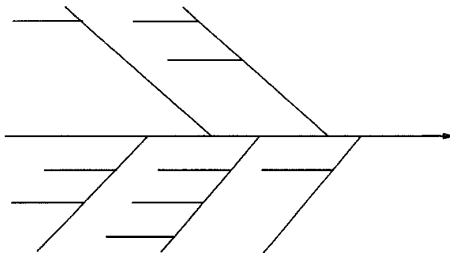


Fig. 7-12 Typical fishbone diagram. Each branch is an input, which could be a material, a process stage, an auxiliary stage, documentation of instructions, etc.

Final process analysis requires the complete process flow diagram (Fig. 7-11) and completed fishbone diagram (Fig. 7-13). What one may have thought was a simple process resulted in a multicomponent diagram. In constructing the fishbone diagram: (1) include all factors; (2) do not prejudice inclusions; and (3) reexamine the diagrams, revise, add, or delete (Fig. 1-1). The final fishbone diagram is a cause-and-effect relationship as known at that time. Fishbone diagrams can be drawn for any process (plastics, etc.) no matter how complex. Diagrams

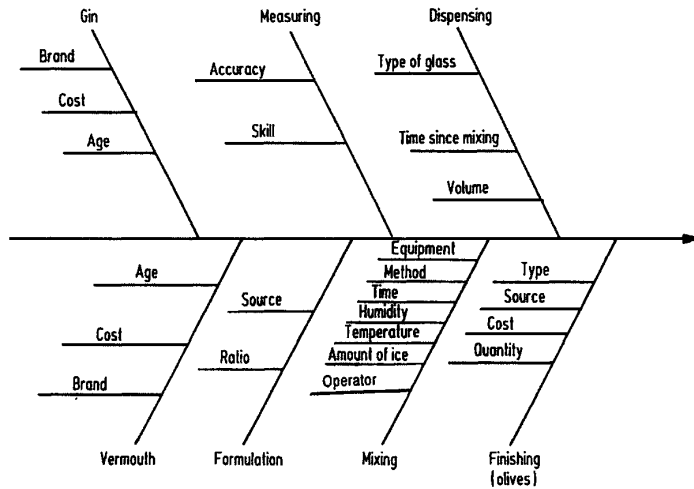


Fig. 7-13 Home martini mixing fishbone.

will often highlight factors or relationships that were unknown or ignored.

Cause-and-effect relationships can be summarized in a two-dimensional grid or “influence matrix” (see Table 7-1). Each cause-and-effect relationship is indicated in the input-output grid as strong *S*, moderate *M*, weak *W*, none *N*, or unknown?. Variables can be classified as those that have a major influence or intermediates, finished products, yield, and cost. These variable classifications can be used to (1) establish areas for problem resolution, (2) set up control points, and (3) select characteristics to be used for (a) process control, (b) acceptable testing, and (c) capability studies.

Overview

Control of IMM continually offers dramatic improvement in easing machine setup, allowing uninterrupted operation, simplifying remote handling, reducing cycle times, cutting energy costs, boosting part quality, and so on. The process of making an injection-molding product has many dynamic fragments that must come together properly for successful results. Lack of sufficient process control over any of these fragments will result in a less than desirable product. Suc-

cess involves three key ingredients: sufficient dynamic performance, sufficient repeatability, and selection of proper control parameters. Scrimping on these ingredients can result in unacceptable products, higher scrap rate, longer cycles, higher part cost, etc.

The control unit is composed of input, signal-processing, and power stages (Chap. 11, Plastic Material and Equipment Variables). The control system includes all the equipment and hardware necessary to control the basic IMM and mold factors. Controls are provided for barrel and mold heating, clamping forces, plastic melt flow rates, and oil and/or electrical pressure (Chap. 2). These parameters are controlled in such a way that they are generated and available in the required magnitude and direction at the proper time during the logical sequence of one molding cycle or several consecutive cycles. The quality of a molded product is mainly determined by temperature and pressure. Overall the design of the process control system has to take into consideration relationships of product parameters with effective PC parameters such as: (1) mechanical properties versus melt temperature, injection speed, mold temperature, cavity pressure, and holding pressure; (2) dimensional accuracy and absence of distortion versus melt temperature, mold temperature,

Table 7-1 Martini mix influence matrix

Variables	Taste ^a	Smoothness ^a	Temperature ^a	Thirst- quenching ^a
Gin				
Brand	S	S	N	M
Cost	W	W	N	W
Age	?	?	N	?
Vermouth				
Brand	S	S	N	M
Cost	W	W	N	W
Age	N	N	N	N
Formulation				
Source	S	S	N	S
Ratio	S	S	N	S
Measuring				
Equipment	M	M	N	M
Skill	S	S	N	M
Mixing				
Equipment	W	W	N	N
Method	W	?	N	N
Amount of ice	M	W	S	S
Temperature	N	N	S	S
Humidity	N	N	N	N
Time	?	?	M	?
Operator	?	?	?	?
Dispensing				
Glass	W	W	W	W
Time since mix	?	?	S	M
Volume	N	N	W	S
Finishing (olives)				
Type	M	M	N	M
Source	W	W	N	W
Cost	W	W	N	W
Number	M	M	N	W

^a S = strong; M = moderate; W = weak; N = none; ? = unknown.

cavity pressure, and holding pressure; and (3) surface quality versus melt temperature, mold temperature, and injection speed.

The design of the control system has to encompass the logical sequence of all principle functions such as clamping and opening of the mold, as well as so-called secondary functions, such as opening and closing of actuating cams, etc. (583).

Process controls all have one thing in common: They monitor the process variables, compare them to values known to be acceptable, and make appropriate corrections without operator intervention. The acceptable range of values can be determined by using melt flow analysis software or by trial

and error. Using this approach, the acceptable process values are known before the mold is ever built. It should be noted that none of the PC solutions address the problem of the lack of skilled setup people. Most of the PC systems available today are rather complex and require well-trained operators to use them efficiently (1, 13, 217, 561).

All data relevant for the definition of the molding process are recorded and stored. This action is also taken to document the quality of the production. Obviously, the correct selection and proper installation of recording devices is of major significance. Thus, the direct objective of the PC systems is the supervision of the process and its indirect

assurance task of the quality demands on the finished product. Controlling denotes keeping a certain quantity constant during a definite period of time.

Conventional PC systems are generally designed for closed-loop control parameters such as injection velocity, holding pressure, cushion, and recovery stroke. Other parameters to be considered include melt temperature and cavity temperatures that affect and relate to the important condition of the consistency of the molded part (530).

Technology

Process controls for IMM can range from the simplest to the most sophisticated devices. As this chapter will review, they can (1) have closed-loop control of temperature and/or pressure; (2) maintain preset parameters for the screw ram speed, ram position, and/or hydraulic position; (3) monitor and/or correct the machine operation; (4) constantly fine-tune the machine; and (5) provide consistency and repeatability in the machine operation. Figure 7-14 machine complexity shows why process controls are needed.

Process control demands a high level of expertise from the molder. The price that must be paid for the use of process control is not

always just the capital cost of the equipment. There is also the price of responsibility for using the control correctly—and that takes time, patience, and a willingness to learn new ways of molding good parts.

The quality of injection molding parts has been considerably improved by converting injection molding machines to fast processor systems and closed control loops. The reproducibility of the process guidance system of machines is aided by rate control loops, pressure and position control loops (Fig. 7-15), and adaptive controls. Acquiring processing data by means of precision sensors is necessary for such controls to function.

Closed control loops consist of a fast computer, actual valve sensors, for example, for temperature and pressure, and a control valve or controller. In the injection side control loop, the signals for path and pressure or rate are processed by 8- or 16-bit computers. Since injection molding controls are modular in construction, computation processes for the individual control loops are carried out by the respective computers. Only after the completion of individual sequences are the computer signals (responses) combined in the central processing unit (CPU) of the master computer and further processed (7).

Pressure sensors in the hydraulics are, apart from the strain gauges, predominantly

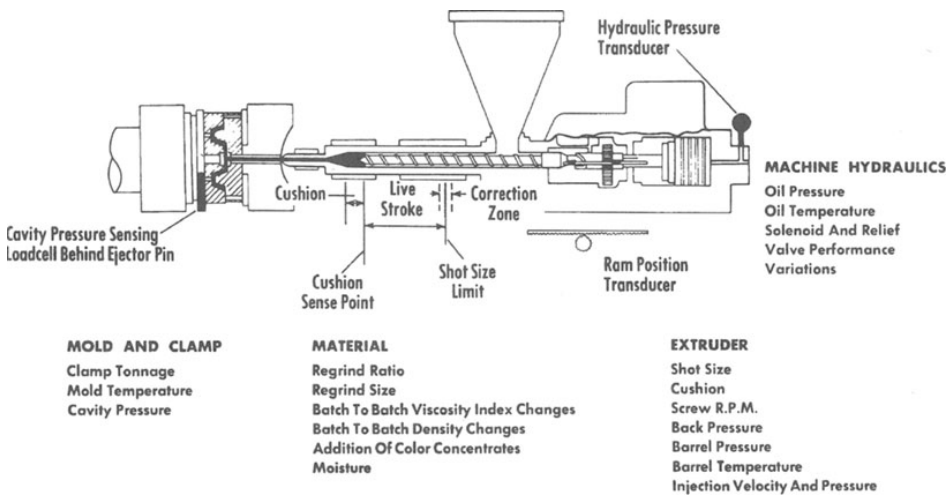


Fig. 7-14 Why injection process controls are needed.

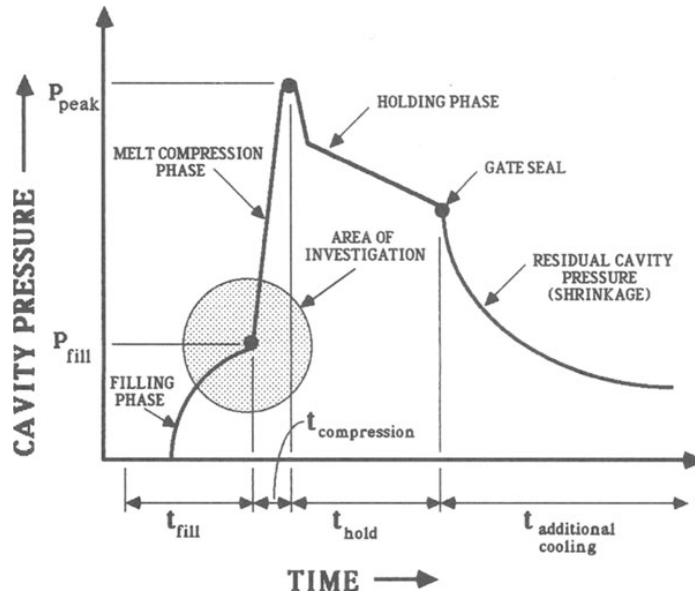


Fig. 7-15 Typical cavity pressure trace.

piezo-resistive pressure transducers. Piezo-electric transducers are in general use for pressure measurement within the mold or melt flow path. Paths are measured, for example, by means of wear-free, contactless ultrasonic path measuring systems and rates from the first deviation of the path with respect to time. The signals from the sensors are constantly compared with the setpoint values and adjusted so as to keep control deviations as small as possible. The same sensor system is also best suited for display of the process.

By process graphics, we generally refer to the graphical display of the curves for pressure, temperatures, or signal voltages from electric components. Displays of curves can show screw travel, setpoint and actual hydraulic pressure, and internal mold pressure. The curves can be spread in the *X* direction and *Y* direction or sections can be magnified. Cursors permit exact analysis in the 1- to 100-sec range.

Inaccuracy in every injection unit, consisting of the addition of very small individual disturbance factors, results in a variable actual pressure. Individual disturbance factors in the area of the injection unit can be

(1) changed temperature characteristics in the machine, barrel, mold, hot runner, and surroundings; (2) changed behavior at the hydraulic valves and mechanical components (dependent on operating hours); (3) differences in material processes; and (4) mechanical wear at the cylinder fittings.

The tolerance band set by the operator characterizes the upper and lower boundaries. If the actual value of an injection parameter lies outside these boundaries, an active signal can separate the reject parts. Injection processes explained by this type of display help the operator to localize faults and to isolate the effects of partly unavoidable disturbance factors from good moldings.

The best analysis by far can be made with curves for the variation of pressure and path. Both adaptive and integrated systems can be rationally used to adjust the material processing temperatures and to localize pressure spikes caused by incorrect injection conditions. Achieving such a quality improvement in a very short time increases the degree of utilization of the machine.

The advantages of the adaptive system are its compatibility and mobility between

machines. The graphics are plotted without plotter misalignment, are generally multicolored, and can be magnified to highlight certain of sections. Process monitoring has the equally important advantage for the operator of good/poor parts separation via analytical observation. Once curves are found, they can be stored as such and dimensioned with a tolerance band. It is important to know that the tolerance bands can have altered boundaries for each product. If these boundaries are conscientiously programmed, very fine errors can be revealed.

To the conventional displays of curves, the display of the hydraulic or melt pressure against injection position can be added. With the aid of a computer program, the injection work can be computed. This so-called work integral enables a direct graphical evaluation over a specified period of time. It permits rapid interpretation and rational monitoring of the tolerances. Since the integral boundaries are easy to change using the cursors, a product-specific computation can be made.

Fast Response Controls

Onboard computer controls for injection molding machines are becoming much faster. Since the early 1980s, improvements have steadily increased the speed at which closed-loop controls can adjust the injection molding process. New hardware based on state-of-the-art microprocessor chips and computer architectures is building on that performance geometrically.

Among the latest developments are (1) an advanced (but economical) microchip that bypasses the need for trafficking routine instructional messages, thereby enabling the computer to operate much more quickly; (2) dedicated control boards that speed up reaction to changes in the molding process (there are communication controls that can process data 20 times faster than conventional microprocessor-based controls); and (3) the quest for more powerful expert systems, yielding one that responds rapidly and accurately to online changes in material flow characteristics.

Increased speed and computing power bring several advantages that have direct impact on injection molding quality and cycle times. Most important, faster hardware reduces the time necessary for the injection control to detect change in a process parameter and react to it. More control speed means more profitability, particularly when the injection machine shifts from one task to another. An example is the critical switch from the injection to holding phase. This fast hardware can provide other benefits. Increased computing power in the control system makes possible improved computer graphics that present process data in ways easier for operators to understand. Also, advanced computer concepts such as expert systems and fuzzy logic are making their appearance on the factory floor. In certain applications, these should ease the operator's job by suggesting courses of action in "upset" conditions or by making the machine more self-regulating.

Fuzzy logic has become a common means of providing temperature control. It builds expert intelligence into the standard PID (proportional/integral/derivative, to be reviewed later) controller, enabling it to adjust its response to process conditions rather than respond by a fixed set of instructions. This adaptability is particularly important in preventing overshoot and reaching a stable condition faster during start-up, when changing setpoints, or when recovering from a process upset. During start-up, for instance, a typical controller keeps the heaters on continuously until the lower limit of the proportioning band is reached. It then starts to vary the ratio of on-off time as the temperature approaches the setpoint.

However, in many cases, because of the thermal characteristics of the machine or process, the proportioning action may start too late, resulting in overshoot and oscillation. Or, if too soon, the approach to the setpoint may be too slow. Fuzzy logic monitors the dynamics of the process and acts like an expert operator to optimize the heater response if the preset tuning variables are not doing the job. In some systems, it can learn the process characteristics as the process proceeds and

can then further sharpen controller performance.

In any process or experiment, control is the reference base with which the results are compared. The control represents known or target requirements of facts and/or figures. The use of a control is vital to provide interpretation of the final product. The digital age has transformed many traditional design and implementation methods in actuator and control manufacture. Chief among these transformations is the use of serial communications in conjunction with a programmable logic controller (PLC or PC) used to oversee machine operations.

The advantage of a serial communications network is that its single common thread runs throughout the plant floor, replacing large, hard-wired umbilical that is costly both to install and maintain. The overall advantages are well documented in many industrial applications.

A *change control* comprises those activities that deal with product changes from the proposal to the implementation stages. It encompasses areas of raw materials, software, devices, processes, labeling and packaging, inspection, etc. Change control problems affect different plants in different ways. Therefore, device manufacturers must implement a procedure for managing changes in a product or in the manufacturing processes.

Each manufacturer needs to find a model that complies with quality system regulation (QSR) and is suitable for its product and company, making appropriate adjustments as experience reveals new or better ways of handling changes. As with other similar situations, the start-up costs of such a project may seem high, but they should be weighed against the long-term benefits of improving efficiency and reducing the likelihood of recalls or lawsuits.

There are closed-loop systems used with microprocessors for control of a machine's line from start to the finish. A controller compares input signals with set inputs; corrections are made when required. The system feeds back information such as dimensions to adjust line speed and to correct for dimension shifts.

Derivative control ensures that a continuous linear relationship between controller output and the derivative of error signals that the computer receives is maintained.

Virtually all machines in a production line are electronically line shafted or designed as individually powered sections that are then precisely synchronized by digital control. The excellent performance of these "shaftless" machines is rapidly leading to the demise of the mechanical line shaft. Electronic line shafting sectionalizes the machine into separate sections, each powered by its own high performance digital servodrive. A master control electronically synchronizes all machine operations, communicating in real time with each section's drive motor over a single fiber-optic cable. This shaftless design eliminates mechanical inaccuracies and provides for electronic registration with minimal loss of product during start-up. Trial and error mechanical adjustments are replaced with highly precise push-button electronic control.

Control Approaches

Control approaches must be thoroughly analyzed and studied to obtain the desired performance of the complete line and/or its parts. The first task is to determine what is required and how to approach any problem. Adequate process control and its associated instrumentation are essential for product control. Sometimes the goal is precise adherence to a control point, while at other times it is sufficient to maintain a control within a comparatively narrow range. For effortless controller tuning and lowest initial and operating cost, the processor should select the simplest controller (temperature, time, pressure, flow rate, etc.) that will produce the desired results.

Controls are neither a toy nor a panacea; they demand a high level of expertise from the processor. There are those that:

1. Provide closed-loop control of temperature, pressure, thickness, etc.
2. Maintain preset parameters

3. Monitor and/or correct equipment operations
4. Constantly fine-tune equipment
5. Provide consistency and repeatability in the operations and
6. Self-optimize the process.

Most processes operate more efficiently when functions must occur in a desired time sequence or at prescribed intervals of time. In the past, mechanical timers and logic relays were used. Now electronic logic and timing devices are used based on software programmable logic controllers. These lend themselves to easy set-up and reprogramming (Chap. 9).

Process Control Methods

Process control of one type or another has always been used to mold products. They can range from unsophisticated, such as manual, open-loop, and closed-loop methods, to very sophisticated electronic/computer processors, such as computer integrated manufacturing (CIM). The various techniques can be classified as:

1. Manual control
2. Control of electromechanical devices after manual setting
3. Control by electronic circuits and manual settings
4. Control of definite programs
5. Open-loop control of some important parameters (speed and pressure) with manual programmed sequence control
6. Programmed open-loop control and
7. Programmed closed-loop control (1, 7, 298, 550).

Open-loop and closed-loop controls With open-loop control one or more input signals from a signal device(s) are modulated into an output signal based on the interrelations of the control system. Open-loop control is characterized by an open sequence of actions across the individual transfer ele-

ments of the control system. The control mechanism is capable of compensating the effect of any interference that can be measured by the system. Such a control system can result in excellent product constancy of separate process steps if distinct control circuits prevent any influence of other variable elements. However, the other variable elements, such as melt viscosity, could influence results.

A closed-loop control feeds back the output signals from signal devices and continuously compares its value with the input set signals. Any deviation from the set signals produced by interference is used to correct the controlled output. A process controller determines the difference between setpoint and actual performing output and takes appropriate steps based on its software program so that the difference is eliminated. Thus the output signal is measured and the closed-loop controller returns the output signal to the required reading.

Both of these "loop" controls have their place. To say closed-loop control by itself is the best is not correct. If a very constant process has to be carried out and repeated, then a stable open-loop control can be used. If the process is not constant (i.e., exhibits unsystematic temperature and/or pressure disturbances) then closed-loop control can be used to control the individual disturbances. This summation has to be related to the accuracy and reproducibility of operating the IMM, which depends essentially on the machine's hydraulic and/or electrical methods and repeatabilities of controls.

Production Monitoring

For over a quarter century various systems have been available for monitoring the efficiency of the injection molding production floor. Usually these systems do not reside on the individual IMMs but resides in the foreman's office. Most of these systems use a simple interface with the molding machines. Usually the closing of a contact at the beginning of injection is used to monitor cycle time. In addition there is usually a provision for a report

from a local station identifying the cause of any downtime. This information is then transmitted to the foreman's office. These are passive systems in that no corrective action is taken by the system. It remains for the expert foremen to decide what action is to be taken.

Expert advisory systems can be divided into the two classes: off-line systems and on-line systems. Offline systems are those that are not connected to the network or molding machine. They gain all their input through a question and answer session with the molder. Online systems are those that get much of the input directly from the molding machine or network. These usually require input from the molder or quality control (QC) person about the physical characteristics or attributes of the products being molded. None of these systems hit the mark of being a true online expert system for injection molding.

Online expert systems utilize hardware and software programs that require devices (sensors, transducers, etc.) to obtain all useful information. Examples of the devices required include special nozzles to sense melt temperature and pressure, hydraulic or electrical system temperature and pressure, screw position and rate of travel, and so on. All these devices will pass through a machine-mounted terminal. This action will allow communication with a computer (Chap. 9) and allow for an interface with the machine operator for information such as the molded part characteristics and reason(s) if downtime occurs.

By applying proper statistical methods (Chap. 13), flow simulation algorithms, and experimental techniques, process variations can be predicted. Using the operator interface, alarm situations can be displayed along with recommended corrective action before the process produces any bad parts. Through this approach the molder gets closer to the goal of unattended molding, which alleviates the problem of finding experienced set-up people (217).

Developing algorithms The development of these control systems involves the development of algorithms (procedures for solving a mathematical problem) to be used by the system. Much of the work centers on develop-

ing techniques for modeling the process from empirical data. Many of the system's frameworks allow for the execution of external programs that use these algorithms (298, 491).

Two tools that can be useful in the development of these algorithms are designed experiments and abductive induction. Designed experiments make use of orthogonal arrays to reduce the amount of data required to investigate the factors affecting a process (480). Induction is a reasoning process whereby one takes information on specific cases and develops general principles. This process can be used when the information is known with certainty. However, frequently the information may be in the form of a probability of a value being true. To deal with such uncertainties, C. S. Peirce introduced abductive reasoning in the 1880s (407, 450). Thus abductive induction is the process of developing general principles from information that may be uncertain. This extremely powerful tool makes it possible to obtain solutions for applications too complex to solve using other methods, in particular for: (1) finding solutions for missing or contradictory data, (2) problems involving unknown relations among variables, and (3) obtaining real-time solutions to complex problems. Different case studies have been prepared to demonstrate the use of abductive induction to develop algorithms, such as those at the Erie Campus of Penn State University (217).

On-Machine Monitoring

There are a number of different monitoring schemes available. First, for clarity, let us distinguish "monitoring" from "controlling." Monitoring means watching or observing—in our case, the performance of a molding machine. Traditionally, on an injection molding machine, this is done in a variety of ways: by time and temperature indicators, screw speed tachometers, hour-meters, mechanical cycle counters, and the like. Controlling means just that: command and directional capability.

Often, a control function is combined with monitoring in one instrument. These devices may be called "indicating controllers."

This review will focus on monitoring as opposed to controlling—specifically, monitoring parameters such as cycle time, downtime, rate, and totals as opposed to temperature, pressure, and other process parameters.

There are several levels of sophistication available in monitoring devices for molding machines. The crudest, the old technology, is the mechanical stopwatch. There are two serious deficiencies with monitoring by mechanical stopwatch:

1. The worst indictment is that it is impossible to monitor the machine with sufficient frequency to be certain that the cycle time has not changed, because stopwatch monitoring is very time consuming for whoever is taking the readings. There is also often a conflict between responsibility for operation and responsibility for monitoring: The person running the machine may be supposed to monitor it but may not do so very often.

2. The accuracy of mechanical stopwatch measurements is notoriously poor. The major variable is the human one. The monitoring of machine cycle times is too important to allow human error in measurement to contribute to poor productivity.

More sophisticated “electronic stopwatches,” or monitors, are available that take advantage of the fact that molding machines have numerous signals that are specifically indicative of the cycle. These signals can be utilized to trigger the electronic watch by direct electrical connection to molding machine contacts. With these direct connections, accurate cycle times are assured. For example, measuring from the injection forward relay (a frequent choice) can provide an accurate, continuous display of overall machine cycle times (Fig. 7-16).

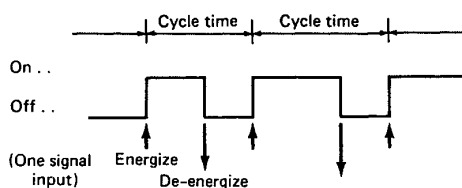


Fig. 7-16 Overall machine cycle.

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

1. Production can be maintained at the established optimum cycle time. Display resolution to 0.01 sec quickly shows changes. For example, if a mechanical or hydraulic problem is developing, it can be detected before it progresses to a breakdown. If unauthorized people are meddling with machine settings, they can be observed. When changes are easily seen, unauthorized people are deterred from making them.

2. Product quality can be kept high because cycle variations are minimized. Further, material changes that contribute a small cycle effect but have a significant product effect can be picked up with continuous, accurate monitoring.

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

In addition to monitoring overall cycle time, elapsed time displays can yield precise information about the individual elements that comprise the overall cycle. For instance, with a single-signal input cycle time display, the time at which a specific relay switch, valve, etc. is energized can be measured and displayed (Fig. 7-17). Other digital electronic stopwatches are available that accept input signals from two independent sources and can measure a variety of times between them (Fig. 7-18).

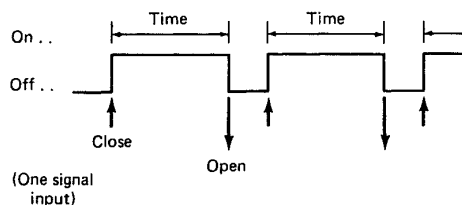


Fig. 7-17 Single-signal input cycle time display.

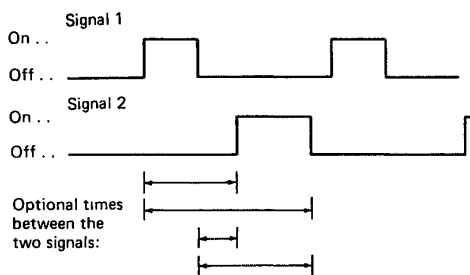


Fig. 7-18 Two-signal input cycle time display.

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

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

Before discussing more sophisticated monitors, let us examine why it is critical to optimize. It is simply a case of economics. As inflation has driven up the cost of everything, time has become more valuable. A cycle that is, on the average, 1% slow, in one year will cost more than one man-week’s production

Table 7-2 Lost time: 1% slow

Standard cycle (s)	10.00	30.00	59.0
Actual (s)	10.1	30.3	59.6
Lost time (h)			
(5,000-h year)	50	50	50

(Table 7-2). Note that 1% on the standard cycles listed is only a fraction of a second; many injection molding machines have cycle times less than standard.

Machine-hour rates, determined in a variety of ways, may range from \$15 to \$50/h. With the 1% slow losses shown in Table 7-2, the dollar losses in production would be at least \$750 to \$2,500/year in machine time. In general, these figures are conservative. Our experience in the field with elapsed time displays has shown payback on investment periods as short as 1 day, more typically 1 week to 1 month.

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

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

Additional data that may be compiled with these powerful monitors include totals, run

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

Monitors may also be obtained with outputs to drive typical machine audio and visual alarms. These outputs can be energized when downtime occurs, a slow cycle occurs, and a rate is below a user-input standard. (The latter is only available with the most sophisticated type of monitor, one that communicates bidirectionally to a key-board and computer.)

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

Temperature Control of Barrel and Melt

A quarter century ago, controlling the temperature on injection machinery was limited to a choice of either manual selection of the power to the heaters or simple on-off closed-loop switches. Today, a bewildering assortment of control theory approaches and techniques have been promulgated, and a broad selection of products is available to implement the application of the chosen theory.

Comprehensive literature exploring a variety of theories is available, but it is not

the intention of this presentation to explore or summarize this body of literature. This discussion will acquaint you with the latest developments in the quality of temperature control, present both the component and systems approaches, and provide some insight into what the future holds.

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

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

1. Is the thermowell too big for the TC protection tube? Air is an excellent insulator.
2. Is there contamination inside the thermowell? Rust, scale, and residue prevent proper contact of the protection tube with the thermowell.
3. Is the TC junction partially open?
4. Are there oxidation and corrosion inside the protection tube?
5. Is the proper extension wire being used? Copper wire allows another thermocouple junction.
6. Is extension wire polarity observed? A single reversal will give a downscale reading; a double reversal will result in an erratic input to the controller.
7. Are wire terminations properly isolated? False cold junctions are a common problem.

8. Is the cold junction compensation at the extension wire termination on the controller working properly? A poorly positioned or poorly connected compensation component will allow the input to vary.

