HANSER

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Runner and Gating Design Handbook

Tools for Successful Injection Molding

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3 Filling and Packing Effects on Material and Molded Part

The flow of thermoplastics through an injection mold and its relationship to the molded part is quite complex. This chapter focuses on the development of melt conditions within a part-forming cavity and their relationship to the molded part. This will help the reader establish an optimum gating and molding strategy.

3.1 Process Effects on Material Viscosity

In Chapter 2, the basic behavior of thermoplastic materials was discussed and the relationship between a thermoplastic's viscosity, temperature, and shear rate were explained in detail. The initial viscosity of the melt entering a mold is determined by the melt temperature, as delivered from the molding machine, and the injection rate. High melt temperatures and high injection rates result in low viscosities for the plastic melt. This combination of high temperature and flow rate can result in lower fill pressures; however, pressure can begin to increase at extreme fast or slow fill rates. High melt temperatures are normally limited by potential degradation and longer mold cooling times. It is often desirable to perform a mold filling analysis to determine the optimum balance of melt temperature, processing conditions (primarily injection rate), and runner diameter that will produce a quality product for a given part design. Use of molding techniques, such as *Scientific Molding* [1] or *Decoupled Molding* [2] can be used to determine the optimum fill rate of an existing mold. Variations of these methods are presented by Bradley Johnson in Chapter 15 of this book.

3.1.1 Melt Thermal Balance – Conductive Heat Loss vs. Shear Heating

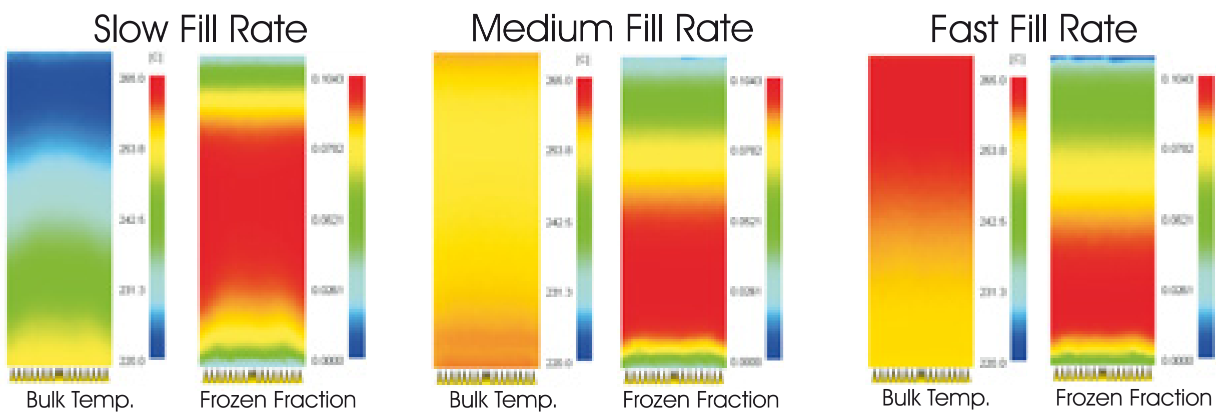
During injection, a hot thermoplastic is forced into a relatively cold mold. As the melt travels through cold portions of the mold, heat is continually being drawn from the plastic material. Plastic directly adjacent the cold mold walls will freeze almost immediately. The thickness of the frozen layer is dependent on the balance between heat lost to the mold through conduction and heat gained from shear. If the injection rate into a mold for a thermoplastic material is too slow, the thickness of the frozen layer builds up to a point where material can no longer be fed into the cavity and a short-shot is created.

A short-shot is the extreme outcome when the injection rate is not adequate to keep the thermoplastic melt temperature elevated enough for molding. At faster fill rates, frictional heating can overcome the heat lost through conduction and allow the material to remain molten during filling of the entire cavity. Figure 3.1 shows the result of a series of mold filling analyses of a simple rectangular plaque at three different fill rates. The plaque is 50 mm wide by 150 mm long and 2 mm thick. It is edge-gated as indicated (along the bottom edges of the figures) and molded with an ABS and a melt temperature of 255 °C. Note the change in melt temperature and frozen layer variations in each of the figures dependent on flow rate. At the fastest flow rate, it can be seen that the melt temperature at the end of fill is actually 10 °C higher than the injection temperature.

Control of frictional heating during mold filling can sometimes be difficult to achieve. With most parts, the geometry does not allow for the flow velocity of the melt to be constant without profiling the injection. Varying flow front velocities will result in a variation in the development of the frozen layer. A common example is the center gating of a disk-shaped part. At a constant injection rate from the injection molding machine, the flow front speed near the gate will be relatively high, but continually decreases as the melt progresses into the expanding cavity (see Fig. 3.2). This will cause a high amount of shear heating near the gate, but as the melt front progresses, it slows down and will begin to lose more heat to the mold than it is gaining from possible shear heat. This effect can be minimized by utilizing an injection profile with an initial slower fill rate and then gradually increasing the injection rate. However, most molding is performed without the use of profiles.

Variations in wall thickness within a part can create significant variations in flow rate and the resultant thermal balance. Thin regions will create a resistance to the flow front and cause the melt to *hesitate* as it fills other thicker regions. The hesitating melt will quickly lose heat and potentially freeze off. This is discussed in more detail in Section 4.2.10.

Figure 3.1 Effects of injection rate on bulk melt temperature and frozen material fraction as predicted by Moldflow's MPI