9. In the panel, are the thermocouple leads isolated from the ac wiring as required? Are the TC and ac wiring run in separate conduits from the control cabinet to the machine as required?

10. Is the control cabinet thermal environment within the specification of the controller? Excessive cabinet temperatures can cause a controller to drift.

11. Examine the power contactor. If it is a mechanical contactor, deterioration of the contacts can result in reduced power delivered to the heaters.

12. Are the heaters sized correctly? Modern temperature controllers can compensate for limited missizing but cannot substitute for proper design.

13. Heater bands must be secured tightly to the barrel; again, air is an excellent insulator.

14. Check the voltage being supplied to the heaters. High voltage leads to premature heater failure.

15. Inspect wiring terminations at the heater band; connections must be secure.

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

Microprocessor-based designs provide several distinct advantages. Already mentioned is the inherent ability to control the temperature at setpoint. Sometimes, they do this too well. There are reports, in fact, of cases where the customer claimed the controller was not

working, because the process reading was the same as setpoint for an entire shift. Microprocessors do not drift; they either work perfectly, or they experience a catastrophic failure. They are absolutely repeatable, allowing the operator to duplicate a log of setpoint temperatures perfectly the next time that particular job is run. Microprocessors allow a natural avenue for providing digital displays of process information. Values are not subject to inaccurate interpolations and misreadings. In new installations, the precision of the digital readout has sometimes proved to be a two-edged sword. We have provided start-up assistance in plants where the operator reports the process reading to be several degrees different from the setpoint. An investigation usually will discover a problem in one of the control loop segments previously outlined. One has to conclude that the problem had existed for some time; the customer just never knew it because the process drum meter on his or her old instrument could not be read to any finer resolution than perhaps 10 deg.

Microprocessors allow the implementation of PID (proportional, integral, derivative) control at little or no cost. PID has been shown to reduce process variations by as much as 3 or 4 deg. Discussions of PID advantages are available from all major temperature control suppliers.

Microprocessor technology is relatively trouble-free. It is about six times more reliable than analog solid-state designs and about twelve times more reliable than millivoltmeter designs. Based on customer data, the maintenance costs on an analog instrument average \$100 annually; on a microprocessor design, the costs are reduced to \$12.

Another significant cost reduction effort being implemented recently with excellent results focuses on the controller output and power handling. Although an analog controller output accepted by a phase-angle or zero-angle SCR power controller is ideal in terms of power factor and heater life, it is a relatively costly arrangement. A more acceptable method, in line with cost restraints and providing very nearly the same advantages, is to use a controller with a solid-state

time-proportioned pilot duty output along with inexpensive mercury contactors or solid-state relays. The controller output cycle time can then be reduced to 10 sec or less, thus approaching the same constant temperature and heater life advantages available with the more costly design.

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

1. The unit will identify varying thermal behavior and adjust its PID values accordingly. Variables affecting viscosity include screw rpm, back pressure, variations in heater supply voltage, resin melt index, resin contamination, room ambient temperature, percent colorant, screw wear, barrel lining wear, heater and thermocouple degradation, percent regrind, hygroscopic characteristics, and feed zone instabilities. (The effects of these variables on melt temperature are thoroughly developed in several of this chapter's references.)

2. Savings in management and maintenance activity will result from autotuned temperature control. Documentation of PID values for various jobs and machines can be eliminated. Individual operator preference for PID values that vary from the norm is precluded. Maintenance personnel are not required to dedicate a particular unit to a specific zone; instruments can be interchanged at will, and spares can be installed with no attention other than selection of the appropriate setpoint. A payback through reduction of overhead costs alone can generally be expected in 6 to 8 months.

3. Energy savings is another major benefit. One customer study showed a 50% reduction in power consumed by the heaters, solely because the automatic tuning feature eliminates the cycling around setpoint normally associated with ineffectively tuned instruments.

Microprocessors also provide a means to communicate digital data to information collection stations. Although the economic feasibility of including the function with an

individual temperature control instrument has not been demonstrated in the plastics industry, the feature is beginning to enjoy significant exposure on multiple-zone injection machine controllers because of the low cost of adding another digital card to an existing rack. More commonly found in discreet controllers is an analog communications output that provides a signal to remote recorders.

The ultimate implementation of the microprocessor has been its design in systems installations. Available systems include multizone temperature control and multipoint, multiloop control of sequence. Systems that depend on a single CPU are available from many suppliers to control temperature, sequence, position, velocity, or pressure. Even more cost effective are the total machine controllers, which control all machine parameters from a single keyboard. As compared to individual instruments, these systems typically reduce the per-zone cost of control and provide unlimited future control flexibility as needs change. As production professionals discover the need to manage the process at the least possible cost, machine control systems that can communicate with a central management computer are of increasing importance. Central control systems are available that can simultaneously receive information from the injection machine and transmit required parameter changes or complete job setups at the same time. Many injection machines can thus be interfaced with a single control location. If central online control is not justified, but one-way machine reporting is required, a choice of several management information systems is available.

Electronic Controls

There are a number of different electronic controls: On-off, proportional, and PID (proportional, integral, and derivative) are the most common. The least expensive and easiest to operate is the full on or off control. Even though it has quick response, it is sensitive to input noise, which causes chattering of control output relays leading to a hysteresis effect. Proportional (P) control lacks any switching action. Instead it compares the

difference between the operators set value and the process variable. It controls and stabilizes the output proportional to the deviation within a setpoint called the *proportional band*. With temperature a smooth transition takes place. However, the temperature usually stabilizes with some deviation from the desired temperature, called offset (550).

The popular PID control provides a steady control system. Control is obtained by setting the constants of P (proportional band), I (integral time), and D (derivative time). The purpose of I is to automatically compensate for any steady state of set inherent with a proportional controller. The degree or rate of derivative action (D) is expressed by derivative time in seconds. The controller measures the rate of the temperature increase and moves the proportional band to minimize overshooting. PID is not a perfect control method since it becomes more sensitive to external disturbances. Advance systems are used providing quick stabilization against external disturbances and good response to setpoint changes.

To obtain a wider range of response fuzzy logic can be used. This machine intelligence approach permits computers and controllers to manipulate precise facts simulating the function of an expert operator. It is particularly effective in suppressing overshoot upsets when frequent load changes occur and for shortening IMM start-up time.

Modern process operations and production methods are characterized by an increasing demand for flexibility and integrated information systems with sophisticated human interface. Within the process industries model based predictive control (MBPC) is being successfully applied. This control strategy is based on the prediction of the future system behavior by using a process model (583, 590, 622). Further details of electronic controls will be discussed throughout the chapter.

Fuzzy Logic Control

Fuzzy logic controls (FLCs) were introduced during 1965 (by Zadeh) as a way of expressing nonprobabilistic uncertainties.

Since that time fuzzy theory has developed and found application in database management, operations analysis, decision support systems, signal processing, data classifications, and computerized vision. However, the application that has attracted most attention is control. FLC is being applied industrially in an increasing number of processing plants. The early work in FC was motivated by a desire to directly express the control actions of an experienced operator in the controller and to obtain smooth interpolation between discrete controller outputs. The earliest application of FLC (Mamdani & Gaines, 1981) was based on "mimicking the control actions" of the human expert operator (583).

Classical control methods have shown their use in many practical control problems in industry. It has been shown that the fuzzy control (FC) system approach can be used to solve these problems as well. Many applications of FLC, such as in PID controllers, are related to simple control algorithms. In a natural way, FLC handles the nonlinearities and exceptions that are difficult to deal with when using conventional controllers. In conventional control, many additional measures have to be included for the proper functioning of the controller: antiresist windup, proportional action, retarded integral action, etc. These enhancements of the simple PID controller are based on long-lasting experience and the interface of continuous control and discrete control. The fuzzy PID-like controller provides a natural way to applied controls. The fuzzy controller is described as a nonlinear mapping (Buckley, 1992).

The introduction of FLC has been controversial, resulting in misunderstandings. The controversial situation resides in the control theory community, owing to lack of mutual understanding between the FC and the conventional control communities. It is partly due to exaggerated claims made by the FC community and partly due to the presumptuous attitude of many in the traditional control community. However, in practice, FLC is becoming increasingly popular, partly because of the commercially available programming tools. Nonlinear models play an important role in many advanced controllers because of these programming tools. Modern

production methods and new innovative operations increasingly require control methods for handling nonlinear systems (583).

Process Control Techniques

A very simplified approach will be used in which selected critical molding variables are measured and controlled to maintain product consistency. The purpose of this review, as well as those that follow, is to provide a very basic process control guide so that one can understand how controllers perform. One should also review Chap. 4 (Molding Process Windows). The following Barber-Colman basic approach to injection molding process control involves the measurement and control of two critical molding parameters, ram position and mold (or cavity) pressure, during the mold filling and packing phases of the injection cycle (Fig. 7-19). It is during the filling and packing phases that most variations in molding conditions make themselves

evident and therefore can be easily detected. For example, a change in material viscosity is reflected as a change in ram speed and can be detected by measuring ram position with respect to time. A change in material viscosity also reflects itself as a change in plastic pressure and can be detected by measuring mold or cavity pressure with respect to time. Other variations in molding conditions, such as hydraulic pressure, oil temperature, melt temperature, etc., display themselves similarly and can be detected by monitoring ram position and plastic pressure with respect to time. Since it is possible to detect variations in molding conditions, it is also feasible to compensate or correct for these variations.

Primary injection pressure can be divided into two major phases: mold filling and mold packing (Fig. 7-20). As shown in Fig. 7-21, screw movement occurs primarily during the mold-filling phase, while mild pressure buildup takes place in the mold-packing phase. The association of screw movement with mold filling and mold

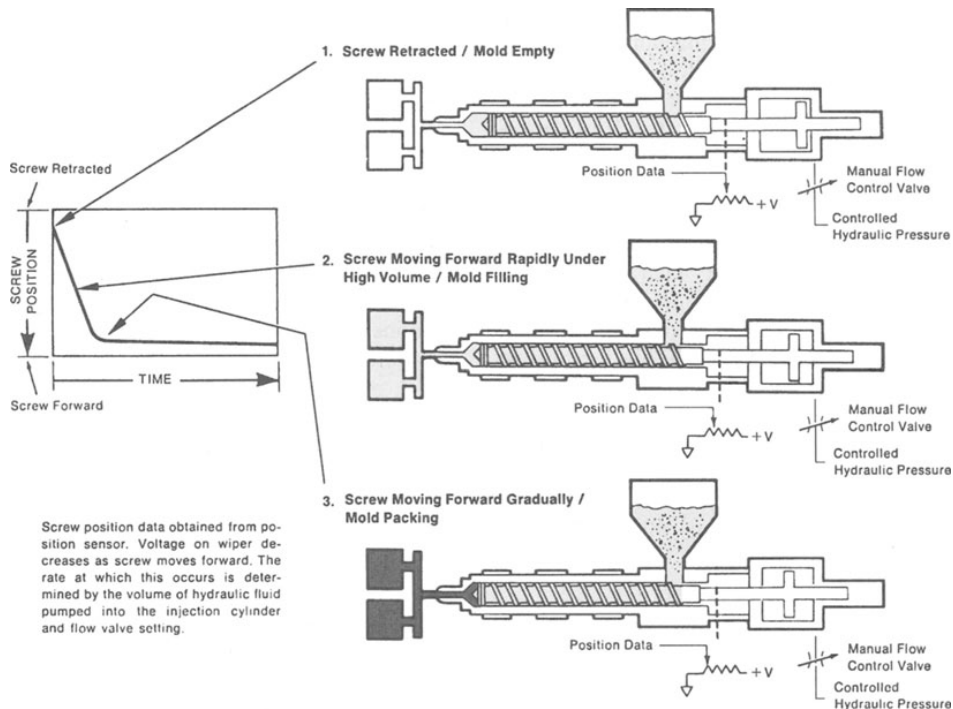


Fig. 7-19 Screw travels during rotation.

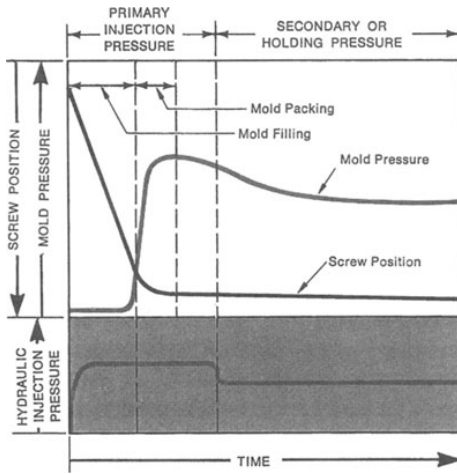


Fig. 7-20 Mold filling and packing segments (solid lines indicate signals before plastic change; dashed lines indicate signal after plastic change or after correction).

pressure with mold packing is important and should be remembered.

Attempting to control the molding process using ram position only or mold pressure only as the measured variable and adjusting primary injection pressure as the control function is not satisfactory because both mold filling and mold packing take place with the same injection pressure value. Changing

the primary injection pressure affects both phases of the injection cycle. For example, assume that a new batch of material with a lower melt index has been put into the feed hopper. Since the melt index is lower (apparent viscosity is higher), ram screw speed under a given primary injection pressure will decrease. This means that the mold will fill more slowly, and mold pressure buildup will occur later. Depending on the change in the material, the mold pressure will also decrease. The effect of the material change on ram screw speed and mold pressure is shown in Fig. 7-21.

To compensate for the material change and get the average injection rate back to normal, the primary injection pressure could be increased. Increasing primary injection pressure will increase the average injection rate, but at the same time this lowers the apparent viscosity by the effect of shear stress and shear rate applied to the material. Dynamically, this apparent lower viscosity carries over to the packing phase to a point that would result in increased mold pressure, overpacking, and a heavier part with stresses. The effects of the increased injection pressure are shown in Fig. 7-22.

The ram curve and thus the average injection rate have returned to their original value, but mold pressure due to the change in apparent material viscosity peaks out at

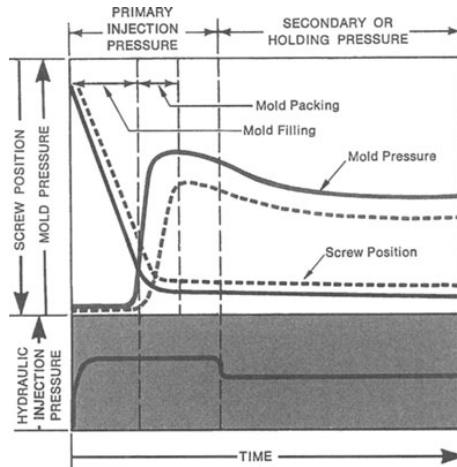


Fig. 7-21 Effect of melt indexes on screw position and mold pressure.

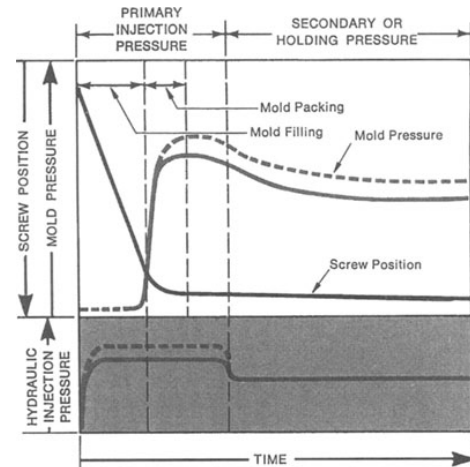


Fig. 7-22 Effect of injection pressure on screw position and mold pressure.

a higher value, resulting in an overpacked, more densely molded part. In all probability, the part would also stick in the mold.

Thus, control of the average injection rate cannot properly compensate for a change in material viscosity and produce an acceptable molded part. Without going into detail, it can also be shown that a control system based solely on the measurement and control of peak mold pressure will not successfully do the job either. In the case of a material with a lower melt index, peak mold pressure control will produce a part that is lighter and less densely packed—in other words, the opposite of that achieved with only ram position control.

The control philosophy of the Barber-Colman molding process controller is based on the independent measurement of screw ram travel and mold pressure during injection. Deviation of either of these variables, when compared to preset adjustment limits, initiates control action to bring the out-of-tolerance variable back within limits. This is accomplished in such a way that correction of one variable has minimal influence on the other.

To provide independent ram position and mold pressure control and eliminate interaction between the two, the mold-filling and mold-packing phases of the injection cycle must be isolated. In other words, you must be able to control the average injection rate during mold filling without creating a change in mold-packing pressure. Conversely, you must be able to control mold-packing pressure without affecting the average injection rate.

The first step in implementing control is to identify that point in time when the transition from mold filling to mold packing takes place. The second step is to identify that point in time when proper mold-packing pressure is reached. These points are readily identified, as shown on the ram position and mold pressure curves in Fig. 7-23. The identification of these points establishes where the control limits should be implemented. Each point of control has an upper and a lower limit, thus providing an operational bandwidth that allows for minor variations and also provides

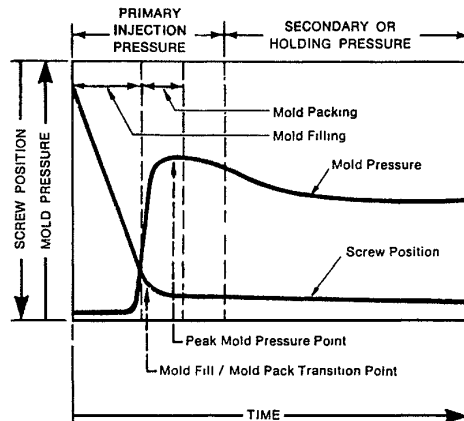


Fig. 7-23 Fill-pack transition and peak mold pressure point.

directional control for increasing or decreasing control pressures as required.

To isolate the mold-filling and mold-packing phases and prevent interaction, you must be able to control the primary injection pressure value for each phase. To accomplish this, a built-in timer that can be set to transfer primary injection pressure to a new setpoint value is provided. In this way, control action can be applied to the mold-filling setpoint value independently of the mold-packing setpoint value, or vice versa.

Figure 7-24 again shows the screw position and mold pressure curves. This time, however, the figure shows that primary injection pressure time is split into filling pressure time and packing pressure time segments.

The control of each segment is achieved via point-in-time sampling of both screw position and mold pressure and comparing the value of the sampled signals to adjustable upper and lower limits. Violation, by either variable, of the respective limits will cause the controller to generate a corrective signal that will add to or subtract from the corresponding setpoint, thereby incrementing a change in injection pressure. The pressure change, however, is applied only to that time segment where the violation occurred. In some cases, violations will take place on both variables, and a correction will be generated for each segment.

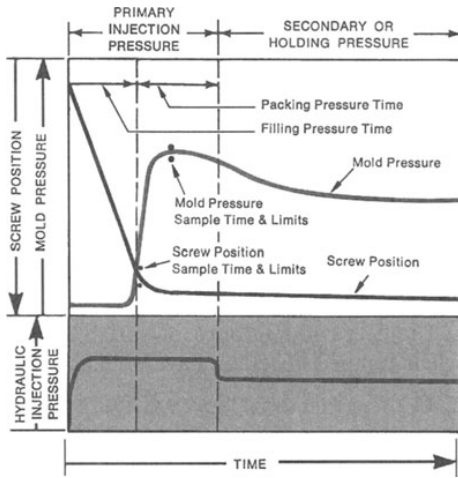


Fig. 7-24 Ram position-mold pressure control points.

For example, assume that the same conditions exist as used previously when a new batch of material with a lower melt index is put into the hopper. Since the screw moves more slowly, it violates its upper limit. Mold pressure, because it does not reach the same peak value, will violate its lower limit. Both conditions call for an increase in injection pressure. The effect on the ram position and mold pressure curves is shown in Fig. 7-25.

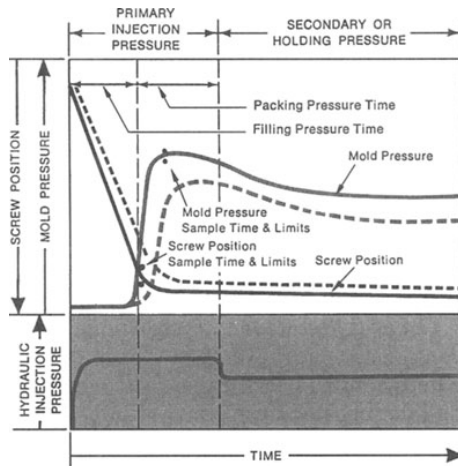


Fig. 7-25 Effect of increased viscosity on ram position and mold pressure.

The amount of correction applied to each pressure setpoint is independently adjustable, thus allowing mold filling and mold packing to take place with different injection pressure values. The increased pressure applied during fill pressure time will cause the ram screw speed to approach the original value. Just how fast it approaches the original screw speed depends on two factors: the amount of deviation and amount of correction applied by the controller.

The mold pressure lower limit violation called for an increase in injection pressure during packing pressure time. Here again, the rate at which it returns to the original value depends on the amount of deviation and amount of correction applied by the controller. The effects of applying independent corrective signals are shown in Fig. 7-26.

Even though we have segmented the mold-filling and mold-packing phases by using separate pressure setpoints and a timer, we cannot totally remove the interactive effects caused by the machine dynamics. The response of the hydraulic system and the machine mechanical parts must be considered, particularly in setting the filling pressure-packing pressure transfer point. This is normally set to transfer just prior to the ram position sample point to

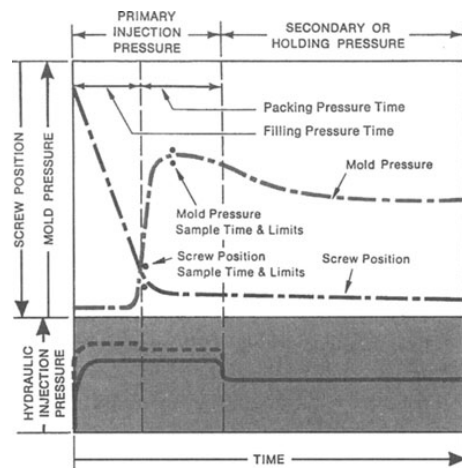


Fig. 7-26 Effect of pressure correction applied to ram position and mold pressure.

accommodate the dynamics of the hydraulic system.

Pressure correction should be applied such that the respective process variable (average injection rate or mold pressure) returns to its original value in small incremental steps rather than in one abrupt rather large step. Approaching control in adjustable incremental steps allows time for the machine dynamics to respond and eliminates the possibility of cycling above and below the control points. Independent control of mold filling and mold packing allows each segment to be brought back in control independent of the other in the least amount of time without interaction.

Process Control Approaches

To mold successful products requires many dynamic fragments that must come together properly. Lack of sufficient process control over any of these fragments will result in a less than desirable product. There are three key ingredients that the plastic injection molding process must have to make a good product:

- Sufficient dynamic performance
- Sufficient repeatability
- Selection of proper control parameters

A lack of these ingredients can result in:

- Higher scrap rates
- Longer run times
- Higher part costs

The purpose of this section, based on Moog controls, is to:

- Point out what variables are a part of the injection molding machine and how they manifest themselves.
- Select parameters for control that best eliminate variability and understand why they do.
- Discover what enables controllability.
- Discover what features a basic process controller should have.

Applications of these basic features will also be presented.

What Are the Variables?

To judge performance, there must be a reference to measure performance against. In the case of a plastic mold, the cavity pressure profile is a parameter that is easily influenced by variations in the process. It is selected as a reference for this discussion. This subsection points out how the variables affect this parameter and their effect on the part being molded.

There are four groups of variables that when lumped together have similar influences.

Group 1: Melt viscosity and fill rate Typical nonprocess-control machines apply a fixed injection hydraulic pressure to the ram piston. The resultant force, in turn, is counteracted by the speed of the ram in the viscous plastic melt. The result is a fill rate inversely proportional to the viscosity of the melt and proportional to the hydraulic pressure. The lower the viscosity and/or the higher the hydraulic injection pressure, the faster the fill rate. Fill rate variations with a constant boost time are shown in Fig. 7-27. If the fill rate is too fast (curve a), the cavity pressure increases long before boost time out. The result is overpacking of the part. Some of the effects are flashed and/or out-of-tolerance parts on the (+) side. If the fill rate is too slow (curve c), just the opposite happens; cavity pressures indicate underpacked parts, resulting in poor surface finish, voids, and/or dimensional problems. Group 1 variables (injection pressures, melt temperatures, melt viscosity, and fill rate) are clearly interrelated and have dramatic effects on part characteristics, as evidenced by the cavity pressure variations of Fig. 7-27.

Group 2: Boost time Typical nonprocess-control machines have a boost timer to terminate the fill and pack cycle. Even with good fill rate repeatability, variations in peak cavity pressures can result from variations in the time the ram is in the boost mode (see Fig. 7-28). These variations typically result from valve and solenoid response times from

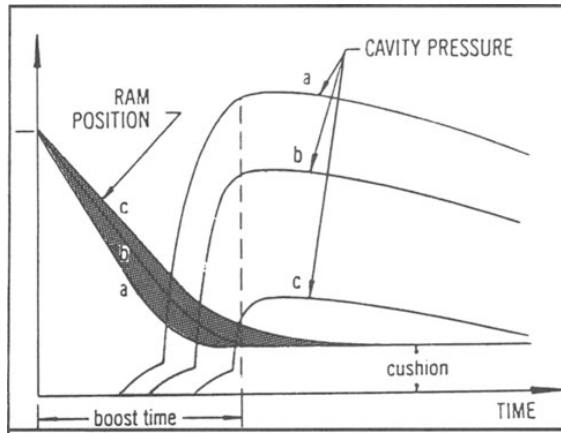


Fig. 7-27 Cavity pressure variations resulting from different melt viscosities and different fill rates.

one cycle to the next, as well as long-term drifts of these components. Cavity pressure variations that occur when coming out of boost have the same effect on parts as the group 1 variables. The problem is addressed separately here because its solution is different from that for group 1 variables.

Group 3: Pack and hold pressures Typical nonprocess-control machines use the same ram pressure setting during the packing of the mold as was used during the filling of the mold. The level of the pressure setting is that which gives good mold fill-out without flashing the mold. Variations in this pack pressure result in cavity pressure profile variation (see

Fig. 7-29). These cavity pressure variations indicate an inconsistency that can be causing dimensional and surface finish problems. These pressure variations are a result of relief valve repeatability problems caused by valve wear and temperature conditions, as well as shot-to-shot variations. In addition, the final pack pressure setting may be limiting you to a less than time-optimal part fill ability.

After the part has been packed, the boost timer reduces the applied hydraulic pressure to a hold pressure while the part cools. At this point, the cavity pressure sensor starts to lose accurate plastic pressure readings because the part surface is beginning to harden. Further deductions made from this signal would

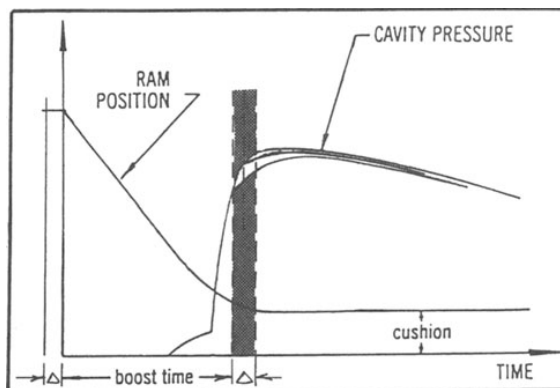


Fig. 7-28 Cavity pressure variations resulting from boost time variations.

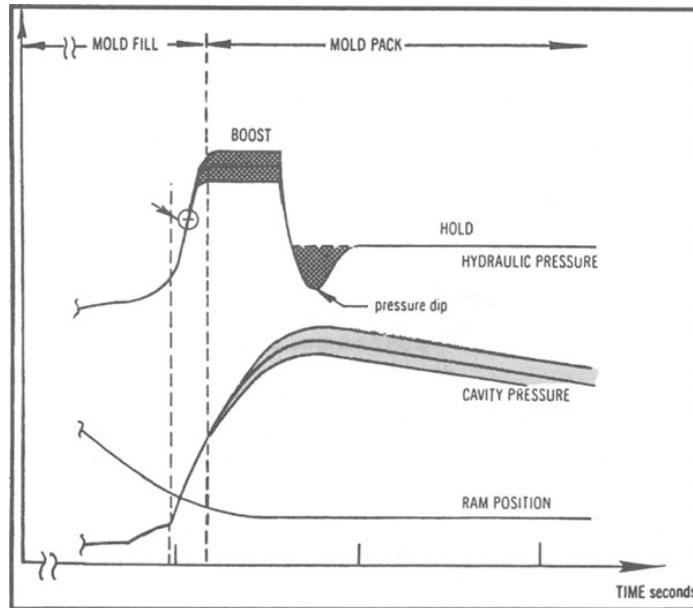


Fig. 7-29 Cavity pressure variations resulting from boost pressure variations

be inaccurate. Experience has shown, however, that in switching from pack to hold, a pressure dip (see Fig. 7-29) can cause sinks in the part surface.

Group 4: Recovery or plastication The variables that are involved during recovery do not appear on the cavity pressure profile until the next fill cycle. Recovery has much to do with the viscosity of the melt (see under group 1 variables.) Recovery variables can be identified, however. These variables have to do with how much energy is added to the plastic material; this energy and the resulting viscosity will vary,

The three main variables in descending order of importance are:

- Screw torque times speed
- Back pressure times rate of ram withdrawal
- Barrel temperature

Efforts to control these variables typically have to do with flow and/or relief valves, which have their own short- and long-term problems.

Why Have Process Control?

Simply stated, there are three reasons for a process controller:

- To select a group of controlled parameters that will gain control over the process variables
- To improve the parameter repeatability
- To improve the parameter setability

Control of Which Parameters Can Best Eliminate Variability?

Fill cycle To eliminate variations of mold fill resulting from all the group 1 variables, a control scheme that modulates the hydraulic pressure as viscosity variations and mold reaction forces occur would be desirable. This is known as fill velocity control. Velocity is the independent parameter, and hydraulic pressure is the dependent variable. Figure 7-30 shows how the hydraulic pressure may have to vary to keep the independent velocity (rate of ram position change) at the commanded

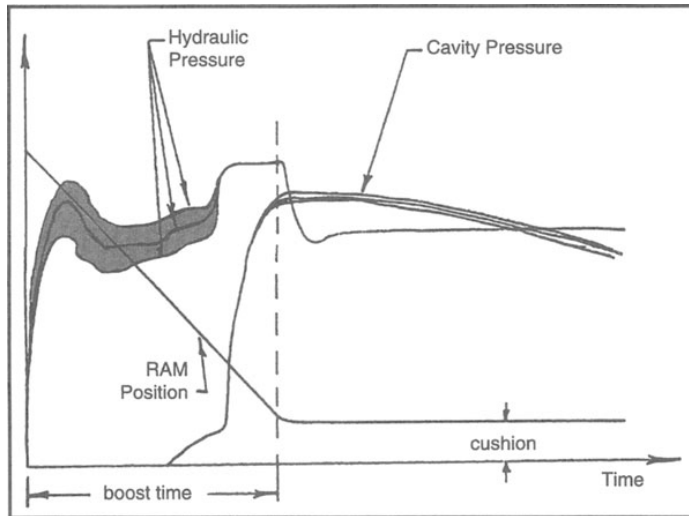


Fig. 7-30 Cavity pressure consistency despite different melt viscosities, a result of closed-loop control.

level. The result is a more consistent filling of the mold and more consistent cavity pressure profile. One added benefit is that injection pressures may exceed back pressures if necessary to achieve a desired fill rate.

Fill-to-pack The elimination of boost time variation is possible by simply removing the boost timer. However, something must replace it that is sensitive to the occurrence of the operation following fill. At this portion of the cycle, the mold will be essentially filled, and any further filling will result in extensive compression of the plastic melt. Plastic compression is necessary for good part qualities, and the extent of compression must be properly controlled. When this event is close at hand, a dramatic rise in hydraulic and cavity pressure is experienced, as seen in Fig. 7-31. Sensing the dramatic rise in hydraulic pressure will place the end of fill at its proper time without the use of a timer. Connecting the detection of this event to a specific region (see Fig. 7-31) allows higher injection pressures during fill if they are needed.

Pack and hold In the case of pack and hold, the proper parameter has already been selected: pressure. However, the methods of

pressure control can be improved. The level of pressure in pack or hold and the dynamic performance are important, and ways to improve them are discussed later.

Plastication Proper melt viscosity is the desired end for the plastication phase of a machine cycle. There is not yet a good way to tell if the plastication phase has done its

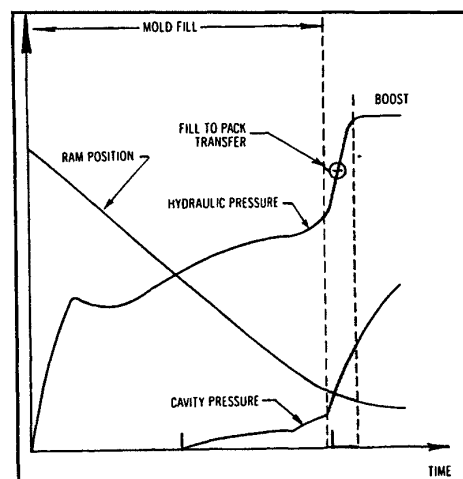


Fig. 7-31 Fill-to-pack transfer.

job properly until the next part is made. This might be fertile ground for the development of a transducer to measure viscosity at the tip of the screw as feedback to an algorithm for control of screw speed and back pressure. In the absence of such a device, attempts are made to keep the energy added to plastication as repeatable as possible. The three parameters that are controllable are the melt screw speed, back pressure, and barrel temperature. Speed and pressure control on standard machines imply flow and pressure valves, and each of these devices brings with it short- and long-term variations. Ways to improve flow and pressure control are dis-

cussed later. Temperature, the third parameter, appears to be sufficiently controllable with state-of-the-art devices.

In summary, most variables can be eliminated through the use of two parameters: velocity and pressure. The more repeatable, the more dynamically controllable these parameters are made to be, the better the ability an injection molding machine will have to mold a part. Figure 7-32 seems to demonstrate the repeatability brought to making a part with improved parameter control. This figure shows the difference in cavity pressure repeatability with open- and closed-loop machine control.

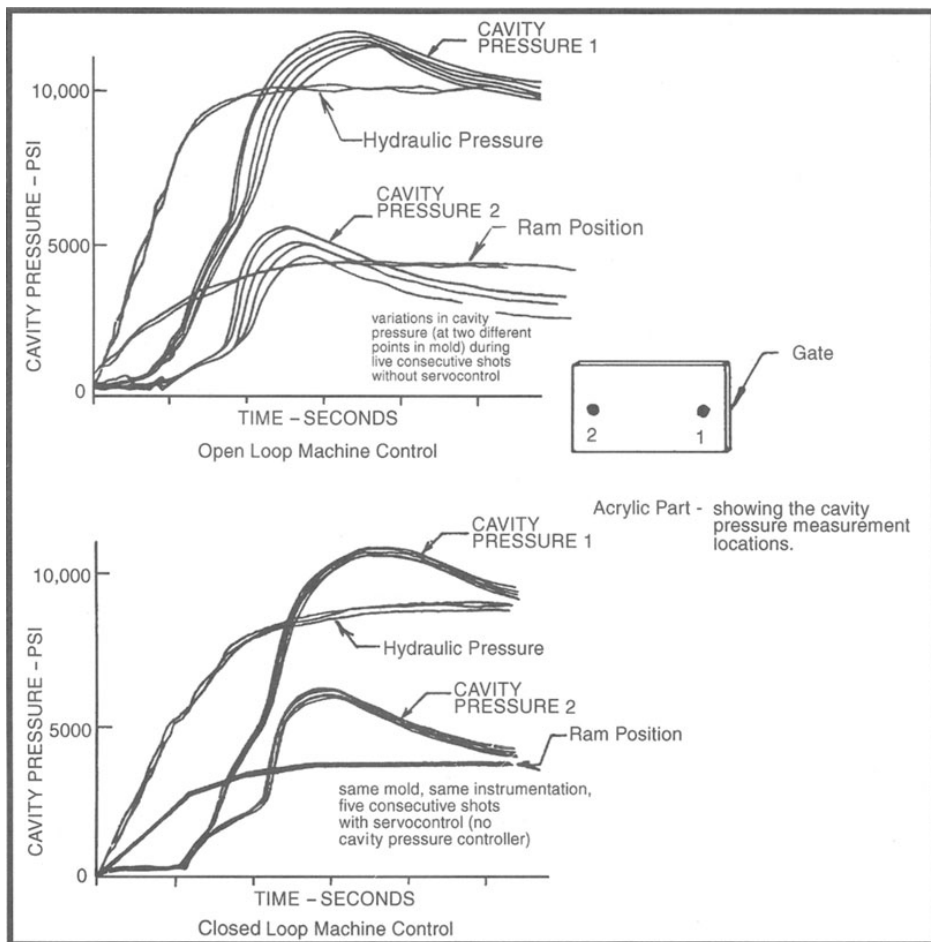


Fig. 7-32 Repeatability data; five shots.

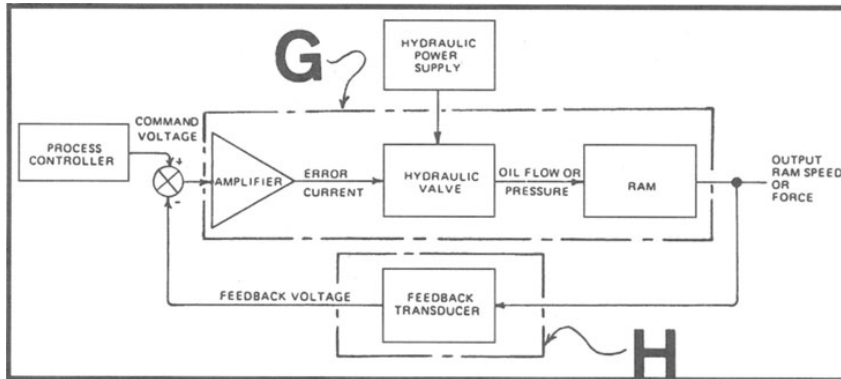


Fig. 7-33 Closed-loop control.

What Enables Parameter Controllability?

Closed-loop servocontrol is the best known way to control a parameter. Closed-loop theory says that a parameter is measured with a sufficiently accurate transducer. The signal from the transducer, representing the parameter's value, is compared with a desired signal level for the parameter. The difference or error is amplified as much as possible before being sent to a control element for correction of the parameter.

Figure 7-33 depicts a closed-loop control of ram speed or pressure (force). A transducer (one for speed and one for pressure) measures the parameter under control. It creates a feedback voltage in accordance with its transfer function H in volts per unit pressure or volts per unit velocity. A summing junction compares the feedback voltage to one commanded by the process controller. The difference is sent to the forward-loop elements (amplifier, control valve, and ram piston) whose lumped parameter transfer function is G , with units of speed per volt or pressure per volt. Using the lumped parameter transfer functions, we can express the servoloop transfer function mathematically as the following equation:

$$\frac{\text{OUTPUT}}{\text{COMMAND}} = \frac{G}{1 + GH} \bigg|_{\lim G \rightarrow \infty} = \frac{1}{H}$$

Using differential calculus, it can be shown that as G gets very large, the servoloop transfer function becomes that of the transducer.

This is an important concept because it eliminates all the anomalies of the forward-loop elements such as drift and nonlinearity. The controlled parameter's value is now a function of the transducer used, not the controlling elements of the forward loop. This, then, is what gives closed-loop control the ability to provide better control over the parameters of velocity and pressure, as well as others not used here.

The ability to make G large depends on three factors:

- Load natural resonant frequency
- Valve response and load flow characteristics
- The type of frequency compensation used in the amplifier

Load resonance Load natural resonant frequency is a physical phenomenon resulting from the ram piston and screw mass interacting with a hydraulic oil spring. The desirable condition is one of high load resonance. Little can be done with the mass involved to improve the resonant frequency, but the oil spring can be influenced. The oil spring is made up of all oil volume directly influencing the ram piston. Figures 7-34 and 7-35 are hydraulic schematic representations that use piloted relief and flow divider valves. When ram piston pressure is to be raised or lowered for control purposes, all the oil volume from pump to piston must be pressurized or depressurized. This larger volume of oil ends in causing a less than maximum possible load

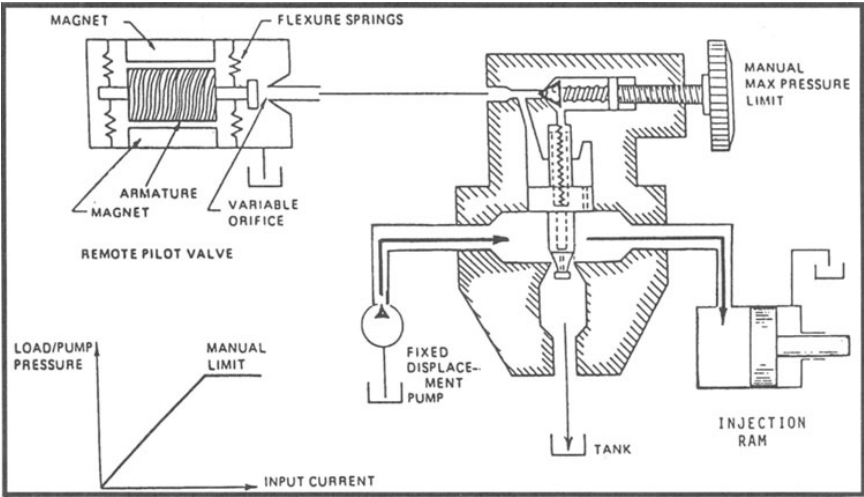


Fig. 7-34 Remote piloted pressure relief valve.

resonance. The closed-center servovalve, depicted schematically in Fig. 7-36, provides the higher load resonance because the only oil to see load pressure variation is that between the valve and piston. The best results are obtained when the valve is mounted closest to the ram piston. The higher the load natural resonant frequency, the better the dynamic performance exhibited by the servo. The key to choosing a method is the type of performance needed from the machine.

Control valve response and load flow The ability of a control valve to react to an input from the forward-loop amplifier directly affects the amount of forward-loop gain G that can be added to a servoloop. Since there are various manufacturers of valves that exhibit different performances, the valve selected should have sufficient performance for what is expected of the servoloop. Figure 7-37 shows the response capability for three different valve manufacturers.

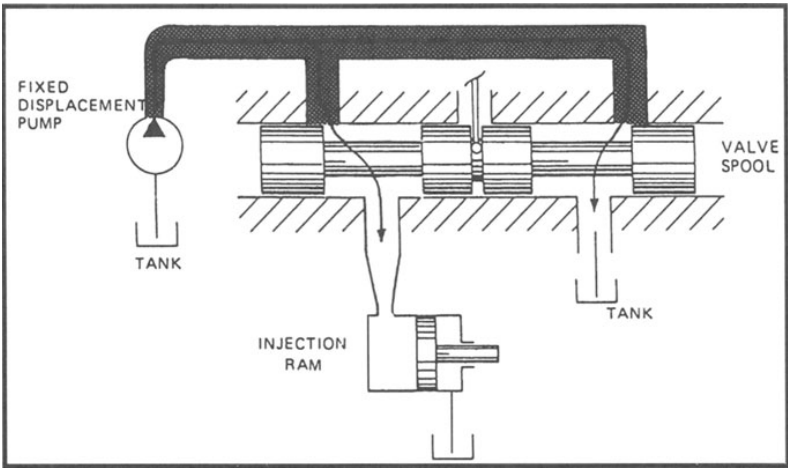


Fig. 7-35 Flow diverter.

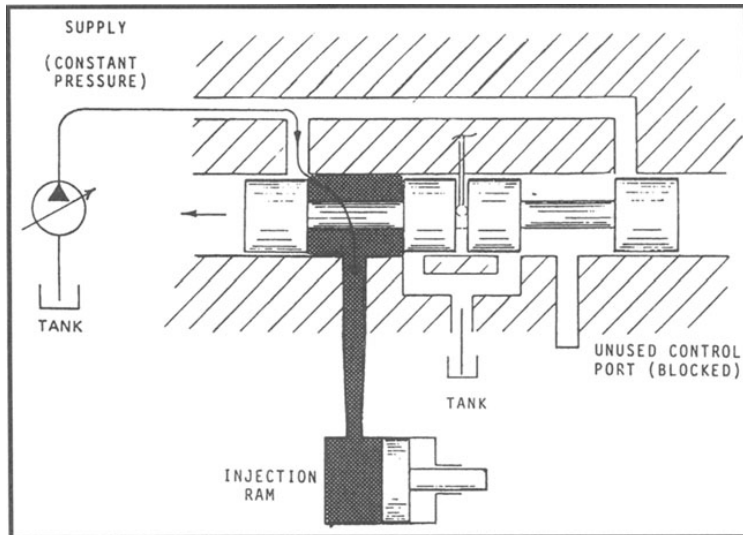


Fig. 7-36 Closed-center servovalve.

The type of load flow a control valve exhibits can also limit the amount of forward-loop gain G that can be achieved in a given servoloop. As the valve is required to deliver flow to the ram, its flow gain (change of load flow for a change of input command) will vary as the load pressure varies. This characteristic is shown in Fig. 7-38 for a closed-center ser-

vovalve. As the load pressure increased from 0 to 1,500 psi (0 to 10.3 MPa), the valve drop went from 2,000 to 500 psi (13.8 to 3.4 MPa). This 4 : 1 drop in available valve pressure was accompanied by a 2 : 1 drop in valve flow (see the dotted line of Fig. 7-38.) It is a square root relationship. As the load pressure increases and the valve drop decreases, the valve flow

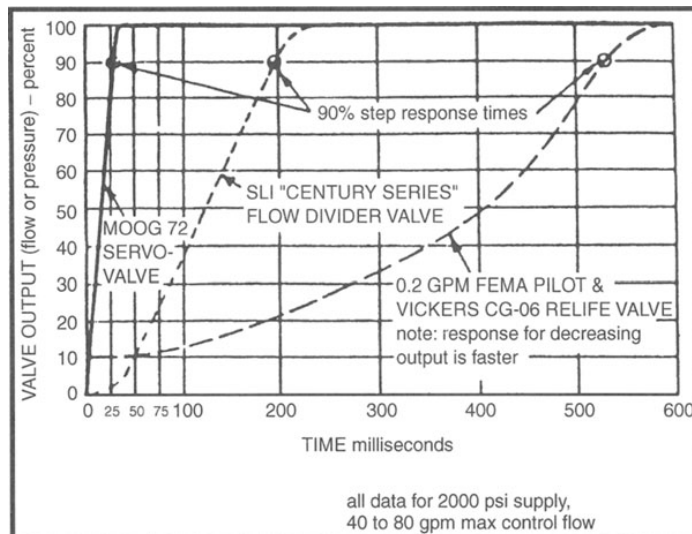


Fig. 7-37 Response capability of three valves.

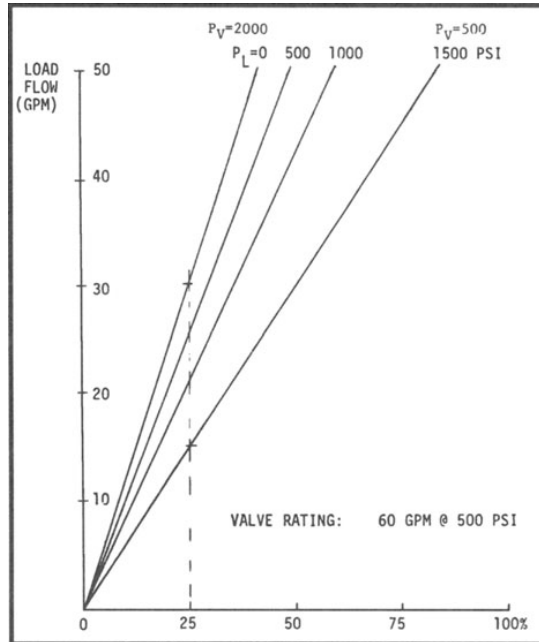


Fig. 7-38 Closed-center servovalve flow plot.

gain drops as the square root of the change in valve drops. Although this reduces the valve's contribution toward forward-loop gain G , it is *not* a destabilizing effect. In the case of the flow divider whose characteristics are depicted in Fig. 7-39, the opposite is true. As the ram load pressures increase, the slope of

the flow versus input curve increases. This apparent flow gain increase has a destabilizing effect on the servoloop and limits the forward-loop gain G at lower loads, since the maximum loop gain must be sent for stable operation at higher loads.

The added performance a closed-center servovalve can provide for a servoloop suggests that it should be a favored device. With today's technology, there is little cost difference between the closed-center servovalve and the flow divider.

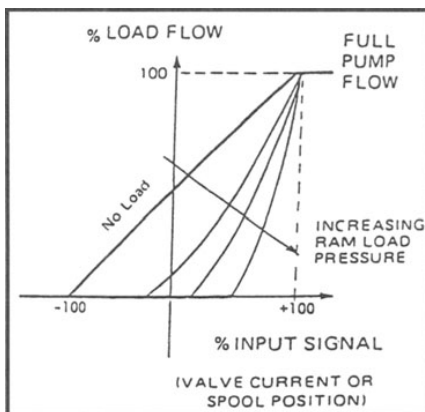


Fig. 7-39 Flow diverter valve load flow versus input signal.

Amplifier The servoloop amplifier occurs where the remaining amount of forward-loop gain G is added, for it is easiest to adjust. It is also good practice to put only as much gain as necessary into other elements of the forward loop and add the remainder to the amplifier, for it has the fewest problems with drift, resolution, repeatability, response, and adjustability. It is also the best spot to add frequency compensation such as integration. Integration adds high static gain to the velocity loop. Adding this feature to the amplifier will

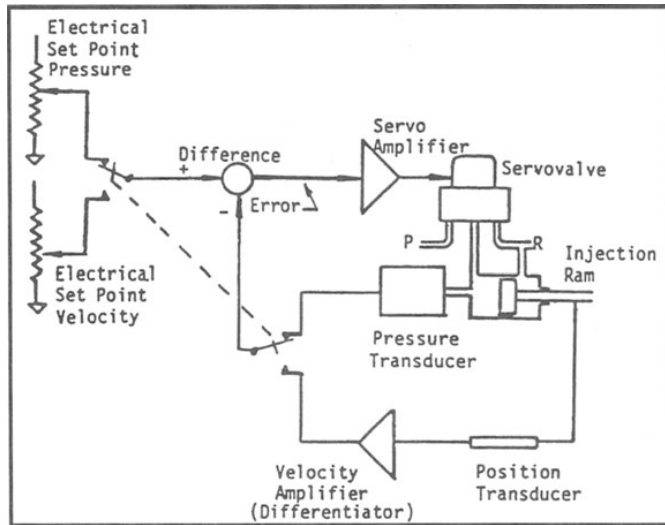


Fig. 7-40 Loop control diagram.

not add the problem of integration deadband, as does happen when this feature is added to the control valve. Other frequency compensation is added at the amplifier to improve the performance of the pressure servoloop also.

Figure 7-40 shows the two servoloop configurations for velocity and pressure control. Each of the elements of the forward loop is shown, and the transducer associated with each loop as well. Changing each servoloop configuration to the other is done by electrical switching of setpoint and feedback sources.

Where Does the Process Controller Go?

Now that control over the variables has been accomplished through the proper selection of control parameters and the use of closed-loop servocontrol, can a process controller be of any value? By itself it is just a toy, but combined with the technology just mentioned it can be of great value. Figure 7-41 shows where the process controller fits in the overall machine schematic. The process controller has the servoloop electronics in it

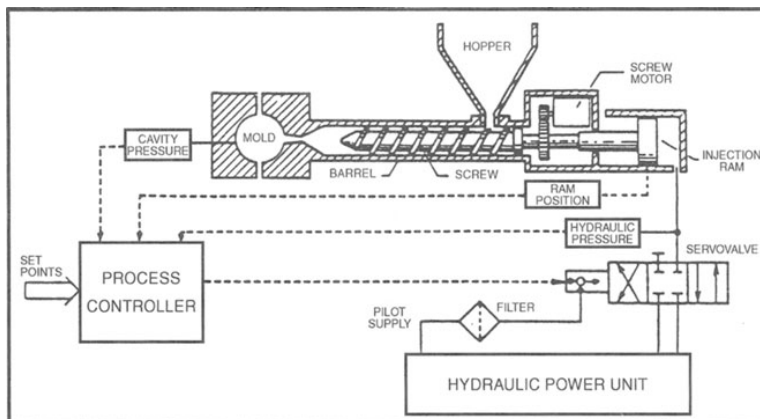


Fig. 7-41 Injection molding machine control schematic.

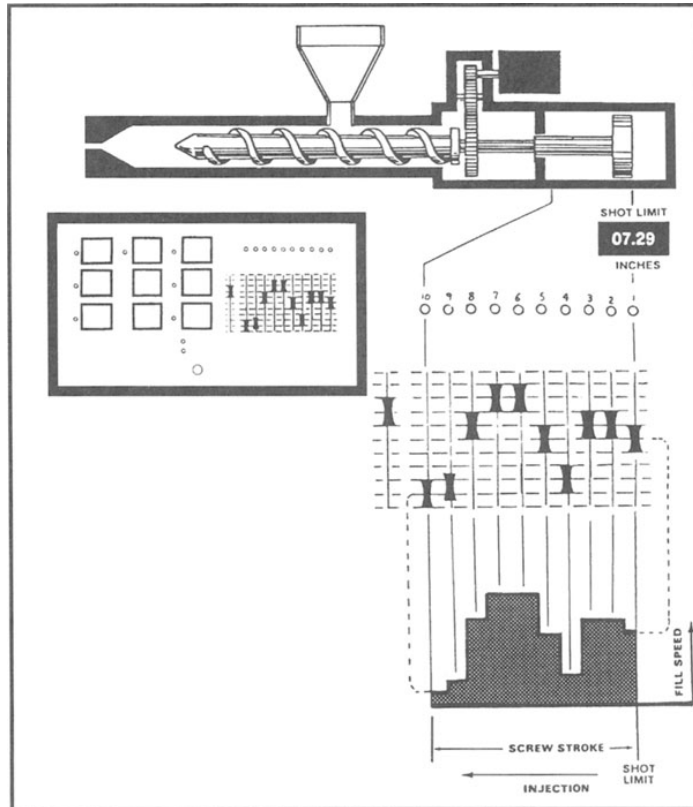


Fig. 7-42 Fill control.

to combine with the transducers and servo-valve of the machine. The process controller is now set to take input setpoints and do a meaningful job of controlling the variables.

Basic Features a Process Controller Should Have

There are four portions of an injection molding machine cycle that have to do with the injection operations:

- Fill
- Fill-to-pack transducer
- Pack and hold
- Plastication

There are many levels of sophistication each of these areas can have in numbers of setpoints, operator presentation interface, and

additional controllability such as cavity pressure pack cutoff or adaptive shot size control. The following are essential.

Fill control A fill control as depicted in Fig. 7-42 should break up the shot into several segments. The speed of injection for each segment should be easily and repeatably setable. With this feature, the best speed for each area of the mold will be setable regardless of how fast or slow the injection levels are elsewhere. This feature is valuable, since it allows the mold to be filled as quickly as possible and still eliminates problems of burning, splay, flow lines, and voids. Filling quickly makes it possible to have hotter material in the mold, which helps surface finish, weld lines and dimension control later in the pack segment. Also helpful would be a group of indicators

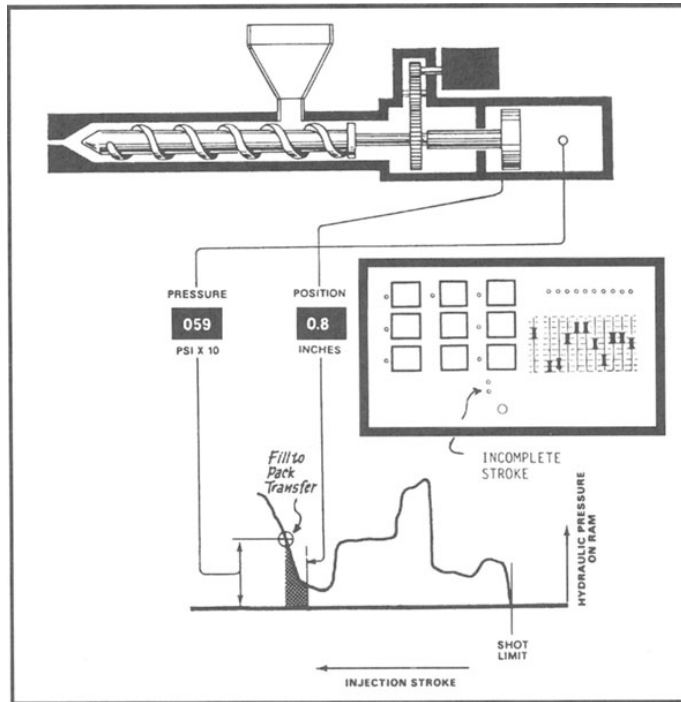


Fig. 7-43 Transition control.

to show where in the injection phase the programmer is, as well as a group of indicators to illustrate that a given segment is not meeting programmed speed.

Transition control When the mold is essentially filled, it is desirable to switch to a packing control because any further attempt to fill the mold with the fill control could result in excessive cavity pressures. The transition control depicted in Fig. 7-43 should provide a settable position in the shot stroke where no high injection pressures are expected. This point serves to arm the pressure-sensing system so that it may detect a rapid rise in ram pressure, indicating that the mold is essentially filled. This feature will allow higher injection pressures earlier in the fill cycle where needed and provide a sufficient indication that it is time to switch the servoloop configuration to a packing operation. Should the transition not occur as a result of setup conditions or a stuck cavity in the mold, an

alternate means of transition, such as time, should prevail to complete the injection cycle. This condition should be indicated as an incomplete stroke, and this logic condition should be output to the machine sequence controller to initiate appropriate actions.

Pack and hold control Once transition has occurred from fill to the pack portion of the cycle, it is desirable to be able to set the packing pressure to fill out the part completely for surface features and density. The amount of time spent in packing should also be adjustable. Figure 7-44 depicts these features. After pack time T1, it will be desirable to switch to a hold pressure independent of the pack pressure. The rate of transition from pack to hold pressure should also be adjustable. This feature will help control warpage that can be caused by abrupt changes in part densities resulting from abrupt pack to hold pressure changes during cooling. The amount of time the hold

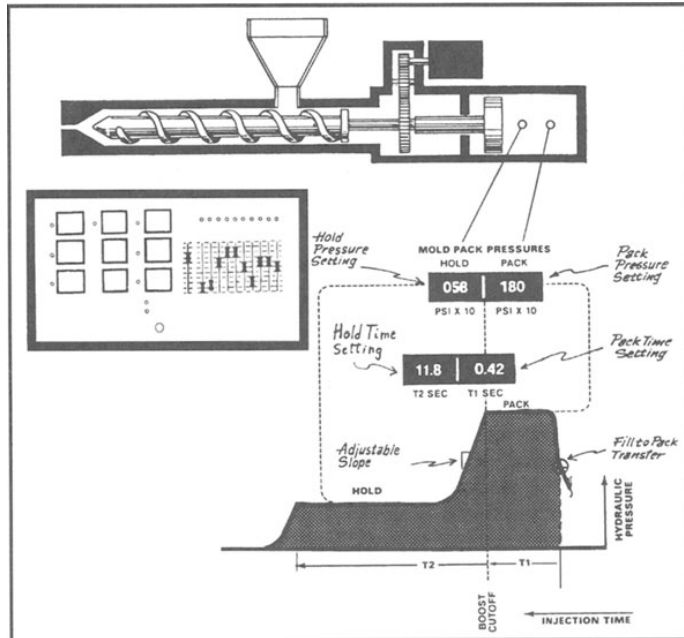


Fig. 7-44 Pack and hold control.

pressure is applied should be setable, independent of pack time.

air is introduced into the barrel and injected into the mold.

Plastication control As mentioned earlier, there are three sources of energy input to the plastication process. Temperature is already well controlled. Of the two remaining, it would be very convenient to control back pressure because there already exists a control loop for that purpose. The pack and hold pressure control can be used to control back pressure as well. Simple electronic switching can implement this feature. Figure 7-45 depicts what would be desirable for this portion of the injection cycle. The amount of back pressure should be setable and apply for the complete plastication phase. The phase is terminated when the proper shot limit is reached. The shot limit will control the shot volume plus the desired amount of cushion. A decompression feature is also desirable and should have a fine range of setability. In most cases, settings will be between 0.05 in. (0.13 cm) and 0.20 in. (0.51 cm). Excessive decompression can cause streaks and splay as

Applications

To better demonstrate the four basic features of a process controller, examples citing where each was instrumental in solving a specific molding problem will be presented, although any given application can most likely utilize more than one of these features to optimize the process. In all cases, the control had the ability to affect a particular portion of the cycle, fine-tune it, and hold the setpoints accurately and repeatably as indicated on the operator's panel.

Fill control and speed profile An optical part, in this case an edge-gated acrylic collimator-lens having dissimilar convex faces, was required to maintain exacting surface curvature and focal point tolerance. Considerable effort had been expended to ensure that the molds were accurate, and indeed acceptable parts were being made, but

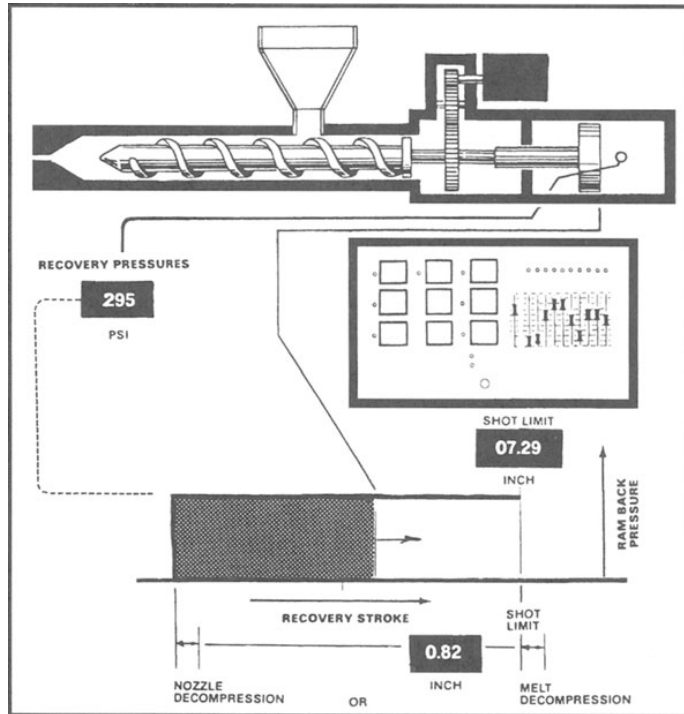


Fig. 7-45 Plastication control.

inconsistently. With a control, it was found that the best fill was a very slow, steady injection of 0.013 in./sec (0.03 cm/sec). As little as 0.0054 in./sec (0.0137 cm/sec) variance could be seen to throw the focal length off specification. The success of the application was demonstrated by molding 100 pieces with a single reject. It would have been totally impossible to achieve such consistency without closed-loop control of injection velocity.

A second example of fill speed control is an all-plastic valve for use in a chemical plant. The one-piece body was molded around the ABS ball and stem with Teflon seals being supported by spin-out cores. A degradation in the surface of the ball, opposite the gate, caused by impingement of the melt, made a low rate of fill desirable. However, a weld line resulted on the other side of the cores, from the gate, if injection was not kept fast enough to prevent a cold melt front. The solution was to begin injection quite slowly and then accelerate quickly to complete the part. This al-

lowed a skin to form, insulating the ball from the heat of the following material. The weld line could now be prevented by maintaining a high fill rate throughout the remainder of the shot. Leakage from an imperfect ball surface was all but eliminated, and burst pressure was increased more than threefold by improving the weld of the material around the cores.

Fill-to-pack transfer An example of a part requiring precise fill-to-pack transfer is a carburetor body for a two-cycle engine. Molded in a mineral-filled nylon, it required 100% inspection because of problems such as flashover of two small holes in the throat area. A characteristic of the material was that it required a great deal of pressure to fill the cavity, but once it was filled, the nylon easily flashed over the pins, kissing off against the throat core. It was essential here that the control switch out of the speed loop, to stop the fill without overpacking at the instant the transfer pressure was reached. In this case,

accurate transfer allowed a reduction in QC inspections to once per shift, and a reduction in clamp tonnage was possible because it was no longer needed to hold against flashing.

A dramatic demonstration of transfer control is found on machines running materials such as a polyamide-imide requiring a very high speed of fill, possibly boosted by a hydraulic accumulator. Although capable of impressive fill rates, they are subject to a wide variance in shot size because of their inability to stop the fill at a repeatable point. Our experience has been on machines injecting at over 40 in./sec (102 cm/sec) with hydraulic flows of more than 500 gpm; while this is a rather extreme example of the fill-to-pack transfer feature, the consistency attained here can be beneficial to any molder trying to hold tighter control over shots or flash.

Pack and hold control Process controls permit added flexibility over the standard molding machine in that the molder can sense the actual point at which the cavity is filled. This now becomes the most important event in the cycle, since it signals the separation between filling of the cavity and densification of the part. On the standard machine control, the boost pressure is used to fill the cavity, but only after the cavity has completely filled is this pressure actually felt by the material. As the fill time varies, so does the length of time in which boost pressure is applied to densify the melt in the cavity. This is a chief source of part weight inconsistency. Process controls are capable of holding pack and hold pressures to within a few psi for a very specific length of time.

Returning to the example of the carburetor body, we observe that part weight was held consistent despite changes in hydraulic fluid temperature, environment, material lot, etc.

Further, the parts were shipped by weight, and it was found that 12% more parts were being shipped in a given container weight because dimensions could be held without overpacking.

Another example of a common problem that is easily resolved by process control is ram bounce. Whereas it may be desirable to go from a rather high boost pressure down to a much lower hold pressure, the resulting decompression on the ram causes material to be withdrawn throughout the gate, putting stress into the part and possibly affecting adequate pack-out. Any thin flat part susceptible to warpage can benefit from a control's ability to change pressure gradually.

Plastication As noted earlier, a process control should be able to maintain hydraulic pressure to within a few psi of setpoint. However, it can allow far more control of the energy being put into the melt. Since many molds provide a separate path back to the tank that bypasses the machine's manifolds, a process control can allow lower back pressures than found in the standard machine. This can be of use with highly filled materials.

Although process controls may once have been oversold as a panacea for all the molder's problems, they have come of age through the maturity of technology and application, and the understanding by a growing segment of the industry that many of the so-called process controls are more placebo than performance.

Summary

The following simplified example shows how pressure process controls can properly and repeatedly fill a mold cavity (Figs. 7-46

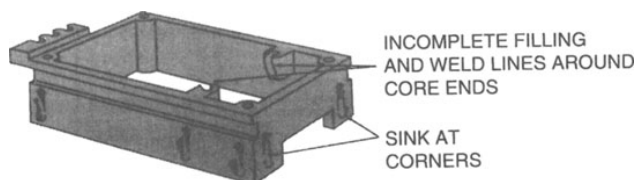


Fig. 7-46 Inconsistent results (sink marks and incomplete fill) while molding this product can easily occur.

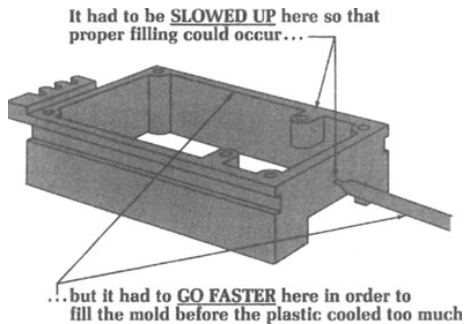


Fig. 7-47 The problem was mold filling speed.

to 7-49). In this example, controls are used for shot size, speed control of mold fill, mold pack with recovery, and cushioning. Programmable mold fill speeds can eliminate or significantly reduce conditions such as flow lines, weld lines, splay, laminations, and burning. Programmable mold-packing pressures eliminate sinks and voids, porosity, shrinkage, overpacking, and flash. Programmable recovery pressure eliminate nonuniform melt, excessive plasticizing time, and cycle-to-cycle changes in the melt. Booster cutoff from the cavity or hydraulic pressure eliminates wasted power. Automatic shot size control eliminates the long-term drift of setup parameters. Digital process settings eliminate inaccuracies and excessive resetup time.

Process Control Problems

Purchasing a sophisticated PC system is not a foolproof solution that will guarantee perfect products. Solving problems requires a full understanding of their causes, and these

may not be as obvious as they first appear. Failure to identify contributing factors when problems arise can easily result in the microprocessor not doing its job. The conventional place to start troubleshooting a problem is with the basics of temperature, time, and pressure requirement limits (Chap. 11). Often a problem may be very subtle, such as a faulty control device or an operator making random control adjustments. Process control cannot usually compensate for such extraneous conditions; however, these factors may be included in a program that can accommodate new functions as needed.

There are two basic approaches to problem solving: 1) Find and correct the problem applying only the control needed. 2) Overcome the problem with an appropriate PC strategy. The approach one takes depends on the nature of the processing problem and whether enough time and money are available to correct it. In most cases PCs may provide the most economical solution. To make the correct solution, one must systematically measure the magnitude of the disturbances, relate them to product quality, and identify their cause so that proper action can be taken (Chap. 12).

In expensive systems the processor should first methodically determine the exact nature of the problem to decide whether or not a better control system is available to solve the problem. For example, the temperature differential across a mold can cause uneven thermal mold growth. The mold growth can also be influenced by uneven heat on tie-bars. The uppers can be hotter causing platens to bend where the change could be reflected on the

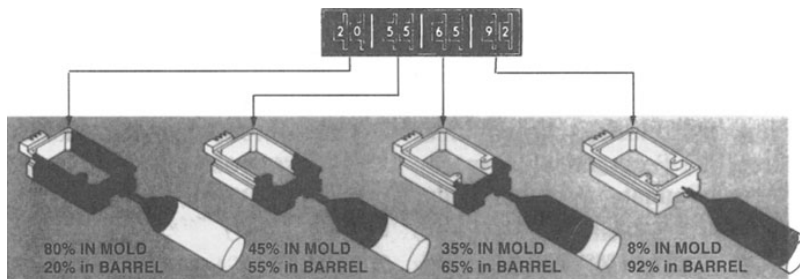


Fig. 7-48 Mold filling speed is adjusted using a process controller.

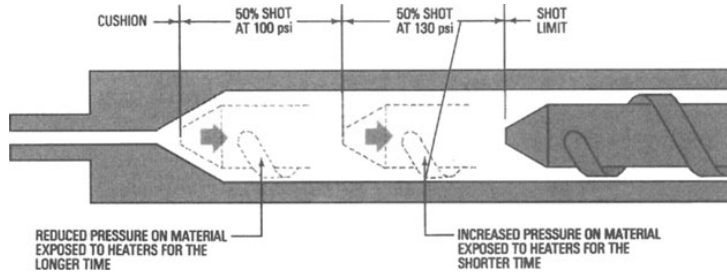


Fig. 7-49 Example of controlling shot size with pressure changes.

mold operation. Perhaps all that is needed to correct the mold heat variation is to close a nearby large garage door to eliminate the flow of air upon the mold. With air conditioning all that may be required is to change the direction of airflow.

Cavity Melt Flow Analyses

The purpose of flow analysis is to gain a comprehensive understanding of the mold-filling process. The most sophisticated models provide detailed information concerning the influence of mold-filling conditions on the distribution of flow patterns and flow vectors, shear stresses, frozen skin, temperatures and pressures, and many other variables (7). Other, less sophisticated programs that model fewer variables are also available.

From these data, conclusions regarding tolerances, as well as part quality in terms of strength and appearance, can be drawn. The location of weld lines and weld line integrity can be predicted. The likelihood of warping, surface blemishes, or strength reductions due to high-shear stress, can be anticipated. On this basis, the best mold-filling conditions can be selected.

Figures 7-50 and 4.26 show melt pattern entering the mold cavity from an injection molding machine; a fountain (or balloon) stretching effect results. The stretching melt-front-oriented outer surface covers the inside wall of the cavity. Melt that follows basically fills within the fountain flow, resulting in a nonuniform orientation in the cross section of the molded part (which can still meet performance). The type of plastic and processing conditions of melt and wall cavity (including

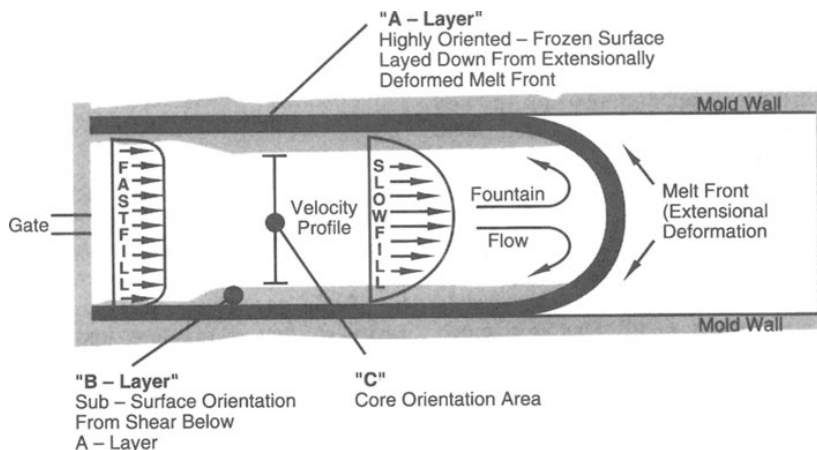


Fig. 7-50 Mold cavity melt flow. Phenomenon causing flow to deviate from 2-D flow between parallel plates.

speed of melt) can have a significant influence on certain properties of the molded part, such as degree of gloss, warping, impact resistance, and strength. Basically, the degree of ballooning or bubble formation is controllable so that specific desired properties can be obtained.

As flow analysis technology enjoys more widespread use, refining its application becomes increasingly important. The method presented here can be used to test new and existing molds with respect to the pressure drops through the molds. We can then attempt to compare them with conclusions reached with flow analysis (7). The data can be used to determine the optimum flow rate for a given mold. This can be adjusted so that the process has optimum stability with respect to material viscosity caused by non-Newtonian behavior during filling.

Problem

Flow analysis programs used throughout the plastics industry utilize both two- and three-dimensional models of parts in conjunction with rheology equations. Models range all the way from a simple Poiseuille's equation for fluid flow (Eqs. 1 and 2 in Table 7-3) to much more complex mathematical models involving differential calculus. It is important for the user of this technology to recognize that, from the simplest flow analysis to the most complex of these models, all are only approximations. The user must also understand that their relational techniques, coupled with the user's assumptions, determine whether or not the findings of the flow analysis have any real validity. Whether the flow analysis used is an inexpensive two-dimensional model or a highly complex and expensive three-dimensional model, the only significance is that the results represent what actually happens in the injection mold.

Table 7-3 Poiseill's equation for fluid flow

$Q = \frac{R^4 \Delta P}{8 \mu L}$ (round passage)	(Eq. 1)
$Q = \frac{WH^3 \Delta P}{12 \mu L}$ (rectangular passage)	(Eq. 2)

In discussing the use of flow analysis with scores of users, it appears that the primary method of testing findings is to determine whether or not the last point of fill has been predicted by the system. This seems to be the universal method of checking whether or not the flow analysis is accurate. However, a major part of flow analysis modeling deals with the prediction of pressure losses during flow into a mold. This is a much more complex analysis to perform and is what typically separates the results of different flow analysis programs.

It is important that all users realize that flow analysis only predicts dynamic pressure losses during filling of the mold and does not take packing into account. Some systems are now including packing in their algorithms, but pressure losses during the packing of the mold are significantly different from those that exist during fill.

A diagram of the dynamic and static pressure losses in the mold is shown in Fig. 7-51. The diagram reveals a static and dynamic pressure loss that exists for each flow channel in the mold—mainly across the sprue, runner, and gate and down through the cavities. For a flow analysis program to predict fillability, clamp force required, and size of machine needed, the system must be able to predict both dynamic and static pressure losses.

Melt Viscosities versus Fill and Pack

Based on rheological and thermal properties of various plastics, radial flow simulations can be used to demonstrate the effects of small changes in the melt viscosity on the filling and packing stages. This approach relates to production floor operations as it influences quality control measurements. It also defines the fabricating window in which the melt can be regarded as sufficiently consistent.

For $\pm 10\%$ viscosity variations, the filling results indicate that the injection pressure, injection energy, and flow length of the melt are only affected by $\pm 5\%$. In comparison, the packing results show that changes in the part weight are predicted to be less than $\pm 3\%$.

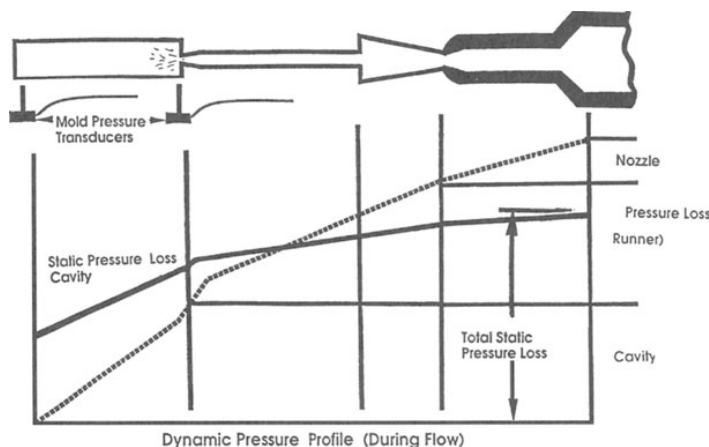


Fig. 7-51 Static and dynamic pressure profiles through the mold and injection unit (filled and packed).

The influence on injection molding of $\pm 5^\circ\text{C}$ shifts in the glass transition temperature (T_g) is even less important, typically in the order of $\pm 2\%$. However, if the process is bounded by a pressure limit on the molding machine, the same viscosity and T_g variations can lead to significantly higher injection energies, longer fill times, and in the worst case undesirable short shots. To guarantee molding repeatability, the part and the process should be designed for flow lengths that are easily obtainable under unlimited pressure conditions (304, 461, 488).

Test Methodology

The static pressure loss component can only be measured by installing pressure transducers in the mold at strategic locations. Typically, pressure transducers will be installed near the gate and at the end of the cavity so that a pressure loss across the cavity can be measured. This pressure loss measured can show both the static and dynamic pressure losses through the cavity and also back into the injection cylinder if hydraulic pressure is being observed at the same time. In Fig. 7-52 such a graph is shown. In this case, the dynamic pressure loss across the cavity is 16.33 MPa (2,400 psi). The static pressure loss is 40.82 MPa (6,000 psi) – 20.41 MPa (3,000 psi) or 20.41 MPa (3,000 psi). The

dynamic pressure loss from the injection unit to the end of the cavity is 125.80 MPa (18,500 psi). The static pressure loss from the hydraulic cylinder to the end of the cavity is 63.95 MPa (9,400 psi) – 20.41 MPa (3,000 psi) or 43.54 MPa (6,400 psi).

The optimum way to check the fillability and packability of the mold is to instrument it for monitoring during all mold tryouts. This allows the molder to ensure that there are no changes in true in-mold processing conditions during the mold tryout sequence. However, at the present time, relatively few injection molds are instrumented to allow the use of cavity pressure data. In molds of this type, the dynamic pressure loss component, which is the one most universally applied in flow analysis, can be monitored by taking a series of short shots across the mold. This procedure is as follows.

When testing a flow analysis that has been completed, it is important that the machine be set up in such a way so as to truly duplicate the conditions set forth in the flow analysis. It is important that the actual plastic melt temperature be delivered to the mold at the temperature assumed in the flow analysis. In the absence of accurate direct melt temperature readings, purging the machine on cycle and measuring the temperature using a preheated probe that has been heated to 15°C above the highest barrel setting will allow accurate readings of actual melt temperature.

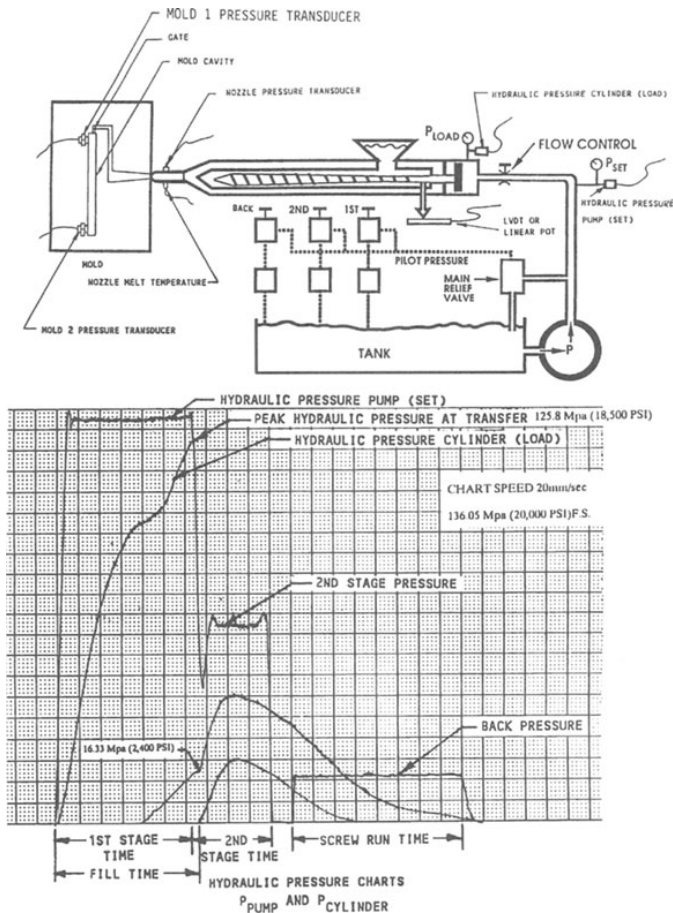


Fig. 7-52 Measured pressure losses.

Readings taken using this procedure should be observed precisely 30 sec after insertion.

It is also crucial to fill the mold at a speed of fill specified in the flow analysis program. Therefore, if the findings specify that the mold is to be filled in 2 sec, the injection speed on the machine used must be set to precisely fill the mold in that period of time. To do this, the mold should be filled using first-stage pressure set high enough to allow the flow control on the molding machine to control the rate of fill accurately from beginning to end. Position cutoff should be used to stage the machine from first to second stage with second and subsequent stages of holding set to zero. On successive shots, the mold should be partially filled while slowly advancing

the cutoff position forward until a very slight shot is observed in the part. The injection rate should be then adjusted until fill time observed either on a fill time clock or strip chart recorder indicates that the correct fill time is being obtained. The screw back position and cutoff position should be tuned so that the screw bottoms directly after cutoff. This ensures that packing caused by injection unit inertia does not flash the mold. One technique is to use a forward cutoff position approximately 10 mm from screw bottom and adjust the shot size for a slight nonfill using the screw back position.

It is also important at this point to measure the weight of the shot by weighing the partial, slightly short shot parts. One of the

assumptions that could be incorrect in a flow analysis is the volume of the material used to fill the cavity. Shear rate is volumetric flow rate that could be incorrect based on incorrect assumptions of cavity volumes or even incorrect cavity building by the tool-maker. In all cases, the amount of material injected into the mold in the time allotted must be monitored. If the volumetric flow rate does not agree with the one derived in the flow analysis program, then the injection speed should be readjusted until the volumetric flow rate in actuality is equal to the one assumed in the flow analysis program.

With this slightly short part using only first-stage injection, it is now important to precisely monitor and detect the peak hydraulic pressure at the time the machine is transferred from the first to second stage. This peak hydraulic pressure represents the instantaneous pressure loss from the hydraulic injection cylinder down to the end of the cavity. In Fig. 7-53 this is 12.58 MPa (1,850 psi). At this point, one must know the area ratio between the screw and hydraulic piston pushing it. Normally, on older machines, this is a 10:1 ratio; however, many newer machines have ratios of 13.3:1, 14:1, or even higher. Hydraulic pressure should be multiplied by this conversion factor to give a theoretical nozzle pressure that represents the pressure loss from the tip of the screw to the end of fill. The machine used in Fig. 7-52 has a 10:1 ratio so the theoretical nozzle pres-

sure is 125.80 MPa (18,500 psi). This dynamic pressure profile is depicted in Fig. 7-53.

Once this is done, the screw back position should be moved forward on successive shots to make short shots that coincide with the primary isobars shown in the flow analysis program. The minimum number of isobars should be one at the end of fill and one near the gate and at the end of the sprue. The peak pressures and time to fill must be taken using the same injection speed as was employed to fill the entire mold.

This is best done on a machine with closed-loop velocity control or on a conventional machine with a load compensation installed. With this complete, it is only necessary to determine the pressure loss through the nozzle of the molding machine. This can range from relatively insignificant to a highly significant amount and can be obtained by retracting the nozzle of the injection molding machine from the sprue and purging into the air on cycle, while again monitoring the peak hydraulic pressure at the injection speed used to fill the mold (see Fig. 7-54).

This last piece of data, 22.10 MPa (3,250 psi) in Fig. 7-54, represents the pressure loss through the nozzle of the molding machine and can be subtracted from the other data to determine the pressure losses throughout the various flow channels of the mold. These data can then be directly compared with those of the flow analysis program to determine its accuracy.

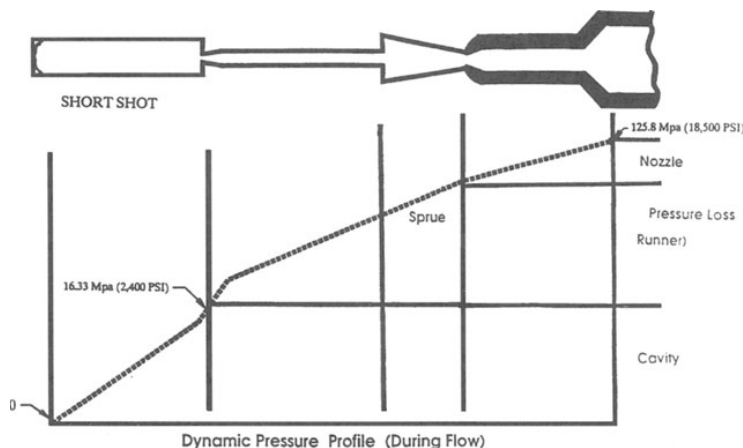


Fig. 7-53 Dynamic pressure profile through mold and injection unit (mold just filled).

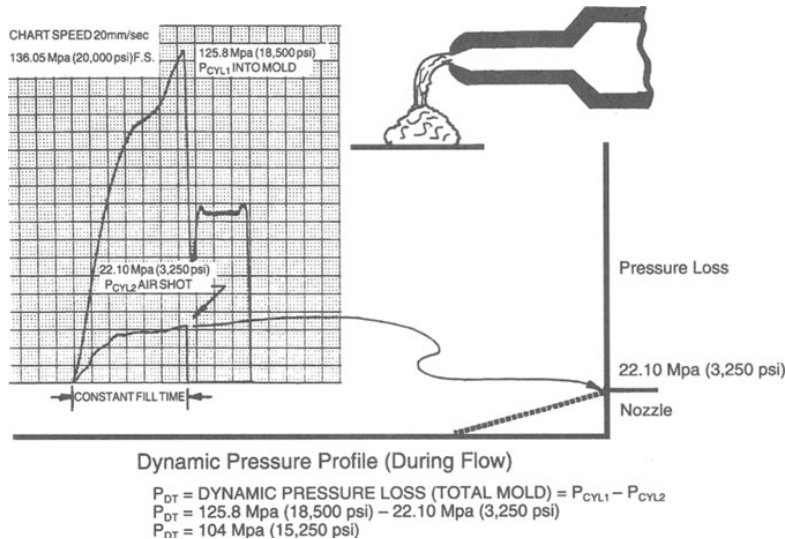


Fig. 7-54 Dynamic pressure profile through the injection unit (while purging).

Analyzing Results

Analyzing results requires first determining the type of error, if any, that exists. If the pressure loss data are in error, is it in error in thin sections, thick sections, or virtually all sections? If the error appears in all sections of the mold, it may mean that there is simply an offset caused by a difference between the viscosity data used in the flow analysis and the actual viscosity of the plastic used during the injection. If this is true, changing the injection speed should allow the flow analysis data to be duplicated with a different fill time.

If, however, the flow analysis overstated thick sections and understated thin sections, there could be a serious problem with the mathematics involved. This technique has been used to test in excess of fifty flow analysis programs to date. Results have ranged from highly accurate to highly inaccurate with the variation most likely the result of invalid operator assumptions or improper viscosity data.

In an attempt to take out as many of the variables as possible, a simple variable depth test plaque was utilized in the laboratory to show as an example here. This mold is easily and accurately modeled with any flow analysis program. The thickness of the cavity can

be adjusted and therefore the mold tuned to the actual values used in the flow analysis. This mold is highly instrumented, which allows the short shot technique and full shot instrumented techniques to be compared.

Example Test

One of the programs tested using this mold was of a simple two-dimensional flow analysis program. Viscosity data for the material were provided by Dow Chemical USA. The cavity was modeled as shown in Fig. 7-55 by Tom Harcourt of Tom Harcourt and Associates. The mold fill was simulated at various injection speeds, as shown in Fig. 7-56, and illustrated a pressure loss across the cavity of 54.27 MPa (7,977 psi) when corrected for melt temperature differences. Actual results of the short shots are shown in the data taken with the XYIS Data Acquisition System. It shows that the instrumented shots showed a pressure loss of 78.63 MPa (11,560 psi) while using a fill time of 0.5 sec. These data were taken with a mold temperature utilized in the flow analysis program of 50°C (122°F). The test utilized showed that for the particular flow analysis program, an error of 31% at this fill rate exists.

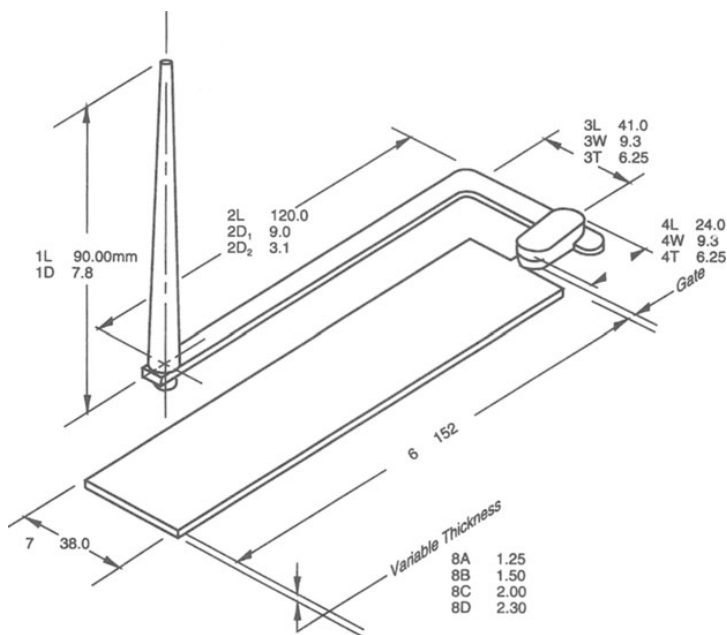


Fig. 7-55 Variable thickness mold.

Using Empirical Test Data to Optimize Fill Rates

The short shot technique for testing flow analysis programs has an additional and possibly more important use in determining optimum fill rates. A viscosity versus shear rate curve plotted in linear-linear form is shown for polystyrene in Fig. 7-57. These data were derived empirically using an injection molding machine. The injection nozzle was used essentially as a capillary rheometer. By purging the machine at different speeds while measuring the fill time and pressure loss across the nozzle, data can easily be taken that show non-Newtonian behavior. A similar test while injecting into a mold at various injection speeds and plotting these data is shown in Fig. 7-58. In this case, the mold is filled on first-stage pressure with position cutoff used in such a way that the mold is filled to a slightly short condition at the fastest injection speed to be tested. On subsequent shots, the injection speed was reduced, and on all the shots, the peak hydraulic pressure and fill time were monitored.

It is important when running this test to inject at speeds well beyond what would

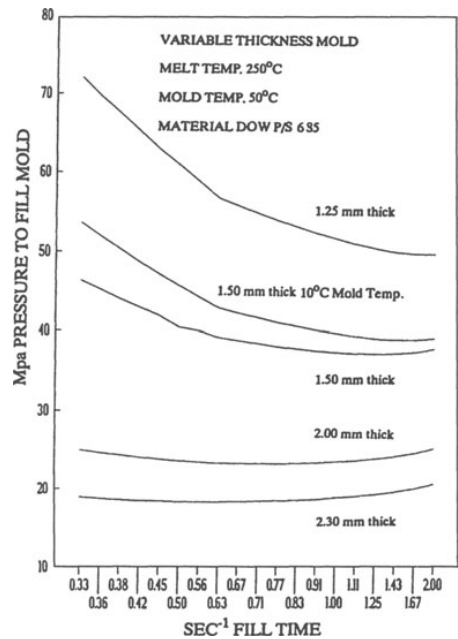


Fig. 7-56 Mold fill simulation.

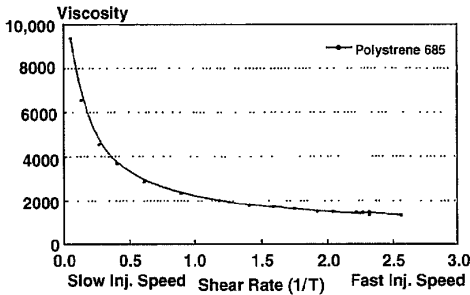


Fig. 7-57 Machine rheology.

normally be considered the limits of molding; thus, if the parts are burned or even if there is significant diffulty in the mold, it is best to run the test as far as possible. In many cases, molds should be filled at faster rates than those limits imposed by burning for instance. If this is the case, the mold should be optimally vented to eliminate this condition.

The graph of this type of test is shown in Fig. 7-58. As can be seen, with fill times shorter than 1 sec, the relative viscosity number approaches a constant. This makes the process less sensitive to changes in the rate of fill. Whenever possible a mold should be run in this flat portion of the curve.

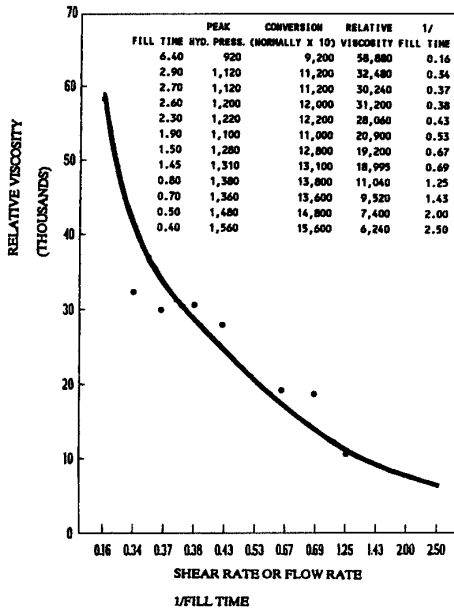


Fig. 7-58 Inmold rheology.

If the flow analysis being tested includes data on several fill rates, this relative viscosity number curve can be plotted from the computer data and compared to actual data. Ideally, if capillary rheometer data plotted in linear format were overlaid on this curve, they would exhibit the same non-Newtonian behavior as predicted by the flow analysis program and empirically measured using instrumented means. This is the ultimate test of the flow analysis program's ability to account for non-Newtonian flow behavior during the filling portion of the injection process.

In conclusion, testing flow analysis programs and existing molds using a short shot technique is a simple, effective means of optimizing the use of flow analysis and processes on existing molds. The only tools necessary to do this are a digital peak-reading hydraulic gauge or strip chart recorder and a fill time clock. The short shot technique allows the molder to test and refine the assumptions used in flow analysis and to compare one flow analysis against another. This approach will also help the molder to optimize processing conditions on any mold whether or not flow analysis has been conducted. This is a simple and effective tool to use on the injection molding floor.

Melt Vibrations during Filling

Melt vibration usually occurs at low frequency during the injection molding filling stage. Melt vibration can be beneficial in that it reduces the melt viscosity, which in turn can ease cavity filling during thin wall molding. It can also lead to higher outputs with less shrinkage in the molded parts. Pressure and temperature effects on shear thinning can influence and/or interfere with melt vibration (142, 286).

Stabilizing via Screw Return Time

Stabilization usually requires the addition of transducers plus the appropriate signal conditioning equipment to measure one or more PC parameters. Although good results are obtained using this approach, several

factors can limit its use, including (1) higher cost of hardware, (2) fragility of transducers, (3) recalibration when product changes occur, and (4) abusive use resulting in maintenance cost.

The J. J. Wenskus invention is an alternative process stability monitoring method and apparatus requiring no transducers nor any significant additional hardware (595). The invention is based upon the discovery that the operations of the plasticizing screw found in virtually all IMMs varies in a measurable way with all common process perturbations encountered in the injection molding process. In most IMMs the time required for the screw to plasticate and position material for the next shot “floats” while other machine parameters occur for fixed times. As a result, the screw recovery time is a bulk indicator, the duration of which is affected by the sum total of many operating parameters such as injection pressure, holding time, back pressure, melt temperature, injection time, cycle time, and mechanical condition of key components in the machine.

It has been determined that perturbations in these parameters produce measurable effects in screw recovery time. Thus by tracking this measurement statistically and analyzing it, using any of a plethora of existing statistical methods and displays, processing anomalies can be detected at levels below which the product may be affected. Also, because of the time frame involved, identification of the cause may frequently be determined by a simple inspection of a display of measured screw recovery time values.

Relating Process Control to Product Performances

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

Monitoring helps relate the process to the product. The sensed molding parameters can

show the relationship among pressure, temperatures, and position (movement) during the process.

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

Sensor Requirements

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

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

Molding Parameters

Pressure

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

1. Hydraulic pressure relief valve setpoint consistency

2. Timer accuracy for switching cutoff pressures
 3. Hydraulic back pressure setting during screw return
 4. Screw return time consistency
 5. Hydraulic pressure changes during injection, reflecting material viscosity changes
- *Machine material pressure transducer.* Monitoring the material pressure can be done with a transducer in the machine nozzle. The material pressure profile will be similar to the machine hydraulic pressure profile. The pressure of the material and hydraulics in the machine barrel become similar as the mold is filled. Sensing of material pressure at the machine nozzle can be done, but its usefulness is questionable.
 - *Mold material pressure.* Material pressure transducers can be installed in the mold's runner system and cavity. Indirect and direct material sensors are available. The type of transducer selected depends on the product configuration in the mold, mold construction, and type of runner system.

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

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

The mold material pressure profile can determine the following:

1. Material filling time
2. Material peak pressure consistency

3. Machine nozzle contamination or freeze-off

Temperatures

- *Machine barrel temperature.* Barrel temperatures are sensed and controlled with thermocouples (TCs). One TC is needed for each zone that is being controlled. Usually, three zones (front, middle, and rear) are sensed and controlled. The nozzle usually has its own control. Accurate temperature control and temperature setpoint requires using current-proportioning controllers, not the time on-off type of temperature setpoint controllers.

Monitoring barrel temperatures can determine:

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

Monitoring of the mold temperature is usually done with TCs. Their accuracy depends on the TC placement. The TC location must be varied to determine the optimum location. Monitoring temperature in the mold is difficult because of the high thermal inertia in the heater-chiller-mold system.

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

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

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

Positions

- *Machine ram position.* The ram position is monitored from a potentiometer, either linear or rotary, mounted on the machine. The sensor indicates the ram during the molding process and can show the following:
 1. Injection rate of material into the mold
 2. Consistency of ram profile during open-loop or closed-loop machine control
 3. Screw position during return to back position
 4. Screw return time consistency
- *Machine tie-bars.* Machine tie-bars stretch when the mold is clamped. This mechanical strain or elongation can be measured with strain gauges, dial indicators, and linear variable displacement transducers (LVDTs). LVDTs eliminate the need to drill holes in the tie-bars or clamping on small indicating devices. Monitoring tie-bar strain can show:
 1. Balance of tie-bar strain during clamp
 2. Mold clamp tonnage
 3. Machine–mold clamp tonnage changes occurring because of thermal effects of machine cycling and mold heating or cooling
- *Mold part line.* Mold part line separation can be measured with indicator gauges and LVDTs. As material is packed into the mold, the part line can open. A direct relationship exists between machine clamp on the mold, material viscosity, and material injection rate. Monitoring for a mold's part line separation can show the following:
 1. Dimensional changes in the product
 2. Mold flashing

Display of Monitored Molding Parameters

Analog display Analog devices include:

1. Chart recorders
2. Voltmeters with a sweep needle
3. Oscilloscopes

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

Digital display Digital devices include:

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

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

CRT display Cathode ray tube (CRT) displays include:

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

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

Machine Controls

Open-loop machine sequence control In a conventional open-loop machine sequence control system, input commands are set, and there is an unknown machine output response.

The monitoring of machine hydraulic pressure and ram position relates:

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

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

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

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

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

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

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

The ram position is programmed to establish a material filling rate into the mold. The hydraulic pressure compensates for material

viscosity changes during the controlled filling of the mold's sprue, runner, and cavity.

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

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

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

Microprocessor Advantages

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

- *Setup time reduction.* Time for setup can be greatly reduced by the ability to record and store timer settings, limit switch positions, and pressure levels. The data can then be fed to the controller in seconds to readjust the machine to the new setup.
- *Easier operator "tuning."* Since the microprocessor inputs can be located at the operator station, adjustments can be made without crawling around the machine.
- *Smoother operation.* This is achieved through ramping of the control signals. We can now eliminate many of the readjustments necessary as the machine temperature changes, simply by setting these ramps such that the time is longer than the response under conditions of startup. Since the signal is now slower than valve response, the signal is always in control, yielding a more uniform cycle.
- *Less down time.* The constant monitoring of machine performance made possible with these systems can allow lower pressures and eliminate shock peaks, thereby

extending component life. A properly applied system will also have fewer components to troubleshoot when a problem does occur, and diagnostic programs can be included.

- *Input energy reduction.* By programming the hydraulic system to respond to the varying demands of the circuit, we can reduce input power requirements.

This is what the “brains” of process control can do for us, but how we interface the controller can affect these advantages. Ideally, we want a system consisting of as few components as possible, and these components should be maintainable, tolerant of the industrial environment, and repairable by general maintenance personnel.

Types of Instruments

There are numerous controllers, signal conditioners, and indicators that can provide measurements of all types of controls, such as temperatures and pressures in different locations of the IMM, as well as other actions such as screw rpm and torque. Controllers receive input and compare this value against a preprogrammed setpoint. If the input value differs from the setpoint, the instrument will modify the output to bring the process equal to the setpoint.

Signal conditioners are instruments that have no display. They receive input and modify the signal to make it acceptable to a recorder or a plant computer system. The indicator instrument receives input and simply displays the value on an LED (light emitting diode). It may have alarm contacts to alert the operator of high or low conditions (352, 528).

Functions

An instrument’s primary function is to receive input and simply display the value in a way that is understood by an IMM operator. It usually has alarms to warn an operator of high or low processing conditions. The alarms permit minimal line supervision. They can be

used to shut down the process if conditions are damaging to the machine or a dangerous situation arises. The instruments can provide a continuous output signal that can have many uses. One instrument may be capable of serial communications to a host computer. This communication can be bidirectional so that the host computer modifies the instrument parameters.

Rotary and Linear Motion

As industry demands motion control with more stringent requirements for accuracy and repeatability, the selection of position feedback becomes more critical. Because of evolving changes in drive technology, there is the potential debate on whether linear or rotary encoders and recirculating ball screws represent the best solution for measurement on numerically controlled machines. A large fraction of new servomotors now feature rotary encoders, which in principle can also be used in combination with the pitch of the ball screw to determine linear position. This method alleviates having to choose either a linear or ball screw–rotary encoder system; rather, with such a drive configuration, the decision becomes whether to add a linear encoder or simply use a preexisting motor encoder working in combination with the ball screw (553).

There is a problem with using a rotary encoder–ball screw system, for costs can quickly escalate if one finds that the accuracy does not suffice in certain applications or that thermal expansion problems are causing the machine to generate scrap. Retrofitting an installed machine is usually much more expensive than having the correct machine delivered in the first place.

Although machine designs vary, the mechanical configuration of their feed drive is largely standardized. In almost all cases, the recirculating ball screw has established itself as the solution for converting the rotary motion of the servomotor into linear slide motion.

A position control loop with a rotary encoder and ball screw includes only the

servomotor. Thus, there is no direct position control of the slide because only the position of the servomotor rotor is being measured and the linear position of the slide is determined indirectly. To extrapolate the slide motion, the mechanical system between the servomotor and the slide must have a known, and above all, reproducible mechanical transfer behavior.

However, a position control loop with a linear encoder includes the entire mechanical feed drive system. The linear encoder on the slide directly measures slide position and the machine control unit automatically compensates for mechanical transmission errors. Potential sources of error include: (1) thermal expansion of the ball screw caused by friction between the ball nut and ball screw, (2) ball screw pitch error, (3) reversal error caused by play and elasticity within the system, and (4) deformation of the drive system due to high accelerations, cutting forces, and friction in the guideways. Of these, thermal growth of the ball screw presents the greatest source of error.

Adaptive Control: PVT and PMT Concepts

The specific volume, pressure, and temperature of the melt in a cavity can be controlled along a defined phase curve in the *PVT* (also called *pvT*) or *PMT* diagram. The *PMT* control was developed from the *PVT* control. It calculates an ideal holding pressure profile under the assumption that a mold cavity, which is considered constant, containing a constant amount of plastic produces constant and repeatable moldings.

The *PVT* diagram describes the dependence of the specific volume on melt temperature and holding pressure. It renders the automatic finding of a point of operation by using measured melt and mold temperatures and a computation of the temperature cooling process. Machine control on the basis of microprocessors permits not only the optimization of individual control parameters but whole process segments. Thus, an optimum point in the *PVT* diagram can be accurately targeted independently from variations in melt

or mold temperature, resulting in parts with constant weights.

These PC techniques are in a continual state of evolution and original developments are being made by the IKV (Institut für Kunststoffverarbeitung) in Aachen, Germany. Uniform time sequences from cycle to cycle are a basic precondition for a desired quality; that is, the injection time, holding pressure time, and cycle time should be kept constant.

In many molding operations it is necessary to change factors such as injection pressure to adjust the holding pressure in order to keep the product weight or dimensions rather constant. This adaptive control is essentially a system that changes the settings in response to changes in machine performance to bring the product back into specification. The shift is maintained so that the control has adapted to changing conditions. It is a technique typically used to modify a closed-loop control system (303, 305, 433).

Optimization via PVT

The *PVT* diagram in Fig. 7-59 shows the typical dependence of the specific volume of a plastic on temperature and pressure. The course of the process in the holding-pressure phase can be readily demonstrated with this diagram. After the plastic, at the most uniform temperature possible, has been injected into the mold, the switch-over point to open- or close-loop control of pressure follows. Then a period of constant pressure arises. This phase of constant pressure control

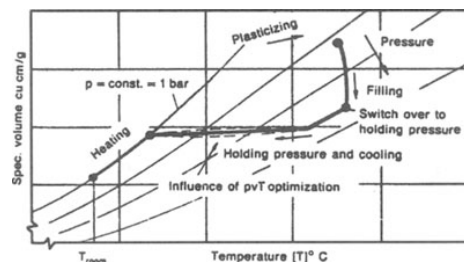


Fig. 7-59 *PVT* method to compensate for variations in melt and mold temperature by adjusting the holding pressure profile in real time.

(isobar phase) changes to one of constant specific volume (isochor phase). Major importance is attached to the isochor method of process control since, in the simplifying case assumed of negligible mold breathing, it is synonymous with a minimum of plastic movement inside the mold cavity. The situation is the one generally aimed at reducing orientations, stresses, and distortion of the part.

To obtain moldings of constant dimensions and constant mass, it is essential to reach the 1-bar line (Fig. 7-59) at the same specific volume on every cycle because the molding separates from the walls of the mold exactly at this pressure and subsequently starts to shrink. The extent of volume shrinkage corresponds to the change in specific volume along the 1-bar line. Two requirements are met: (1) The specific volume of the melt is constant while cooling and (2) the specific volume at the 1-bar line is the same on each cycle. A strategy for process control in the holding pressure phase can also be specified. Thus on every cycle, the same isochor on the *PVT* diagram must be reached as quickly as possible.

A computer program for achieving this pattern for the process was written some years ago; it used knowledge of material behavior and temperatures measured during the course of the actual process (melt temperature, mold-wall temperature), first of all to calculate the pattern of temperature change within the molding throughout the period of postpressurization. Subsequently, in a second stage of computation, pressure values are assigned to the temperatures (and times) from the *PVT* diagram of the material. These values bring about the process control. Thus, the *PVT* program works out the ideal pattern of holding pressure from materials data, molding-part data, and measured process data.

This pressure pattern can be transferred to the machine controller to serve as the target pattern for the holding-pressure phase. This *PVT* optimization program, as it is frequently called, can be integrated into powerful machine controllers. Several machine manufacturers offer such process optimization as an optional feature on their machines. Not

only does the *PVT* program make it possible to accommodate pressure control to variations in process temperatures, it also assists in greatly simplifying the setup procedure, by determining automatically the complete pattern of pressure for the holding-pressure phase.

Conventional process control systems are designed for closed-loop control of injection molding parameters such as injection velocity holding pressure, cushion, and recovery stroke. However, there are processing parameters such as melt temperature and mold temperature that affect the consistency of the molded part to an even greater extent. These are generally left out of the conventional process control concepts. There is a method that compensates for variations in melt and mold temperature by adjusting the holding pressure profile in real time. Compared with conventional closed-loop process control, this method, the *PVT* (pressure, volume, temperature) holding-pressure optimization, results in weight savings, parts with lower internal stress, higher dimensional stability, and significantly less waste in start-up. Essentially, *PVT* holding-pressure optimization is superimposed on a system that already supports closed-loop, process control. Therefore, the degree of control provided is above and beyond that of a system that many would already call fine-tuned.

The *PVT* optimization routine is concerned with the quantities p (pressure), v (specific volume), and T (temperature), as well as the profile of the mean temperature in the mold determined by a cooling calculation. In the diagram, pressure values are represented by diagonal isobar lines. One bar, the uppermost diagonal line, is atmospheric pressure, and the lines below indicate successively higher pressures. Specific volume may be defined as the volume of plastic per unit of weight, for example, cu in. (cu cm)/oz (kg). Specific volume is the inverse of density. The objective of the *PVT* holding-pressure optimization is to reduce the molded part to the same temperature at atmospheric pressure after cooling. This assures that the specific volume (and therefore the density and part weight) will be consistent (513).

PMT Concept

In the course of continuing development of this optimization procedure at IKV in Aachen, a method was found by which the parameters needed for control of the holding pressure can all be recorded automatically during a machine learning phase. The newer *PMT* program developed computes an ideal pattern of followup pressure from the experimental data obtained from the machine itself during the learning period.

The volume of the mold cavity remains during the pressure holding phase, except for changes by mold breathing. The effect of this action on the volume of the cavity should be negligible, since its impact is smaller in the melt flow direction than in the one perpendicular to it. In addition, breathing exerts compressive action on the molding. This is reproducible and sometimes desirable for quality control.

It is also very easy to keep the amount of material injected into the mold constant during the pressure-hold phase, by interrupting melt feed with a valve. This can be achieved by activating a nozzle valve in the injection machine, or a needle valve in the mold. If the mass m of melt and volume of the cavity V are constant, then the specific volume ($v = V/m$) of the melt in the cavity will be constant until the 1-bar line on the *PVT* diagram is reached. Interruption of material feed enforces isochor process control and this achieves the first objective. In this connection, the time at which material flow is stopped is very important.

The time at which the isochor phase of the process is initiated has a decisive effect on the whole subsequent pattern of events and also on part quality. It can be seen from the *PVT* diagram that this time is a function of temperature and pressure. It can, as in the *PVT* program, be determined by computation from the plastics data. However, to remain independent of material data, it was considered worthwhile to determine all the basic data required for process control from process data measured in the machine. Temperatures and pressures can be relatively eas-

ily recorded with the aid of devices that are now readily available.

A direct measurement of the specific volume of a plastic certainly cannot be made in the mold. However, it is possible by systematic variations of parameters to draw reliable conclusions about the shift of isochors from the weight of the molded part. The specific volume under isochor control is determined from the weight of the molded part. Because part weight is very important for controlling the process, it is useful to represent the process on a *PMT* diagram. On this plot, the mass of plastic in the mold, and thus the weight of the part, replaces the specific volume. If the mold is not changed, the cavity volume V remains constant and the mass m is obtained from the equation $m = V/v$.

In *PVT* and *PMT* diagrams, only the plastic state relevant to the pressure-holding phase (the liquid state) is represented. The diagram applies to one plastic-mold combination only. It must be plotted for other combinations. The sequence of injection and cooling is not changed when a *PMT* plot is to be used instead of a *PVT* plot. After the mold is filled at constant temperature, the system switches over to closed-loop pressure control. This is followed by a period of constant pressure (earlier isobaric phase) that is succeeded by the later isochor phase. Isochor process control, as with *PVT* optimization, can be achieved by means of the pressure or by interrupting mass movement with a nozzle valve. The isochor phase ends as soon as the pressure in the mold falls to that of the environment.

At this point, the molding separates from the wall and shrinks. From this point on, the *PVT* and *PMT* diagrams diverge. This is because the volume of the molding changes while the mass of the part remains constant, but the specific volume decreases with decreasing mold temperature. The weight of the molded part is the same as that of the melt injected into the mold before the feedpath is closed, since the nozzle valve stops the exit as well as the entry of plastic.

The line of constant mass ("isomass" line) on the *PMT* diagram corresponds to the isochors on the *PVT* diagram. If one of the

parameters (pressure, period of holding pressure until nozzle valve closure, or temperature) changes during the process, it affects the properties of the molding. For proper process control, therefore, a determination must be made of how a variation in one process parameter can be compensated by a suitable adjustment to another. Thus, another objective of the *PMT* concept is to achieve automatic, comprehensive determination of an ideal pattern of holding pressure by the machine itself.

Controllers

Controllers are instruments measuring pressure, temperature, time, etc. used to control and regulate the fabricating cycle. Compared with older proportional controllers, automatic set controller techniques used in modern controllers, permit more accurate control of temperature, etc. at setpoint even in the presence of lag time from remote locations.

As control choices continue to expand, users are faced with a choice of controllers ranging from soft, to programmable, to hybrid, to entirely new architectures. Amidst this potential confusion, control vendors are waging their own debate over which technology is least expensive, most popular, or will outlive others.

One should define control not by the “box” performing it, but rather by virtue of the problem it solves. This approach focuses on what the unit “does” instead of focusing on which solution is typically used. To do this, users must consider the choices available at each level within a controller. Proper selection requires personal knowledge or help from a reliable source to determine which type of controller is appropriate for a specific application (Chap. 9, Computer Controllers).

Today’s programmable controller operating system, like the hardware platform, is the result of over a quarter of a century of evolution in providing the available repeatability and reliability required on the plant floor. In the past, achieving these objectives meant choosing a vendor-specific operating system

and choosing that vendor’s entire control system. This can be a benefit if risk is to be avoided, but it can be detrimental if a high degree of in-house customization and integration is desired (522).

Controllers are fairly simple devices, but if they do not function properly, all kinds of problems develop. A checklist for eliminating problems includes: heater element burnout, location and depth of sensor as related to response time, type of on-off control action (for instance for a proportional controller), setpoint control, and proper electrical component selection. The sensor must be at the proper depth in a barrel to obtain the best reading for the melt; the deeper the better. Where water is involved, as in mold cooling controllers, improper construction can lead to leakage (due to expansion or contraction not being properly incorporated). External pressure relief valves can ensure discharge outside the cabinet. With inside discharge, severe damage can occur to mechanical and electrical components.

Computer coordinator controllers are groups of controllers connected together so that they can all be changed at the same time from a single point. Also used are multizone microprocessors. These monitor temperature, pressure, output rate, etc. signals from several sensors to achieve more reliable and efficient performance, either independently or coordinated.

Designs

A microprocessor or multiprocessor system has to carry out various control and monitoring functions such as (1) standard functions (sequence control, timer, malfunction indication, etc.), (2) monitoring functions (self-diagnosis of malfunctions, control of setup procedures, calculation of operating data, etc.), and (3) control functions (different temperatures in the IMM, process control of speed and holding pressure, etc.).

The advantages of this type of equipment for direct machine control can only be fully realized if the equipment carries out

all monitoring and control functions. Determining operating points by trial and error is inevitably eliminated. One must ensure that all system actions include what has to be carried out to produce the required products.

Sensor Control Responses

Some sensors are designed to respond to a physical stimulus (temperature, pressure, motion, product gauging, product weight, etc.) and transmit a resulting signal for interpretation, measurement, and/or operating a control. A very broad selection of sensors with extremely different sensitivities, capabilities, and repeatabilities are available.

To select the correct sensor you should know something about how the different sensors work, and which is used for what application. This is important since not all sensors measure in the same manner. The three most common sensors used downstream are nuclear, infrared, and caliper. There are also specialized types such as microwave, laser, X-ray, and ultrasonic. These sensors sense different conditions for operating equipment (temperature, time, pressure, dimensions, output rate, etc.) and also sense color, smoothness, haze, gloss, moisture, dimensions, and other properties.

The importance of measurement of a variable and the corresponding control action to the precision which can be realized in production cannot be underestimated. For example, because of a response lag in a pressure sensor, by the time an increase in pressure is transmitted to a control device the actual system pressure continues to change. The controller that receives this information then must process it and transmit an appropriate control response. This can usually take "some" time.

Transducers

The term transducer is frequently used interchangeably with sensor. It is a device that converts something measurable into another form. It is often a physical property such

as temperature, pressure, and/or flow. For example a piezoelectric device can convert high-frequency electrical energy into high-frequency mechanical vibrations (287).

Linear Displacement Transducers

The use of linear displacement transducers (LDTs) for IMM has evolved over the past decades. They are used to control mold closing, determine the location of feed screws, and track the position of part ejectors (7). In high-performance systems, they have largely displaced mechanical limit switches and potentiometers. Although these contact methods of switching and linear measurement worked satisfactorily, they did have their drawbacks, including mechanical wear and the limitation of determining only the end position of the components being monitored.

Since the linear displacement transducer provides continuous position feedback and is a noncontact method of measurement, it is ideally suited for either open- or closed-loop molding operations. Various types of outputs are available that can enhance both the positioning accuracy and processing speed of injection molding machines.

Transducers consist of three major components: a magnetic ring that acts as a traveling marker; the signal medium, or wave-guide, which is enclosed in a stainless-steel rod and deforms to mark the point of position; and the electronic end or head, which generates and processes the return signal from the waveguide.

The magnetic ring is permanently affixed to the part whose movement is being monitored and determines the exact location of the point of measurement. The ring's position is typically sampled at 2 kHz, for an update time of 500 msec. The magnetic field generated by the ring induces a mechanical twist in the waveguide. This twist ripples back on the waveguide and is picked up by the receiver located in the head.

The signal is processed inside the head and converted into an output signal for the machine's control system. The resulting position

reading is exactly proportional to the travel time of the pulse. Depending on the requirements of the control system, the output can be transmitted as analog voltage or current-controlled pulse.

Linear Velocity Displacement Transducers

A linear velocity displacement transducer (LVDP) is a transducer used for measuring relatively small amounts of movement in the vertical or horizontal plane. The amount of movement is detected by means of a change in an electrical signal caused by the movement of an iron core within a coil; this change is then amplified and converted into a linear measurement. Very accurate readings of tie-bar extensions can be obtained when using these devices.

Pressure Transducers

Pressure transducers are used in equipment such as plasticators to improve output and melt quality and enhance production safety. They aid in obtaining optimum processing pressure to ensure the quality of product features such as output dimensions and surface finish, and they minimize material waste.

Transducer specifications Specifications on pressure transducers from different manufacturers can vary significantly so it is important to understand their accuracy. An ideal device would have an exactly linear relationship between pressure and output voltage. In reality, there will always be some deviations; this is referred to as nonlinearity. The best straight line is fitted to the nonlinear curve. The deviation is quoted in the specifications and expressed as a percent of full scale. The nonlinear calibration curve is determined in ascending direction from zero to full rating. This pressure will be slightly different from the pressure measured in descending mode. This difference is termed hysteresis; it can be reduced via electrical circuits.

Transducer Calibrations

If possible, a calibration check should be made on a regular basis. ISO 9000 standard dictate frequent checks. A visual examination should be made before proceeding with the check to determine if the diaphragm is flat and free from any damage. Zero balance, full-scale sensitivity, and R-cal @ 80% parameter reference points for calibration can be used. The transducer manufacturer provides these parameters.

Transducer Environments

Some of the more common problems caused by a plant's hostile environment that can affect equipment such as transducers are noise interference, mounting holes (which must be concentric and clean), installation, diaphragm considerations, and transducer calibration.

Transputer Controllers

During 1991 the state of the art in IMM control technology was redefined in Meinerzhagen, Germany: Battenfeld formally introduced the Unilog TC 40, a computerized machine control system based on transputer technology (7).

Transputers are high-performance microprocessors. They belong to the family of RISC (reduced-instruction-set computer) processors. These are special microprocessors whose processing speed was increased by reducing the instruction set. Today, systems of this type are used whenever large amounts of data have to be processed within a very short time. Example applications can be found in telecommunications, image processing, and automation technology.

Transputers were developed by the British company INMOS in 1985. INMOS became part of the worldwide SGS-Thomson electronics group a few years ago. At first, transputers were only used in Europe. Through the merger of INMOS with SGS, Thomson,

the potential of worldwide marketing was opened up. Since then, transputers have made their appearance in the United States and Far East.

Transputers differ from traditional microprocessors in two ways. As mentioned above, they have a special architecture, the RISC architecture. It is particularly suited for applications in which a large number of open-and closed-loop control tasks have to be processed simultaneously. Second, they have four serial interfaces, the so-called LINKs. These are used to interconnect transputers. The transmission rate of these interfaces is up to 20 Mbit/sec, 20 million bits of information per second. For a comparison, today's serial printers for personal computers work 2,000 times slower. These LINKs are the strength of the transputer.

The advanced computer architecture of the transputer allows the Unilog TC 40 to be a real-time, multitasking computer. Functions such as calculating, controlling, measuring, and communicating run in parallel. Transputer power and speed allowed Battenfeld to create fully closed-loop injection molding machines, which means *every* machine movement can be accurately closed-loop, controlled, and self-adjusting in real time, as it happens and not on the next shot.

Today, microelectronics offers integrated circuits whose capacity is far superior to what was state of the art just a few years ago. Within the past few years, great progress has been made, particularly in the fields of computer architecture, memory capacities, and visualization technology.

This control system was designed for use in the upper capacity range, that is, for complex machines with a high number of controlled systems, which cannot be covered by today's technology. It does not replace the successfully employed Unilog 4000B control system; it is just a supplement for the higher capacity ranges. TC in the name of the new control system stands for "transputer-controlled." This is to point out that the heart of this control system is a transputer.

Temperature Controllers

Injection molding is a thermal process with the major task to ultimately control temperature. Too much or too little heat at the wrong place can cause many problems (short shot, galling, splay, brittleness, plastic degradation, etc.). You cannot see this thermal energy, only its effects (303). Thermal energy radiates in the IR spectrum, outside the spectrum of visible light. Use has been made of IR video cameras to detect energy color patterns in all locations around the IMM and auxiliary equipment. This IR thermography reveals that every plastic has its own wavelength, and temperature readings are related to the IR color patterns. It also provides IR signatures for each plastic using the Fourier Transfer Infrared Spectrum (FTIR).

Mold temperature control units are manufactured to give operators more oversight during processing, enabling increased product precision. Plastic to be processed is melted and prepared in the barrel of the IMM. The quality of this procedure is crucial to the injection of the melt into the cavity(s) and performance of the molded product. The following temperatures are important: barrel internal diameter wall temperature, melt temperature, machine operating temperature (hydraulic fluid and/or electric motor), tie-bar temperatures, sprue temperature, mold temperature [runner(s), gate(s), and cavity(s)], and ambient temperature. All temperatures have to be measured and in most cases controlled. The goal is to have uniform and constant required temperatures (405).

Temperature control involves the barrel, mold, machine operation (hydraulic oil and/or electric motor), coolant, etc. The demands on temperature controllers to obtain quality-molded products require accuracy of their dynamic behavior such as response time and transient performances. Temperature controllers differ widely depending on requirements such as short response time, minimal overshooting, high circuit stability amidst system (IMM and plastic) variations, transient suppression, and sluggishness

to keep temperature variations small. Most controllers provide a derivative term, called the rate term. This is an anticipatory characteristic that shortens the response time to changing conditions. There is also a circuit that limits overshooting.

Since not all demands can be met in an optimal manner at the same time, compromises must be made in the adjustment of controllers and in the selection of suitable control elements. Controllers operate in a digital mode and employ microprocessors. The input signal is converted into a numerical value and mathematically manipulated. The results are summarized to obtain an output signal. This signal regulates the power output in such a way that the temperature is maintained at the set value.

Previous proportional controllers did not allow the actual temperature to be at the set-point. To compensate, the offset was squared, resulting in a larger deviation that carried more weight than a smaller one. Regardless, the temperature always differed by some fraction of the proportional band and the offset was always constantly changing. Since the input signal is continuous, the microprocessor performs an integration and adds an averaging term that permits the temperature to be kept at a preset point from ambient temperature to full heating even if larger time lags are present. This function is called automatic reset.

Temperature Variations

Temperature is an important process control variable in plastic processing. It has a decisive effect on the quality of the molded product, as well as on raw materials and energy costs. For optimum processing, the temperature has to be controlled at several points in the process from the plastication cylinder into the mold. Temperature controllers in these control systems usually operate independently of each other. However, interlinked control systems are used. The demands made of temperature controllers relate first to the achievable control quality but also to monitoring or documenting the process.

With barrels, a thermocouple is usually embedded in the metal to send a signal to a temperature controller. In turn, it controls the electric power output device regulating the power to the heater bands in different zones of the barrel. The placement of the thermocouple temperature sensor is extremely important. The heat flow in any medium sets up a temperature gradient in that medium, just as the flow of water in a pipe establishes a pressure drop, and the flow of electricity in a wire causes a voltage drop.

Barrels are made of steel, which is not a particularly good conductor of heat (being ten times worse than copper). Thus, there is a gradient in the steel barrel from the outside of the barrel to the inside next to the plastic. In $3\frac{1}{2}$ -in. (88.9-mm) and $4\frac{1}{2}$ -in. (114.3-mm) extruder barrels, these gradients or differences in temperature can routinely be 75 to 100°F (23.9 to 32.8°C) or more, as the zone heaters pump in heat or zone coolers take out excess heat. However, for years users routinely accepted extruders with sensors mounted in very shallow wells, or, even worse, mounted in the heating-cooling jacket.

Consider a barrel with a shallow well for its sensor. Assume a perfect temperature controller set at 400°F (204°C). There is a 75°F gradient from the outside to the inside of the barrel; thus, the actual temperature down near the plastic would be 325°F with the sensor set at 400°F. If the extruder started to generate too much heat, the temperature could reach 475°F before the sensor detected the increase. With this on-off control action, even with the controller set at 400°F, the plastic temperature variation would be 150°F. The result could be poor product performance and increased cost to process the plastic.

A deep well sensor will respond much more quickly than a shallow one to changes in the plastic's temperature. However, it responds slowly to changes, for example, in the heater line voltage or cooling water heat. The time constant for heat to propagate from the heater down to a deep well location is about 6 min in a $3\frac{1}{2}$ -in. barrel. Thus, an upset due to a cooling water temperature change might take 20 min or more to settle out. This system does not respond to ambient

conditions rapidly, but it retains part of the temperature error inherent in the use of shallow wells. In the example just given for a shallow well with 150°F variation, the variation would be only half as great, or 75°F, if two sensors were used, one deep and one shallow.

The DUO-Sense process (Holton/Harrel Inc., U.S. Patent 4,272,466, June 9, 1981) solved this problem, retaining the advantages of both deep and shallow wells by using a cascade control loop. The primary temperature loop is a shallow well, and a secondary loop senses the deep well temperature, using it to adjust the setpoint of the shallow well. This system offers such advantages as preventing the temperature of the heater from rising as high as it otherwise would, greatly extending the heater band life, etc.

These on-off controllers are unsatisfactory for a loading having a long time constant, such as an extruder barrel, a die adapter, a die, etc. The temperature will oscillate violently at an amplitude that is set not by the characteristic of the controller, but by the delay in the load, as reviewed in Fig. 7-60. To reduce this variation, a proportional control was developed. It is similar to the on-off controller but operates in between full on and off, with its output proportional to the deviation of temperature from the setpoint value (Fig. 7-61). Variations still exist with this system, but they are less than those of the on-off control.

Proportional controllers have three characteristics: (1) The actual temperature of a single proportional controller will never be at the setpoint; (2) the error in temperature, or droop, will vary over a considerable portion of a proportional band as the process varies; and (3) in the case of a large time lag, the proportional band of a simple proportional controller will have to be quite large. A significant portion of the proportional band will normally be used, so the temperature will vary considerably during normal operation of the extruder. Thus, a simple proportional controller is better than an on-off control, but it does not do the best job of controlling temperature.

The introduction of automatic reset into controllers for the plastic processor made it possible to hold the temperature constant even in the presence of extremely long lags. Automatic reset is a characteristic added to a proportional controller that functions as an integrating, or averaging, system, looking at the droop, or temperature error, over a period of time and adjusting the output so that the droop goes to zero. As a result, the actual temperature goes to the setpoint (Fig. 7-62). Automatic reset is almost always used with an additional "rate" term, which adds an anticipatory characteristic that does not affect steady-state performance but does speed up the response to changes in operating

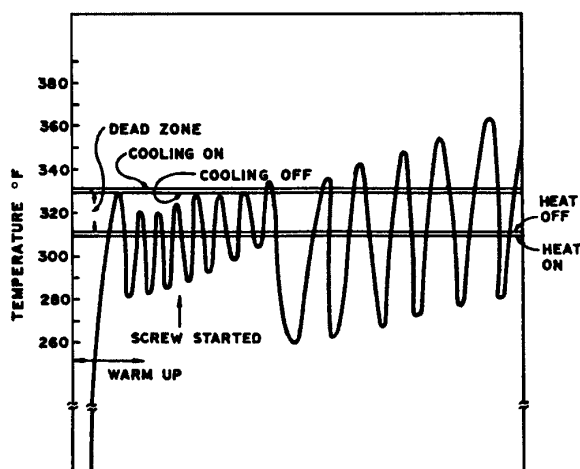


Fig. 7-60 Temperature variations with time in a typical plasticator barrel using on-off controls.

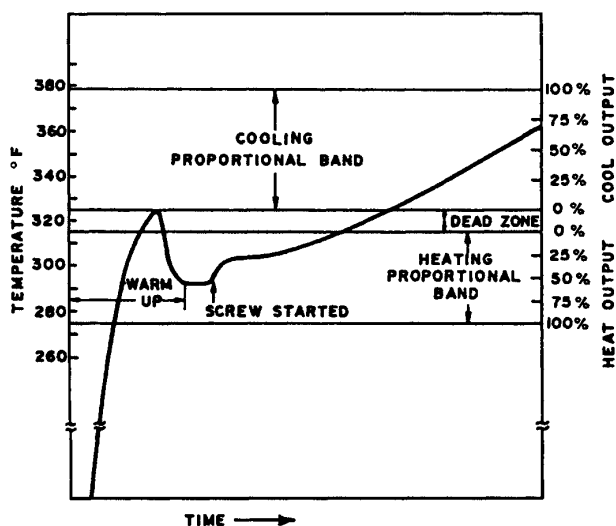


Fig. 7-61 Example of temperature variation with proportional control of a plasticator barrel (no automatic reset).

conditions. A modern proportional plus automatic reset plus rate—a three-mode controller—is capable of controlling within 1°F (0.6°C) of the setpoint all the way from full heating to full cooling, even when controlling from a deep well sensor.

Melt Temperature Profiles

Usually, the melt temperature is only taken or estimated from the inside of the barrel or

the surface of the melt as it moves through the barrel. Various techniques can be used (such as IR sensors) that look at melt temperatures across the entire melt stream, as, for example, when it exits an extruder (or an injection molding nozzle into space, etc.). An automatic thermocouple system (patented by AutoProbe, Normag Corp., Hickory, North Carolina) has a motor-driven, retractable melt thermocouple, which moves across the melt stream while simultaneously displaying temperature and temperature profile

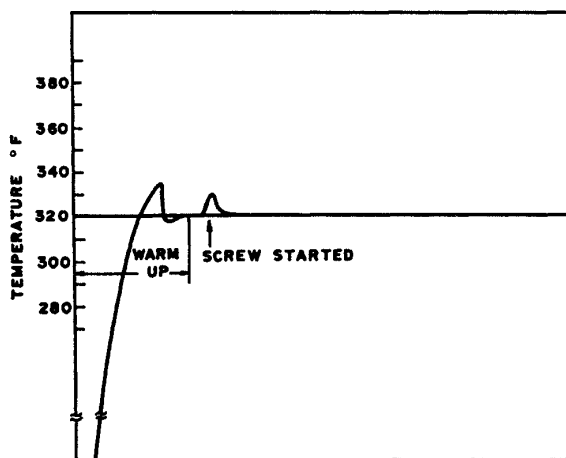


Fig. 7-62 Variation of temperature in a plasticator barrel with time using proportional plus automatic reset control.

position (7). The system shows that temperature variations within the melt stream can be considerably wider than expected.

It had been generally accepted by most extrusion processors and suppliers that the melt temperature variance at the end of an extruder was negligible. Stationary thermocouples had been immersed in melts, but very limited useful data could be obtained, as probes tended to disturb the melt flow or be damaged. Obtaining the profile with a standard immersion thermocouple required that an operator position the probe manually, plot the position, etc. Results were not repeatable or were tentative at best.

Temperatures of the automatic retractable thermocouple have ranged from 402°F on the melt channel wall to 325°F in the center of the melt stream. Melt flowed through a 1-in. melt pipe processing LDPE with a melt index of 2. The flow rate was 1,000 lb/h. The temperature profile was computer generated with 20 separate readings across the melt stream.

Automatic Tuning

There is one major disadvantage to using an automatic reset barrel temperature controller: The coefficients of the proportional, the reset, and the rate terms all have to be adjusted properly to obtain desired performance. It is not difficult to do this, but it can be time consuming. One must follow the manufacturer's instructions.

Temperature Sensors

Sensors used for temperatures in the ranges experienced in injection molding plastic processing equipment include thermocouples (TCs), resistant temperature detectors (RTDs), and thermistors (TMs). Each has advantages and limitations technically and costwise. Thermocouples tend to have shorter response time, whereas RTDs have less drift and are easier to calibrate. Although TCs are more commonly used, RTDs provide better stability for their variation in temperature is both repeatable and predictable.

A thermocouple is a thermoelectric heat-sensing instrument used for measuring

temperature in or on equipment such as the plasticator, mold, die, preheater, melt, etc. Thermocouples utilize the fact that every type of metallic electrical conductor has a characteristic electrical barrier potential. Whenever two different metals are joined together, there will be a net electrical potential at the junction. This potential changes with temperature.

The RTD sensor is based on the fact that the resistance of some metals changes markedly with temperature, whereas the resistance of platinum, the metal most commonly used in RTDs, is extremely stable. Its variation in temperature is both repeatable and predictable to a high degree of accuracy. In the past, TCs offered major cost advantages, but with the advent of low-cost solid-state dc amplifiers, the use of RTDs has become more realistic.

RTDs have about 60 times higher sensitivity than TCs, their amplifiers are less expensive and much less sensitive to electrical noise disturbance, they offer better linearity (are twice as linear as TCs), and they are twice as interchangeable. The RTD does not have the TC's compensating cold junction, so only the desired temperature is involved. With TCs both ends of the wire are sensitive to temperature changes; there is no way of distinguishing between a change in the process and one in the ambient temperature, so there is some residual drift. Although the RTD itself costs more than a TC, an RTD system that includes the sensor plus an amplifier is almost always less expensive for an equivalent quality level. Processors should be aware of the availability and superiority of RTDs (7).

Thermistors are semiconductor devices with a high resistance dependence on temperature. They may be calibrated as a thermometer. The semiconductor sensor exhibits a large change in resistance that is proportional to a small change in temperature. Normally TMs have negative thermal coefficients. Like RTDs, they operate on the principle that the electrical resistance of a conductive metal is driven by changes in temperatures. Variations in the conductor's electrical resistance are thus interpreted and quantified, as changes in temperature occur.

Fuzzy Logic Controls

Although fuzzy logic control (FLC) may sound exotic, it has been used to control many conveniences of modern life (from elevators to dishwashers) and more recently has moved into industrial process control including injection molding plastic processing parameters such as temperature and pressure. FLC actually outperforms conventional controls because it completely avoids overshooting process limits and dramatically improves the speed of response to process upsets. These controllers accomplish both goals simultaneously, rather than trading one against another as done with proportional-integral-derivative (PID) control. However, FLC is not a cure-all because not all FLCs are equal. FLC is not needed in all applications; in fact FLCs in use can be switched off so that traditional PID control can take over.

Fuzzy-PID Controls

Traditionally, PID (proportional, integral, derivative) controls have been used for heating and on-off control for cooling. From a temperature control standpoint FLC has seen the more recent use. One of FLCs major advantages is the lack of overshoot on start-up, which allows the setpoint to be reached more rapidly. Another advantage is its multivariable control, which enables more than one measured input variable to affect the desired output result. This is an important and unique feature. With PID one measured variable can only affect a single output variable. Two or more PIDs may be used in a cascade fashion, but the use of more variables limits their practicality (473, 590, 622).

Temperature Timing and Sequencing

Most processes operate more efficiently when functions must occur in a desired time sequence or at prescribed intervals of time. In the past, mechanical timers and logic relays were used. Now electronic logic and timing devices predominate. These programmable

logic control devices provide sophisticated operations with controllable functions.

Pressure Controls

Different melt pressure measuring devices are important to ensure product quality. They are also required for analyzing machine wear, general operation of equipment, meeting day-to-day consistency (ISO-9000), relating to statistical process control, and providing IMM safety. In the past many pressure measurement gauges were grease-filled Bourdon tubes, which had short life spans and led to possible grease contamination.

Current models use electronic pressure gauges, which provide direct local pressure readings with alarm capabilities. They are flush mounted, eliminating contamination. The pressure measurement transducers provide an electrical signal for display and/or control systems. Devices can have flexible mounting stems with integral thermocouples.

Screw Tips

If installing a pressure sensor in the mold is not feasible for lack of space, has a deleterious effect on the cosmetics of the molded product, or is not justifiable for economic reasons then the pressure in front of the screw tip can be monitored. The pressure in front of the screw tip provides information on the melt flow between nozzle and mold during the holding stage, permitting better insight into the process. Piezoelectric transducers are most commonly used as pressure sensors because of the rapidly occurring pressure changes. Their output signal is proportional to the mechanical pressure loading. It is amplified and converted into a corresponding voltage. Only dynamic and quasi-static forces can be measured.

Cavity Fillings

Cavity pressure depends primarily on the location of the inserted sensor (close to or

removed from the gate). The sensor does not record the pressure (1) during the injection stage before the melt flow front has reached the location of the sensor, (2) during the holding pressure stage, or (3) if the melt shrinks and loses contact with the wall's cavity. For this reason the sensor is usually mounted close to the gate because the pressure pattern there is closest to that in the cavity. However, for monitoring filling it is better to locate the sensor far away from the gate. This location can also be used if eliminating flashing is required (304, 233, 531).

Pressure PID Controls

Accumulators have become increasingly popular to meet the demands for higher productivity and more consistent product quality. They can deliver faster-acting, more precise, and more energy-efficient hydraulic systems and components. They can deliver a large amount of oil at high pressure, making possible very high injection speeds without the need for an extremely large, energy-consuming pump. For variable-volume pumps, either single or multiple, provide just the amount of flow needed at any point in the cycle, for energy-efficient molding; servovalves give fast response as necessary to control the high injection speeds inherent with the more efficient hydraulic systems; and multistep injection speed and pressure profiling accommodate more sensitive control of the process to improve part quality.

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

Hydraulic pressure-control logic is, in fact, the same as that used for temperature control; its most sophisticated form uses three modes of control, known as PID, for proportional, integral, and derivative (also called

gain, reset, and rate, respectively). Each of these mutually interrelated modes of control has an adjustable "tuning constant" that permits the operator to adjust the sensitivity of the pressure controls to the dynamics of the particular machine's hydraulic system.

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

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

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

PID Tuning: What It Means

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

- *Proportional control (gain)*. With this type of control, the magnitude of the control output is proportional to the difference between the actual pressure and desired pressure—in other words, the magnitude of the error signal. The "proportional band"

is the range of error above and below setpoint, within which the control output is proportioned between 0 and 100%.

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

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

- *Integral (or reset) control*. Unfortunately, a characteristic of purely proportional control is that, in response to changing load conditions, it tends not to stabilize the process at setpoint, but rather, some distance away from it. Integral or reset control responds to this steady-state error, or "proportional droop," by shifting the proportional band up or down the pressure scale (without changing the band's width) so as to stabilize the process at setpoint. The amount of reset action to use, expressed in repeats per minute, is the second tuning constant.
- *Derivative (rate) control*. This type of control action responds to changes in error, or the rate at which the actual pressure approaches the setpoint. The faster the change in the magnitude of the error, the greater the rate control signal, and vice versa. It serves to intensify the effect of the proportional corrective action, causing the process to stabilize faster. Rate control's main effect is to prevent the undershoot-overshoot oscillation that may never be

completely eliminated with proportional-plus-reset control alone. The amount of rate action, expressed in percent, is the third tuning constant, usually the last to be set.

The Need for Rate Control on High-Speed Machines

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

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

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

Fuzzy-Pressure Controls

Proper velocity-to-packing (V/P) transfer is vital to the success of injection molding operations. A number of different variables have been proposed to establish the V/P transfer point: injection stroke, filling time, cavity pressure, and nozzle pressure. The first two are volume based. Their accuracy is strongly affected by melt leakage through the screw tip and changes in melt density caused

by variations in the melt temperatures. For the next two variables the V/P transfer takes place when the measurement of the cavity pressure or nozzle pressure reaches a predetermined value. For a specific molding condition, cavity pressure indicates the degree of filling. However, installing such a transducer in a mold increases the tooling cost and introduces undesirable marks on the surface of the molded product. Nozzle pressure, a less direct indication of the material status in the cavity, does not suffer from the installation problem. Nonetheless nozzle and cavity pressures are both strong functions of molding conditions such as material, mold geometry, melt temperature, and injection velocity (357, 583).

For whatever molding condition it may be concluded that a significant nozzle pressure increase will occur when the mold is nearly filled and a V/P transfer should take place immediately. Mathematically this is difficult to describe precisely with an explicit expression. The fuzzy inference system (FIS) is an important tool to solve such problems. It is a fuzzy rule based system that accurately and automatically determines the proper time to switch from injection velocity control to packing control. FISs can handle a wide range of conditions including different molds, materials, and operating conditions (622).

Injection Molding Holding Pressures

During the initial mold-filling phase of the molding cycle, high injection pressure may be needed to maintain the desired mold filling speed. Once the mold is full the cycle enters its "holding phase" and the screw acting as a ram pushes into the mold cavity(s) extra melt to compensate for material shrinkage. This may be done at a lower, second stage pressure or at the same initial high filling pressure; this high pressure may not be necessary or even desirable.

In many cases, a lower second stage pressure therefore follows a high first stage pressure. However, when molding some crystalline plastics, for example nylon and acetal, the use of the second stage pressure may be unadvisable as abrupt changes in pressure

can cause undesirable performance changes in the molded part.

Process Control Fill and Pack

Boost time variation can be eliminated by simply removing the boost timer. However, something else must replace it. At this portion of the cycle, the mold will be essentially filled, and any further filling will result in extensive compression of the melt. Plastic compression is necessary for good part qualities, and the extent of compression must be properly controlled. When compression occurs, a dramatic rise in pressure is experienced. Sensing this rise will place the end of fill at its proper time without the use of a timer.

In the case of fill and pack, the proper pressure parameter has already been selected. However, the methods of pressure control can usually be improved. The level of pressure in pack or hold and the dynamic performance are important aspects of the overall process control.

Process Control Parameter Variables

The process capability of the machine settings is linked with material status variables in the process in order to intercept not only machine but also material-induced variations in product properties. Changes in processing parameters are to be identified and corrected (1) during the injection phase via the injection work and (2) during the follow-up pressure and cooling phase from the *PVT* (pressure-volume-temperature) status curve. The successful operation of the IMM depends upon the selected intervention point, the sensors used, and the control elements in conjunction with the microprocessor.

The starting point for successful molding is a melt that is thermally and mechanically as homogeneous as possible with defined flow properties. The mold filling operation is determined by melt viscosity. Knowing this value directly at the nozzle head is desirable, but a machine nozzle designed to function as a capillary rheometer, which incorporates

several pressure transducers, will only become practical in the future. Excessive residence time, shear fracture leading to degradation, and very often very high injection pressures militate against their current use.

Unlike extrusion, melt feed in injection does not take place under steady state conditions (3). For this reason it is not realistic to expect a homogeneous melt, particularly with the long feed path that occurs during extrusion. Depending on the plastic and screw design, nonuniform axial melt temperature profiles occur in the space in front of the screw. Generally large L/D ratios for the screw and feed paths shorter than $3.5 D$ reduce this effect. Screws with diameters greater than 3.5 in. (90 mm) should be 20 to 24 D long and those with a D less than 3.5 in. should be 18 to 20 D .

Adaptive Ram Programmers

In injection molding a number of variables in plastic materials and machine conditions tend to change during production (Chap. 11, Plastic Material and Equipment Variables). All these variables affect the critical properties of the molded product. When material properties change or the machine drifts outside the ideally preset operating parameters, the operator must reestablish the conditions best suited for making the part. He or she is faced with a complex situation as the interdependency of machine functions and material conditions requires a thorough understanding of the process, and a series of complex adjustments on the machine must be made to maintain part quality. Often, the variables are not controllable to the necessary degree, and the operator has to contend with imperfect production and a high rejection rate.

The Spencer and Gilmore equation developed nearly thirty years ago is now widely utilized to predict the relationships that must be maintained to keep the critical functions that affect part quality constant. This equation indicates that the plastic pressure and volume are inversely related if temperature (or material viscosity) is constant. During molding, filling, and packing, the plastic tem-

perature drops only slightly because of the short time interval involved. The material viscosity tends to change, however, as a function of composition or long-term temperature conditions of the machine.

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

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

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

The Hunkar Model 315 adaptive ram programmer system is designed to perform these functions totally automatically, having the capability of continually adjusting critical

parameters and maintaining a constant process. Figures 7-63 to 7-67 explain some of the control functions.

Injection Molding Boost Cutoff or Two-Stage Control

Two-stage control provides a method of controlling the injection molding process via the cavity pressure control to enable consistent injection fill time. The boost cutoff approach can be interpreted incorrectly owing to its simplicity; some of the subtleties involved in its use are often overlooked. When molding with a machine that has no closed-loop control, the most generally accepted molding practice is to mold with enough pressure on the first stage or high volume pump to fill and pack the cavity as shown in Fig. 7-68.

The first-stage pressure is initiated at the start of the injection cycle and is maintained by the first-stage timer. This timer is set with enough time available so that the mold cavity(s) can be completely filled and packed before the timer has completed its cycle. When the timer completes its cycle, the ma-

chine control switches from a first-stage to a second-stage pressure. Second-stage pressure is set to a level sufficient to hold the material in the cavity(s) until the plastic solidifies. This technique requires a cushion of plastic melt ahead of the screw. The cushion allows pressure in the injection cylinder to be transferred to the mold cavity, thereby preparing the mold for packing and holding.

During the first pressure stage of the molding cycle only enough pressure is used to fill and pack the cavity. When the first-stage hydraulic pressure is set by this method, variations in melt viscosity and temperature as well as mold temperature and fill rate can cause greater or lesser pressure losses through the mold runner(s), gate(s), and cavity(s). In turn, mold variations in mold cavity pressure develop, which then produce variations in the performance of the molded product. In Fig. 7-68 cycle (1) shows a typical pressure reading during the molding cycle. Cycle (2) represents a variation in plastic cavity conditions even though the machine conditions are constant. In injection the mold pressure variations are the greatest single cause of molded product variations. It is this type of process

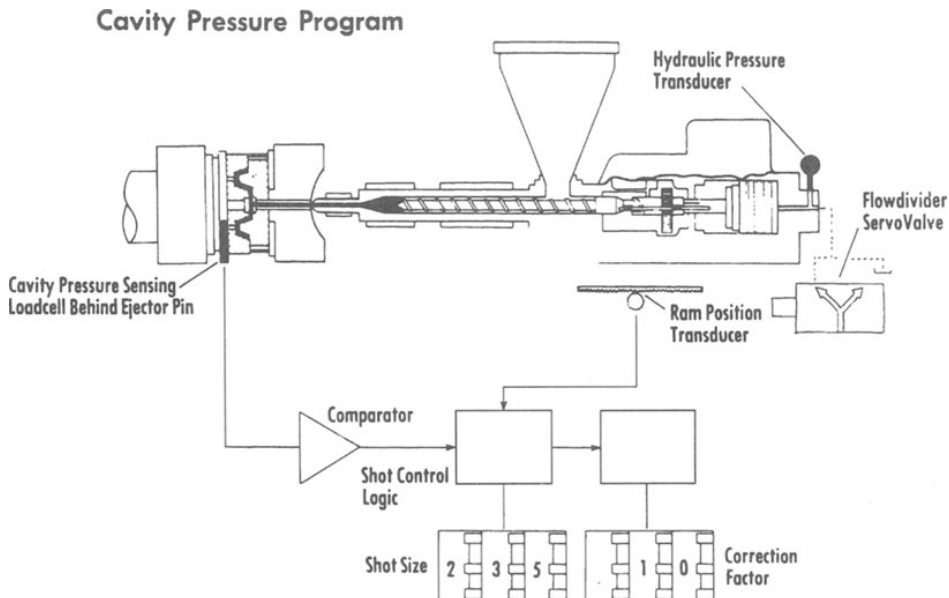


Fig. 7-63 Shot control function.

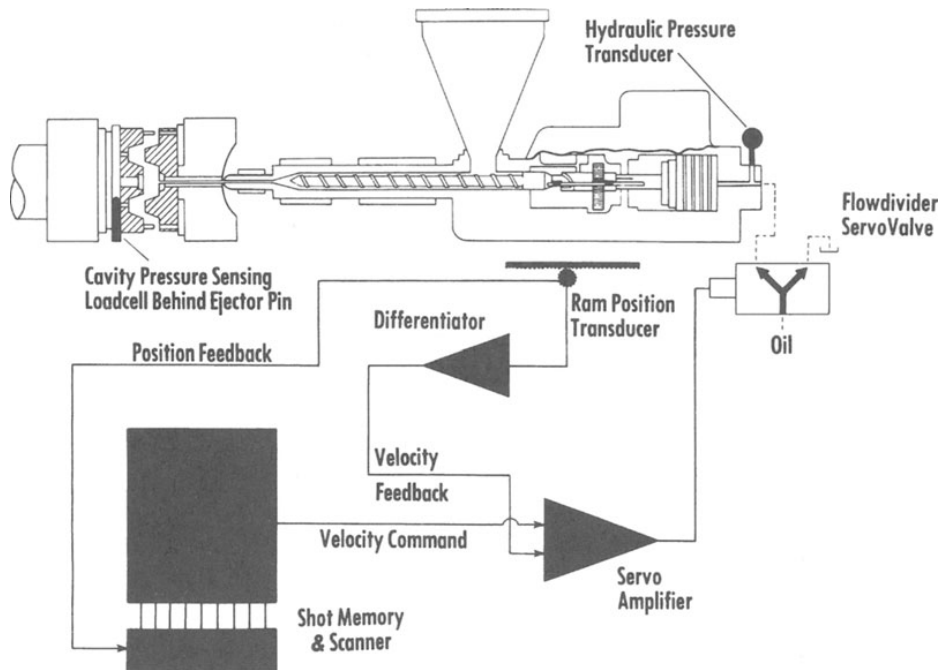


Fig. 7-64 Injection velocity control.

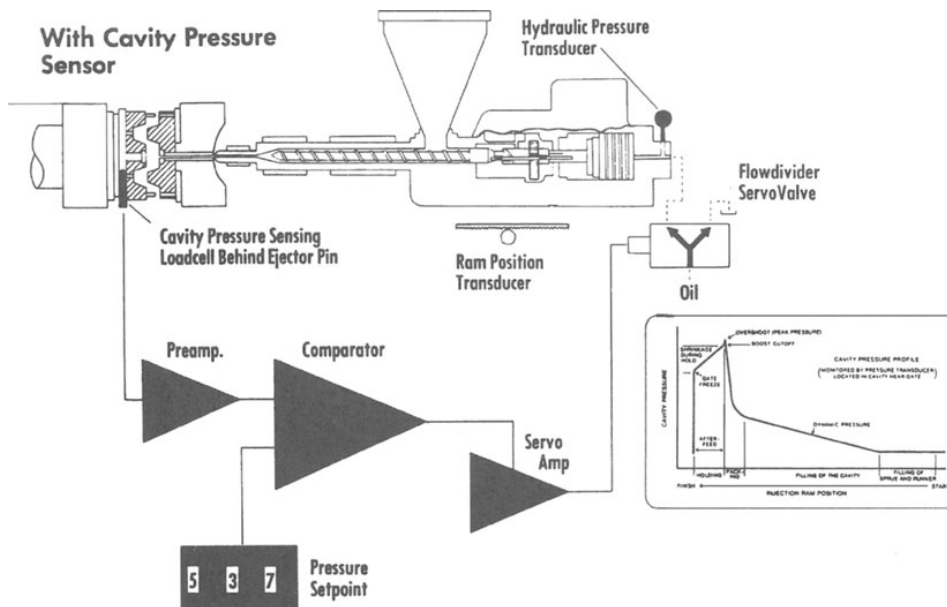


Fig. 7-65 Injection pressure cutoff control. The system also includes an automatic velocity override to prevent product flashing and a programmable pressure transition slope simulating ram bounce, thus ensuring a uniform stress profile throughout the product.

With Hydraulic Pressure Sensor

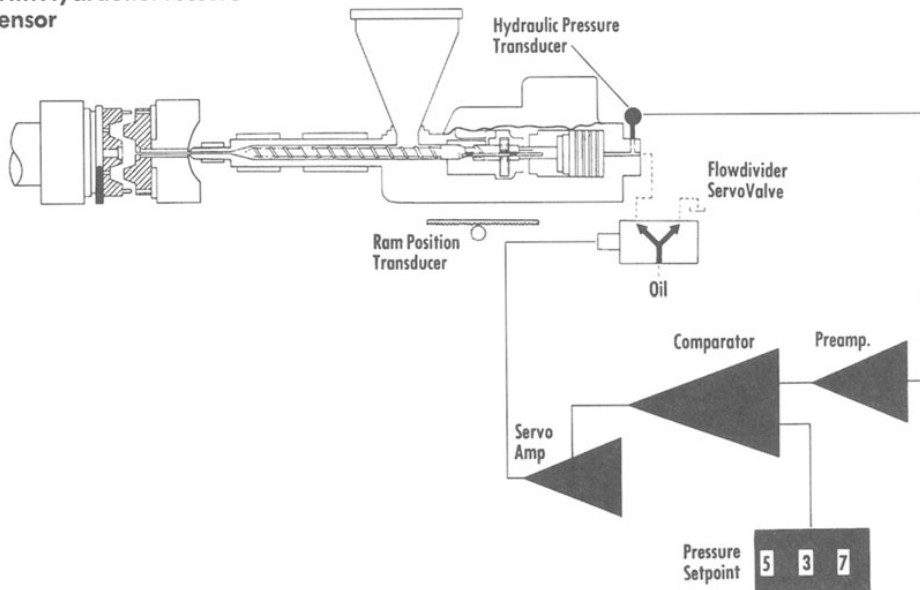


Fig. 7-66 Injection pressure cutoff control.

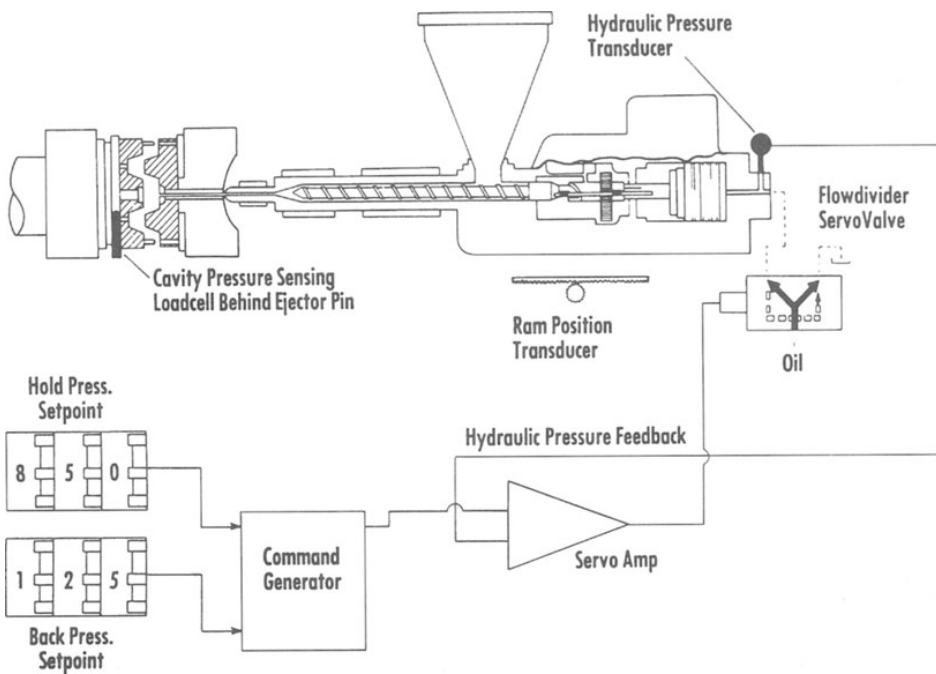


Fig. 7-67 Holding and plasticize pressure control.

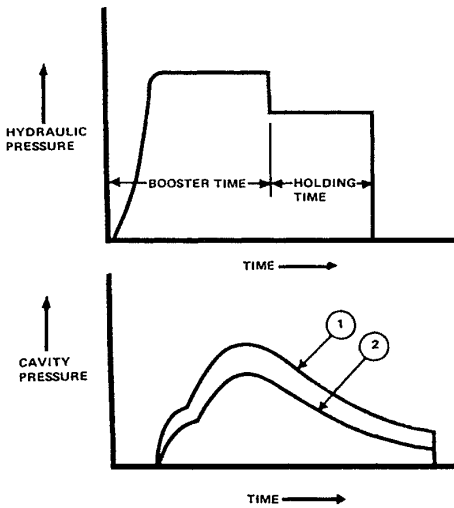


Fig. 7-68 Injection molding without boost cutoff.

variation that the boost cutoff approach eliminates (Chap. 11, Plastic Material and Equipment Variables).

As shown in Fig. 7-69, when using boost cutoff, the boost pressure used to fill and pack the cavity will usually be higher than normally used. If the boost cutoff were turned off for any given shot, the first-stage pressure set for boost cutoff would allow the cavity to be filled

and overpacked. This higher than normal first-stage pressure allows the IMM to deliver high energy to the plastic melt in the form of pressure to fill and pack the mold quickly. This extra high pressure allows the machine to overcome increases in viscosity of the melt.

This excess injection energy enables one to maintain uniformly high injection speeds even with variations in the viscosity of the melt. The proper use of a good manual pressure-compensated flow control to set the injection rate is essential for maintaining a uniform pattern. Even with a noncompensated manual flow valve on the machine, improved uniformity in fill rates can be achieved utilizing the boost cutoff technique. However, with a manual pressure-compensated valve, variations can be reduced to as little as $\pm 1\%$ in fill rate control using boost cutoff.

Having provided the excess energy necessary to achieve cavity fill, coupled with the correct use of flow control to keep the fill rate constant, it is only necessary to know when to turn the energy off in order to ensure that the proper degree of packing is obtained.

Figure 7-69 shows the point where the energy is turned off. It is called the boost cutoff or DPC (degree of packing cutoff)

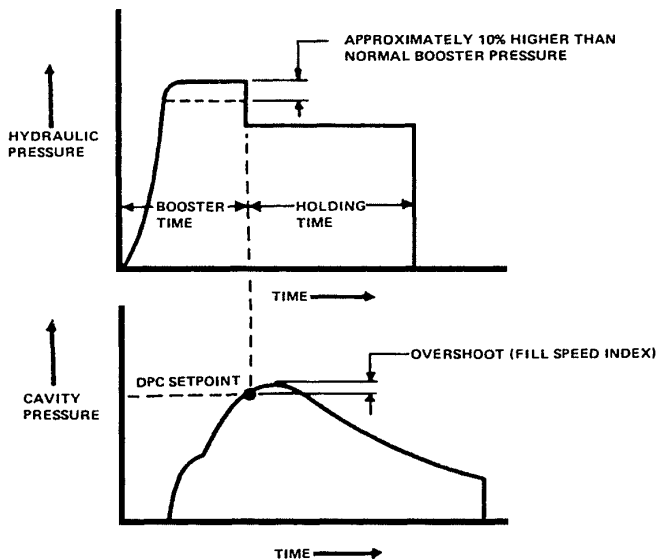


Fig. 7-69 Injection molding with boost cutoff.

setpoint. When this mold pressure setting is reached the machine switches from the first-stage injection pump to the second-stage injection pump automatically. Mold pressure continues to rise after this setpoint is reached until a peak pressure is obtained. This continued rise in pressure above the cutoff setpoint, called “overshoot,” is caused by the response of the molding system when the setpoint is reached, and keyed to the speed of the screw or plunger.

If the screw or plunger is moving at a high rate of speed when the first-stage pressure is cut off, the pressure will continue to rise while the screw or plunger is decelerating. If the screw or plunger is moving at a lower rate of speed when the cutoff setpoint is reached, there will be very little overshoot caused by its deceleration. The amount of overshoot is a variable that depends primarily on fill rates. To compensate for overshoot, the

molder may have to fine tune the boost cutoff setpoint when fill rate changes are made in the process.

Injection Molding Controller Three-Stage Systems

Three-Stage Systems

Three-stage controller systems allow one to use ram position and/or hydraulic pressure to stage the machine between the various stages of the molding cycle when cavity pressure sensors are unavailable in a given mold. A three-stage process control diagram is shown in Fig. 7-70. These controllers can also be used with a programmed injection device on the IMM to provide optimum flexibility and cost-effective control. The three-stage system divides the molding cycle into three

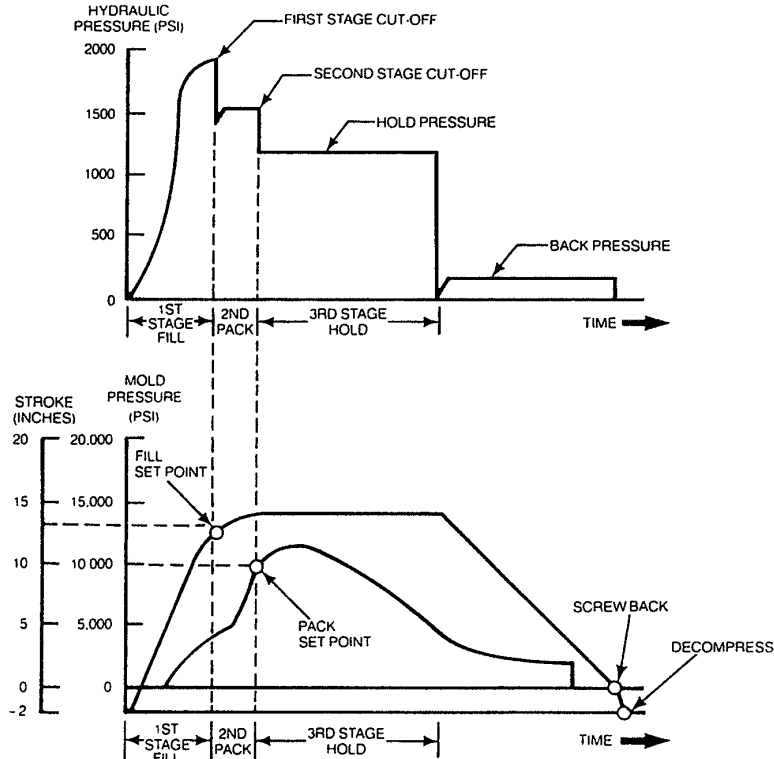


Fig. 7-70 Example of a three-stage control system.

distinct stages of fill, pack, and hold. Its controller allows mold fill rates to be completely independent of the mold packing rates. The degree of mold packing (peak or maximum mold cavity pressure) is controlled independent of fill rate. A third-stage hold pressure control is added to the molding machine and used to hold the correct melt pressure in the cavity during solidification and to prevent problems such as sink mark(s).

This type of controller has both a fill timer and a pack timer to allow monitoring of fill and pack time based on the requirements of the melt. The three-stage controller also controls peak mold pressure accurately because the rate of pack is reduced, eliminating the potential of second-stage overshoot. Other approaches to the use of a three-stage systems allow the mold to fill with melt pressure, pack, and stroke as well as fill with stroke, and pack with hydraulic pressure. Also, fill and pack transitions can be accomplished using only cavity pressure. On a mold equipped with cavity pressure sensors, a full stroke and pack with melt pressure, or filling and packed completely with melt pressure, are the optimum approaches to be used. This control method provides optimum cost and flexibility for process control.

Mold Cavity Pressure Variables

One of the problems in monitoring and controlling melt pressure is that it is not a constant for all positions in the cavity. Pressure in the mold cavity varies significantly from the applied pressure. It also varies with distance of flow and shape of cavity(s) in regard to melt flow pattern, resulting in high cavity pressure at the gate and low pressure at the end of the flow path. However, with proper balance of pressure, temperature, and time, the pressure profile can be made to be relatively even (if required). Another approach involves controlling the upstream cavity pressure and monitoring the last point to fill so that the cavity pressure profile can be maintained. This approach is utilized in intelligent mold systems.

Programmed Molding

Programmed injection can enable speed modification to provide nonuniform melt flow rate. It has many applications, primarily in thick molded parts, optical parts, and a variety of special applications where size and complex shapes are used. If a mold can be used to make good parts in a conventional IMM, then programmed injection is not necessary. A better approach is to keep the injection rate consistent shot after shot. On a machine equipped with a mold pressure control system, increased first-stage injection pressure can be used to overcome viscosity variations.

A simple but effective pressure-compensated flow control can be used to control fill speed. The flow control can be set by observing fill time reading on the control system and adjusting a valve to set the correct reading. Fill time can be held to $\pm 1\%$ using this simple and easy to process method. A servovalve base will greatly reduce flow rate variations.

Parting Line Controls

Part line control is a relatively new addition to the group of injection molding transfer point control strategies (595). An important consideration is its relative effectiveness in the removal of process disturbances compared to the standard group of techniques commonly supplied with most process control packages (7). Transfer point strategies include (1) *time*, the reference strategy, which may be considered an uncontrolled or open-loop process; (2) *in-cavity pressure (gate)*, usually the most effective control point; (3) *in-cavity pressure (runner)*, almost as effective as the gate position but has a slightly differing response; and (4) *ram position*, quite frequently used when it is not possible to put an in-cavity pressure sensor in a mold.

The parting line method controls the process by using the movement between mold halves as the plastic is injected into the mold as the feedback variable. This movement across the mold parting line is used to initiate the transfer from injection to holding

pressure; it therefore performs as a “transfer point” controller. Transfer point control has been around for some time and is a common component of most process control packages for injection molding. Four strategies are included in current commercial transfer point packages; “part line” adds a fifth.

Part line control has a major advantage in that its sensor is simply added to the *outside* of the injection mold. This technique results in little or no machining cost. The initial market has been primarily those manufacturers in search of an add-on to older machines without full control packages.

Although this concept sounds simple, its implementation required numerous developments in sensors, amplifier stability, and special signal processing that have only recently come together in a cost-effective manner. Achieving stable, repeatable resolution of movement at the level of millionths of an inch in a production environment is no simple feat.

Computer Microprocessor Controls

Reduced to a common denominator, the usual requirements for processing are better quality with reduced materials consumption. A control system is expected to provide exact acquisition of the significant process parameters, minimum response time, and high reproducibility. Constant maintenance of production documentation is important, not the least because of the manufacturer's liability for the product (Chap. 9).

Computer Processing Control Automation

Computer processing control automation can be applied to the fabricating process when some degree of precise control is required. Adapting such automation is straightforward if the process is easy to survey and can be described by data. However, clear physical relations can seldom be set up because the flow process is coupled with thermal and mechanical models. A valid description is usually only achieved by experiments such as trial and error. The important

process parameters are changed one at a time to the limits of the working point.

Molding Thin Walls

Conventional melt delivery systems are usually not well suited for thin wall molding. This is particularly true when using hot runner systems with engineering plastics. Extremely high injection pressures, properly controlled cavity fill speed at the start of fill, and stringent gate quality requirements associated with these applications require a specialized melt delivery. For example, without high pressures and uniform high heat at the gate(s), melt tends to freeze at the gate(s). Pressure changes occur with fill rates; faster fill tends to produce parts with less pressure gradients from the gate(s) to the last area to fill in the cavity (75, 118, 156, 299).

Thermoplastics have non-Newtonian melt flow characteristics, that is, their viscosity will change dependent on their velocity or the amount of shear that occurs in the melt. This non-Newtonian characteristic is the key to thin wall molding. As in any molding setup one cannot just simply ram the melt into the cavity. Its flow characteristic, gate(s) size(s) as well as position(s), and venting have to be balanced to obtain the desired structural part and meet tight tolerance requirements (Chap. 5, Molding Tolerances, Thin-Wall Tolerances).

Control System Reliabilities

Control systems must be reliable and that reliability is not a matter of luck but rather a result of thoughtful planning and implementation. Ensuring control system reliability is a critical productivity factor during any stage of system implementation from purchasing to system start-up. With the range of control options available, separating the truth from the hype about reliability from one system to another can be difficult. Is a reliable system one that does not fault, that shuts down at the right time, or that never shuts down despite the external environment? Control

system reliability can be defined as knowing and understanding the control system's expected behavior at start-up, during processing, and at shutdown.

The definition applies to both personal computer-based (PC-based) and programmable logic controller-based (PLC-based) systems with one exception: In a PLC-based system, as part of a supplier's quality check responsibilities, control designers confirm reliability. In a PC-based control system, users who take advantage of the key system benefit of multivendor product integration shift responsibility for reliability from the supplier to themselves. Depending on the extent of control systems integration, this can result in myriad factors, known and unknown, that may contribute to reliability. Although it would be difficult to highlight every factor that contributes to system reliability, it is important to understand the basic factors, risks, and suggestions. These factors include software issues and hardware issues.

Operations Optimized

Many consumers require from the suppliers the delivery of increasingly more complex moldings meeting high quality standards. The material quality is the responsibility of the supplier. To minimize costs and improve the technical quality, it is necessary to continuously monitor and optimize the production by such methods as the FALLO approach (Fig. 1.1). The increasing complexity of injection molding parts requires even more accurate tuning of the manufacturing process. Optimization is not a static process that can be carried out once and left alone but is a dynamic, continuous process. The continuous changes in ambient conditions, material and IMM variables, and mold wear force a constant reexamination of the process operational settings.

Control Tradeoffs

Most control units provide independent control loops and usually only control one

major variable. At present a few handle several variables so that the operation of a complete line requires the skill of one or more operators. Properly installed controls are extremely useful for simplifying setting up, operating, and shutdown of the line. Tradeoffs are inevitable in these complex operations where controls provide a major input on the action to be taken.

Lines have been operating with different degrees of automation via computer-integrated controls. These provide improvements in operating procedures and quality assurance usually resulting in reduced costs. These closed-loop systems maintain long-term repeatability of factors such as melt velocity and pressure, independent of what could be occurring with component wear, unbalance of equipment in the line, and/or plastic material variations.

Usually elaborate control systems cannot correct for problems such as those caused by: (1) a worn screw and barrel; (2) inadequate drive torque; and/or (3) poor screw design. For example, such systems will not yield good temperature control unless all features essential to good control are well maintained. Obviously, burnt-out heating elements cannot be tolerated. Another common deficiency for liquid cooled extruders is fouling or restrictions in the plumbing system or inoperative valves.

Process Control Limitations and Troubleshooting

Shorter cycle times and thinner or more complex parts continually increase the need for precise control in injection molding. At these higher production rates, excessive scrap and rejects become less desirable than ever, and the molder is faced with trying to reduce these levels.

Molding optimization is further complicated by highly automated operations that move the products directly from the molding machine to assembly stations. Effective process control, therefore, is essential to maintain the benefits of modern process technology.

Table 7-4 Example of comparing injection molding processing versus properties

	Control	Check Value	Gate Size	Back Pressure	Screw Speed	Fill Time
Check valve	Ring	Ball	Ring	Ring	Ring	Ring
Gate size, in.	0.13×0.25	0.13×0.25	0.062×0.063	0.13×0.25	0.13×0.25	0.13×0.25
Back pressure, psi	0	0	0	125	0	0
Screw speed, rpm	73	73	73	73	52	73
Fill time,	1	1	1	1	1	4
Notched Izod impact strength, ft/lb/in.	3.2	2.6	1.9	1.5	4.0	3.9
Flexural strength, 10^3 psi	17	17	17	17	19	18
Flexural modulus, 10^6 psi	0.98	0.98	0.98	0.98	1.00	0.98

Purchasing a more sophisticated process control system is not a foolproof solution to molding-quality problems, however. To solve part-reject problems requires a full understanding of the real causes, which may not be as obvious as they first appear. Failure to identify the contributing factors may send the molder on a time-consuming quest for “the perfect part.”

The conventional place to start troubleshooting a problem is melt temperature and pressure. But often, the problem is a lot more subtle; it may involve mold design, faulty control devices, and other machine components (Table 7-4). Sometimes, factors not directly related to the process may be influencing quality, such as an operator making random adjustments of control devices. Process control systems usually cannot compensate for such extraneous conditions.

Despite the benefits that can be realized with sophisticated instrumentation and computerized control systems, there can be many pitfalls in selecting software. You must make sure that the package you choose produces the desired results while considering control objectives and hardware capabilities at the same time.

Control

All processes are under some degree of control. All molding machines are equipped with a variety of controls. However, most of

these controls are of an open-loop type. They merely set a mechanical or electrical device to some operating temperature, pressure, time, or travel. They will continue to operate at their setpoints even though the settings are no longer suitable for making quality parts. The problem is that the total process is subject to a variety of hard-to-observe disturbances that are not compensated for by open-loop controls.

“Process control” closes the loop between some process parameter and an appropriate machine control device to eliminate the effect of process disturbances.

There are several levels of process control sophistication; each uses different control parameters. One level employs cavity-pressure measurement, which is the single most useful control parameter for injection molding.

The most efficient application of a process control strategy requires an understanding of the various aspects of process variation and their relationship to product quality.

There are two basic approaches to solving a molding quality problem: (1) Correct the basic problem, or (2) overpower it with an appropriate process control strategy.

The approach selected depends on the nature of the processing problem and whether time and money are available to correct the problem. Process control may, in some cases, provide the most economical solution. To make the decision, one must systematically measure the magnitude of these normal process disturbances, relating them to

product quality and identifying the cause whenever possible.

Before investing in a more expensive system, the molder must methodically determine the exact nature of the problem in order to decide whether or not a “better” control system will solve it.

Tie-Bar Growth

An example of a problem that most controls do not consider involves the effect of heat on tie-bars, which can directly influence mold performance. The following information provides the calculations for tie-bar elongation and mold thermal growth.

Tie-Bar Elongation

The change in tie-bar length e can be calculated as follows:

$$e = \frac{F \times L}{E \times A}$$

where F = force per tie-bar

L = bar length

E = modulus of elasticity

A = cross-sectional area of bar

At maximum die height (178 in.) on a 500-ton injection molding machine with a tie-bar diameter of 6 in. (or a cross-sectional area of 28.27 sq in.), tie-bar elongation equals

$$\begin{aligned} e_{\max} &= \frac{250,000 \text{ lb} \times 178 \text{ in.}}{30 \times 10^6 \text{ psi} \times 28.27 \text{ sq in.}} \\ &= 0.0524 \text{ in. (0.1331 cm)} \end{aligned}$$

At minimum die height (146 in.), the elongation is

$$\begin{aligned} e_{\min} &= \frac{250,000 \text{ lb} \times 146 \text{ in.}}{30 \times 10^6 \text{ psi} \times 28.27 \text{ sq in.}} \\ &= 0.0430 \text{ in. (0.0430 cm)} \end{aligned}$$

To calculate the effect of a small change in elongation on the force on a tie-bar, we solve for F :

$$F = \frac{eEA}{L}$$

At maximum die height, the change in force

per 0.001-in. elongation equals

$$\begin{aligned} F_{\max} &= \frac{0.001 \text{ in.} \times 30 \times 10^6 \text{ psi} \times 28.27 \text{ in.}}{178 \text{ in.}} \\ &= 4,764 \text{ lb (2,163 kg)} \end{aligned}$$

At minimum die height, the change in force for the same elongation is

$$\begin{aligned} F_{\max} &= \frac{0.001 \text{ in.} \times 30 \times 10^6 \text{ psi} \times 28.27 \text{ in.}}{146 \text{ in.}} \\ &= 5,808 \text{ lb (2,637 kg)} \end{aligned}$$

Thermal Mold Growth

Uneven mold growth can occur with a temperature differential across the mold. Mold growth G is calculated by the following formula:

$$\begin{aligned} G &= \text{mold length} \\ &\times \text{coefficient of linear expansion} \\ &\times \text{mold temperature} \end{aligned}$$

In a 20-in.-long mold, where the temperatures are 100 and 120°F, mold growth equals

$$\begin{aligned} G_{100} &= 20 \text{ in.} \times 6 \times 10^{-6} \text{ in./in./deg} \times 100^\circ\text{F} \\ &= 0.0120 \text{ in. (0.0305 cm)} \end{aligned}$$

$$\begin{aligned} G_{120} &= 20 \text{ in.} \times 6 \times 10^{-6} \text{ in./in./deg} \times 120^\circ\text{F} \\ &= 0.0144 \text{ in. (0.0366 cm)} \end{aligned}$$

The difference in growth on different sides of the mold is then

$$\begin{aligned} G_{120} - G_{100} &= 0.0144 - 0.0120 \\ &= 0.0024 \text{ in. (0.0061 cm)} \end{aligned}$$

Shot-to-Shot Variation

During injection molding, shot-to-shot variations can occur. Major causes of inconsistency are worn nonreturn valves, bad seating of a nonreturn valve, a broken valve ring, a worn barrel in the valve area, or a poor heat profile. To identify the cause, one follows a logical procedure. Any problem caused by the valve will cause the screw to rotate in the reverse direction during injection. To locate the trouble, one must pull and inspect the valve, and check the outer diameter of the ring for wear. The inspector

looks for a broken valve stud (caused by cold start-up when the screw is full of plastic), bad seating of the ring or ball (angles of the ring inner diameter and the seat must be different, in order to ensure proper shutoff action at the inner diameter of the ring), or a broken ring. One checks the dimensions of the valve and compares them with those determined before using the machine.

A poor heat profile for crystalline resins can cause unmelted material to be caught between the ring and seat, holding the valve open and allowing leakage. A change in the heat profile or the machine's plasticizing capacity is not sufficient to correct the problem. For any resin, if the problem does not occur with every shot, the cause may be improper adjustment or damaged barrel heat controls.

Nonuniform melt density could be caused by nonuniform feeding to the screw and/or regrind blend, which could have a different bulk density. Increasing the back pressure may help. This throughput condition, the residence time of the plastic in the barrel, and the barrel heat profile are all important in obtaining the best melt quality. The heat profile is the most important parameter and varies from resin to resin, as well as with different cycle times and shot sizes. As the following example shows, a screw operating under two different conditions will produce different results.

Consider a screw that is a 2-in. diameter, 20:1 L/D with 20-oz melt screw capacity. With a 15-sec cycle and shot size of 2 oz, it operates as follows:

$$20 \text{ oz (screw capacity)} \div 2 \text{ oz} = 10 \text{ cycles} \\ 15\text{-sec cycle} = 4 \text{ cycles/min}$$

$$10 \text{ cycles} \div 4 = 2.5 \text{ min of residence time,} \\ \text{from the time plastic starts} \\ \text{through the screw until it} \\ \text{enters the mold}$$

Another set of requirements uses a 6-oz shot size with the same 15-sec cycle:

$$20 \text{ oz} \div 6 \text{ oz} = 3.33 \text{ cycles} \\ 3.33 \text{ cycles} \div 4 = 0.83 \text{ min of residence time}$$

In the second case, a higher rate of melting will be required, with the probability that the

screw will be inadequate for the melt, and problems will develop.

The inventory in a screw will run between $1\frac{1}{2}$ and 2 times the maximum shot size rating in polystyrene. With other resins, calculate the difference in density to arrive at the maximum shot size and expected inventory.

Injection molding can produce a wide range of products that vary in weight by less than 0.1% (7). This accuracy is a product of electronic controls, hydraulics, and mechanical design. The variable that has the largest repeatability is the scan time of the program. This is the time it takes to complete the controls program once. In many machines, this can be more than 20 msec. Scan time is a product of the length of the program, speed of the microprocessor, and method of running the individual functions. With a parallel processing system (Fig. 7-71), control of the clamp, injection, hot runner, and robotics can occur largely outside of the machine control sequence. A machine with servorobotics and 64 hot-runner zones could have 8 to 10 microprocessors running in parallel and the scan time could still be under 2 msec.

The shot-to-shot repeatability improves dramatically as the scan time is decreased. As an example, when scan time was reduced from 8 to 3 msec, the weight variation dropped from 0.86% to 0.27%. In this case and many others, the relationship is approximately linear. This is true not only for weight variation but also for other key variables such as screw position repeatability and injection pressure repeatability.

Many factors affect repeatability, including fill time, screw design, and nonreturn valve selection. Applications that require fast

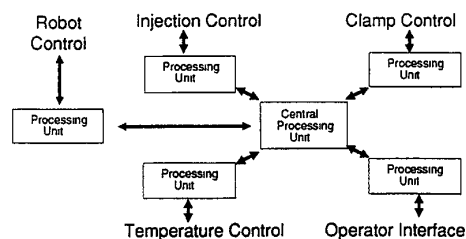


Fig. 7-71 Parallel process system.

injection to be able to fill the part will generally have greater weight variation on a percentage basis. However, the molder has little control over this. Slowing the injection can require more packing and result in higher part weight and molded-in stresses.

Consistent melt quality is an important factor in ensuring shot-to-shot repeatability. As a result, the screw geometry needs to be selected to match the specific requirements of the polymer and/or application. For example, for PET the best results are obtained with a screw having a low compression ratio and deep flights. For HDPE pail applications, the screw must be capable of a high plasticizing rate at a low melt temperature.

Screws with high *L/D* ratios (25:1) improve mixing for a wide variety of resins and help ensure that the melt temperature does not vary from shot to shot. Screw size also affects repeatability and so proper sizing of the screw for each application is important. For example, an 820-g HDPE part can be run with a 70-mm screw or 100-mm-diameter screw. If we assume that the position of the screw can be sensed to within ± 0.05 mm, the 70-mm screw will see a variation of 0.4 whereas the 100-mm screw will experience a 2-g variation from the transducer resolution alone. In instances where an injection unit must be used for a range of applications with different shot sizes, the two-stage injection approach offers advantages over the more common reciprocating screw (RS). RS units lose much of their accuracy in applications where the injection stroke is less than one screw diameter, whereas two-stage units remain accurate.

Most RS-type injection units use nonreturn valves to prevent the melt from flowing back over the screw flights during injection. The type of valve selected affects the level of shot control. For example, a ball check valve generally offers better shot control than a ring check valve.

Closed-loop injection often shows more than a 50% reduction in shot-to-shot repeatability, particularly during start-up or other intervals of unstable conditions. However, as the injection duration decreases, so do the benefits of the closed loop. At 0.1-injection, a closed loop does not significantly improve repeatability as the feedback loop cannot update fast enough to control screw displacement.

Measuring repeatability by percentage variation can be misleading if different molding applications are compared. Table 7-5 shows that an open-loop system, with an 8-msec scan time, can exhibit a smaller percentage of weight variation than a closed-loop system with a 3-msec scan time, if the shot size, fill time, and screw sizing are dramatically different.

The positional accuracy of the injection unit and clamp is essential to repeatability. Linear transducers on today's injection molding machines can be accurate to within 0.05 mm and update the position every millisecond. Response time of the hydraulic system has a major impact on repeatability. The use of cartridge valves, which have fast response times and minimal leakage, ensures consistent performance from shot to shot.

Variations in oil temperature can increase weight variations even with closed-loop

Table 7-5 Effects of resolution on shot-to-shot repeatability

Mold, Machine	Controls	Scan (ms)	Shot Size (g)	Fill (s)	Diameter of Screw	Variance (g)	Variance $\pm$ (%)
32-Cavity hot-runner mold, 300-ton machine	Open-loop	8	1,800	3	3 $\times$ D	2.22	0.06
24-oz Dairy container, 2 $\times$ 4 stack mold, 500-ton machine	Closed-loop	3	450	0.3	0.4 $\times$ D	1.10	0.12

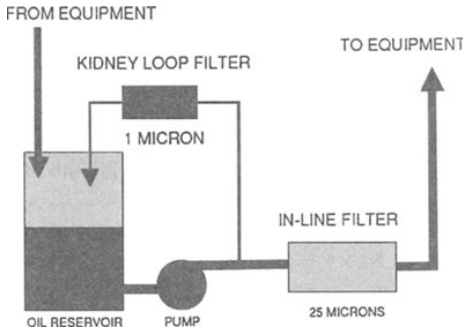


Fig. 7-72 Husky's bypass oil filtration system.

control. With a closed-loop temperature control valve on the heat exchanger and an adequately sized oil tank, oil temperature variation can be held to within $\pm 1^\circ\text{F}$. Excellent oil filtration is essential. Closed-loop control cannot compensate for particles caught under a valve seat. With bypass filtration (Fig. 7-72), particles greater than $1\ \mu\text{m}$ can be removed. This, combined with good oil temperature control, provides a very homogeneous hydraulic medium.

All these developments are of very limited value if vibration in the machine is not controlled. A rigid base and thick platens minimize mold deflection. Figure 7-73 shows the effect platen thickness can have on deflection under load.

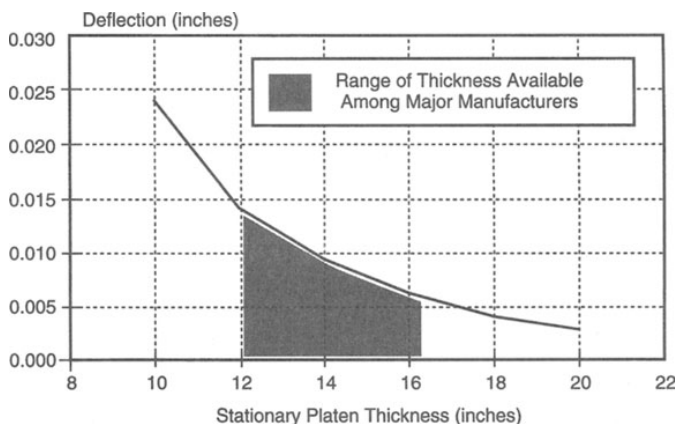


Fig. 7-73 Platen thickness versus deflection for a 500-ton machine at maximum tonnage operating with a 24 in. $\times$ 24 in. (54 cm $\times$ 54 cm) test block.

Intelligent Processing

Inefficiency increases costs. The intelligent processing (IP) of materials is one approach used to deal with inefficiency. This technology utilizes new sensors, expert systems, and process models that control processing conditions as materials are produced and processed without the need for human control or monitoring.

Sensors and expert systems are not new in themselves (Chap. 9, Artificial Intelligence), but what is novel is the manner in which they are tied together. In IP, new nondestructive evaluation sensors are used to monitor the development of a materials microstructure as it evolves during production in real time. These sensors can indicate whether the microstructure is developing properly. Poor microstructure will lead to defects in materials. In essence, the sensors are inspecting the material online before the product is produced (250, 314).

Intelligent Communications

The information these sensors gather is communicated, along with data from conventional sensors that monitor temperature, pressure, and other variables, to a computerized decision-making system. This decision

maker includes an expert system and a mathematical model of the process. The system then makes any changes necessary in the production process to ensure the proper formation of the material's structure. These might include changing temperature, pressure, or other variables and will lead to a defect-free end product.

Systematic Intelligent Processing

There are a number of benefits that can be derived from intelligent processing. There is, for instance, a marked improvement in overall product quality and a reduction in the number of rejected parts. Furthermore, the automation concept behind intelligent processing is consistent with the broad, systematic approaches to planning and implementation being undertaken by industries to improve quality. It is important to note that intelligent processing involves building in quality rather than attempting to obtain it by inspecting a product after it is manufactured. Thus, industry can expect to reduce postmanufacturing inspection costs and time. Being able to change manufacturing processes or the types of material being produced is another potential benefit of the technique.

Processing Rules

There are numerous rules to remember:

1. Processing is a marriage of machine, mold or die, material, process control, and operator all working together
2. The plastics business is a profit-making business, not a charitable or nonprofit government organization
3. Heat always tends to go from hot to cold through any substance at a controlled rate
4. Hydraulic fluids or electric drives are pushed, not pulled, at a rate that depends on pressure and melt flow
5. The fastest cycle or rate of output that produces the most products uses: (a) minimum melt temperature for fast cool-

ing, (b) minimum pressure for lowest stress in products, and (c) minimum production time.

6. All problems have a logical cause—understand the problem, solve it, and then allow the machine to equalize its production to adjust to the change
7. Remember if it does not fit, do not force it.

There are also some rules to forget:

1. The machine has a mind of its own
2. It takes a genius to operate a machine
3. All problems are caused by bad part design, bad tooling, or bad setup
4. My job is secure
5. If a little bit does a little good, a whole lot does a whole lot of good
6. If you twist enough knobs, the problem will go away

Processing and Patience

When making processing changes, allow enough time to achieve a steady state in the complete extrusion line before collecting data. It may be important to change one processing parameter at a time. For example when one changes extruder screw speed, temperature zone setting, cooling roll speed, blown film internal air pressure, or another parameter, allow four time constants to elapse to achieve a steady state prior to collecting data.

Processing Improvements

New developments in equipment and plastic materials usually offer improvements in processing capabilities. Although these improvements do not occur at the rate of computer changes keeping up to date on what is available can be a full time job. As in the past, these improvements reduce cost and aid in meeting the (asymptotic) goal of zero defects.

Control Advantages

Originally, a century ago, the choice of injection molding controls was more or less an afterthought. The user would select the equipment very carefully and then choose a few temperature controllers to keep the temperatures in the barrel and the mold constant. In today's market, if the user wants to stay competitive, he or she must recognize that what is being purchased is performance, and the best performance results when all elements of the line are integrated into one harmonious system. Each element interacts with the others to produce the optimum result. This can only be done by proper controls; controls are just as important as the injection molding, the mold, and the rest of the line. In fact, it is the control subsystem in the last analysis that determines how well the other elements work. To ignore it would be like saying that the only thing that counts in the Indianapolis 500 is the racing car. Everybody knows that the driver is just as important, if not more so.

As controls have become more sophisticated, the proportion of the total purchase dollar that goes into controls has increased, and users have had to break their old habits of spending lavishly on hardware and economizing on controls. And there is no reason why one should resist this trend. Profitability is what counts, and if a dollar spent on better controls pays off more, it makes sense to spend it there.

The types of controls can be categorized as follows:

1. *Machine controls.* Controls that affect some characteristic of the machine itself. Examples are temperature controls and rpm, or speed, controls.

2. *Process controls.* Controls that measure and control some characteristic of the plastic or plastic flow within the machine, for example, melt temperature controls, melt pressure controls, and parison programmers. Process controls usually operate by varying some characteristic of the machine. They are, therefore, usually *cascade* controls that must interact with the machine controls.

3. *Product controls.* Controls that measure and control some characteristic of the final product produced by the machine. They, in turn, tend to operate by interaction with both the machine and process controls. They usually do this by altering the setpoints of the other controls, again in a cascade control fashion.

4. *Plantwide control and management.* Controls that ensure that all of the molding machines of the plant operate in such a fashion so as to maximize quality and profitability.

The advantages in process control and monitoring include the following:

1. Systematic and rapid optimization of injection molding quality and cycle time
2. Quality assurance through automatic processing checks during every cycle
3. Reduction in testing and checking costs of moldings
4. Automatic separation of pass and reject parts
5. High repeatability of molded article quality, even when swapping machines
6. Considerable quality enhancement with older machines
7. Check proof of the machine's processing capability
8. Reduced restarting times
9. More effective fault finding and removal
10. Reduction of mold maintenance costs

Plantwide Control and Management

It is seldom that a molding plant has just one machine. And if it has more, one discovers that it is not what happens on the individual machine that determines profitability. It is the average performance of all of the machines that counts. The more machines there are, the harder it is to keep track of the million and one details that go into proper operation. It becomes harder for process engineers to be present when needed, maintenance people to know when a machine needs attention, and management to know when a decision must be made.

Modern central control and management systems have changed all this. In the past twenty years, they have been known by a variety of terms: supervisory control, distributed control, CAD/CAM, and at this writing CIM. All refer to the same thing: a system that can monitor all operating parameters on every machine in the plant and issue instructions to that machine so as to assure efficient (and profitable) operation.

Modern systems can take over entirely the programming and monitoring of machines. The establishment of parameters for a different product; setting of production rates; continual monitoring of all machines, process, and product parameters, etc. are all done from a central console. The process people at that console can determine a lot more about what is occurring on the line than out of the line; they can, in fact, be everywhere at once. Decisions are made at the central console and implemented there. Only the purely mechanical functions remain to be done on the line: bringing in the raw material and removing the finished product.

Once a center such as this is set up, it quickly becomes the nerve center of the plant:

- a. Management receives periodic reports and statistics that give it at all times a comprehensive picture of how the plant is operating. If desired, a repeater monitor in the plant manager's office acts as a continually updated status board.
- b. Production control receives reports as to the progress of every job and the number of hours at the actual rate of production before another job is required for each machine.
- c. Maintenance receives reports as to the frequency and causes of down time. If any machine goes down, it is informed instantly, along with an indication of the form of the malfunction.
- d. Quality control uses the same console for complete statistical quality control.
- e. Process engineering has a tool for optimizing the process. It can make minor changes and monitor results without ever interrupting production. It can also specify a

process to be run with the assurance that such a procedure will, in fact, be run that way.

There is a limited amount of engineering and management talent in any plant. A central control and management system allows that talent to be brought to bear on the entire plant. In effect, the best people are on duty around the clock because the console is executing their instructions and acting on their behalf 24 hours a day (*Injection Molders Guide to Plant Operations*, 1999 Almanac, Injection Molding Magazine (IMM), 1999).

Automatic Detections

Quantitative information, although important, is not enough to achieve the overall objective. Knowing that a part has been made in most cases does not ensure that it is a good part. Dimensional variation, flash, and short shots, which are the main causes of rejects in an injection molding plant, should be detectable and accounted for automatically.

To achieve these objectives, a straightforward conceptional approach can be implemented. This approach involves putting a mold pressure sensor at the last point to fill in each cavity of the injection mold. This cavity pressure is connected to a mold monitor device that, on each cycle, can detect the presence or absence of cavity pressure and whether or not that cavity pressure falls within a preset range. Using cavity pressure as the variable to be sensed has many advantages. First, the presence or absence of cavity pressure at the last point to fill is a totally reliable method of determining whether or not a part has been made in that cavity. Cavity pressure can normally be reliably detected by sensing the force on existing ejector pins in the cavity without changing the characteristics of the molded part. In cases where ejector pins cannot be conveniently used, flush-mount cavity pressure sensors can be installed to accurately measure the pressure under even the most adverse conditions.

In addition, cavity pressure sensing at the end of fill can detect all the changes in the molding process that reflect on the quality of the molded part. Cavity pressure at the end

of fill will vary because of temperature variations, fill rate variations, and variations in the hydraulic systems pressures, mold temperature, and in the raw materials used in the process. These are virtually all the variations from the plastics point of view. Even variations in such characteristics as back pressure during plasticizing will be detected in cavity pressure during the next cycle. This makes the sensing of cavity pressure the most comprehensive approach to intelligent molding with a minimal amount of complexity.

In large parts, where long flow distances and the need for high dimensional accuracies exist, two or more sensors may be put in each mold cavity. Having a sensor near the gate end of the part and one near the end of fill allows the cavity pressure profile across the part to be monitored. This cavity pressure profile monitoring allows one to detect the qualitative aspects of dimensions and weight in a plastics part.

The cavity pressure profile across a mold cavity indicates the molecular distribution of the material across the plastics part. Not only will this profile predict the overall dimensional integrity of the part, but it gives us the integrity of all the areas of the part as well. In other words, if both cavity pressures, the one at the end of fill and the one near the gate, are duplicated for each shot, the plastics parts made in that cavity must be identical. This ultimate concept of two sensors in each cavity is only necessary on large parts of long flow length where extreme dimensional accuracies are important. Normally, a single sensor in each cavity is sufficient.

On hot-runner molding of large parts where multiple drops are used in each cavity, the ideal approach to the intelligent mold concept is to have a sensor to monitor each zone. This is not necessary in all cases. However, the ultimate in predictability can be achieved by utilizing such a scheme.

Terminology

Accuracy and repeatability Accuracy concerns conformity to a standard or exactness. Repeatability deals with factors

such as how closely the length of a given feed will repeat itself. Repeatability differs from accuracy in that it does not include noncumulative errors. Most applications are concerned with repeatability, which is easier to achieve than high accuracy.

Adiabatic A change in pressure or volume without gain or loss in heat. Describes a process or transformation in which no heat is added to or allowed to escape from the system.

Barrel control transducer Thermocouple and pressure transducers inserted in different zones of the barrel to sense melt condition; they require accuracy in proper locations and recording instrumentation.

Algorithm A procedure for solving a mathematical problem.

Computer control Mode of machine operation. Its software process control sets the parameters of operation. They range from simple to very complex systems meeting different requirements for the processors. Deciding whether to computerize a line (or, more importantly, how to) requires clearly defining the control needs, taking into account many such as improved profitability. Then, based on requirements that have to be met, appropriate action is taken. Note that changes are continually occurring in control programmers and data acquisition systems.

Computer digital controller Microprocessor controller that converts signals from a pressure or temperature sensor to an output signal to a power unit to hold the sensor at the setpoint value.

Control and instrumentation Adequate process control and its associated instrumentation are essential for product quality.

Control comparator The portion of the control elements that determines the feedback error on which a controller acts.

Control, integral A control mode in which there is a continuous linear relationship between the integral of the error signal and the output signal of the controller.

Control loop The signal circuit that provides feedback information for closed-loop process control.

Control, open-loop Also called a front-end control. Provides control of the fabrication process operation, from upstream through downstream equipment, where setting all controls is done by the operator and is not adjusted by feedback information. It will recognize a fault but not correct it.

Control, proportional A control mode in which the output of the controller is proportional to the error.

Control, solid state Control system that superseded relay control; based on electronic components that have no moving parts and yet can, for example, provide switching action.

Microprocessor control A microprocessor control means different things to different people. It can mean anything from a sophisticated temperature controller to a full-blown fabricating line control. As a result of the vast range of computer control and monitoring options available, there is a strong temptation to become "control happy." Selecting what is needed requires setting up specifications on what is truly required to realize a return on investment.

Processing feedback The information returned to a control system or process to maintain the output within specific limits.

Processing fundamentals Conversion or fabricating processes may be described as an art. Like all arts, they have a basis in the sciences and one of the short routes to technological improvements is a study of these relevant sciences.

Processing inline A complete production or fabricating operation that goes from material storage and handling, to part production, including upstream and downstream auxiliary equipment, through inspection and quality control, to packaging, and to delivery to destinations such as warehouse bins or transportation vehicles.

Processing line, downstream The plastic discharge end of the fabricating equipment such as the auxiliary equipment in an extrusion pipe line after the extruder.

Processing line downtime Time interval when equipment should be operating but it cannot. Downtime can be attributed to equipment being inoperative, shortages of material, electric power problems, unavailability of operators and so on. Regardless of reason, downtime is costly.

Processing line, upstream Refers to material movement and auxiliary equipment (dryer, mixer-blender, storage bins, etc.) that exist prior to plastic entering the main fabricating machine such as the extruder.

Processing line uptime Time interval when plant is operating to produce products.

Processing parameter Measurable parameters such as temperature and pressure required during preparation of plastic materials, during processing of products, inspection, etc.

Processing stabilizer Also called a flow promoter. In thermoplastics they act in the same manner as internal lubricants where they plasticize the outer surfaces of the plastic particles and ease their fusion, but they can be used in greater concentrations (about 5 pph). With TS plastics they are not reactive normally and therefore reduce the rate of interactions of reactive groupings by a dilution effect. Thus easier processing may be derived mainly from the reduction in the rate at which the melt viscosity increases. At the same time the overall cross-linking density is reduced.

Processing via fluorescence spectroscopy

System to analyze the fluorescence generated in the plastic during processing and translates it into a numerical value for the property being monitored. Sensor techniques can measure the properties of plastics during processing. The intent is to improve product quality and productivity by using molecular or viscous properties of the melt as a basis for process control, replacing the indirect variables of temperatures, pressure, and time. In fluorescence spectroscopy the plastic must be doped with a small amount of fluorescent dye specific to the application. An optical fiber installed in the plasticator barrel, mold, or die scans the plastic. It can be used to perform other tasks such as measuring the concentration and dispersion uniformity of filler, its accuracy of 1% provides a means of optimizing residence time. It can also monitor the glass transition temperature.

Temperature controller, heating overshoot circuit Used in temperature controllers to

inhibit temperature overshooting on warm-up.

Temperature detector, resistance (RTD)

Temperature sensor made from a material such as high purity platinum wire; resistance of the wire changes rapidly with temperatures. These sensors are about 60 times more sensitive than thermocouples.

Temperature proportional-integral-derivative Pinpoint temperature accuracy is essential for success in many fabricating processes. To achieve it, microprocessor-based temperature controllers can use a proportional-integrated-derivative (PID) control algorithm acknowledged to be accurate. The unit will instantly identify varying thermal behavior and adjust its PID values accordingly.

Transistor Semiconductor device for the amplification of current required in different sensing instruments. The two principle types are field effect and junction.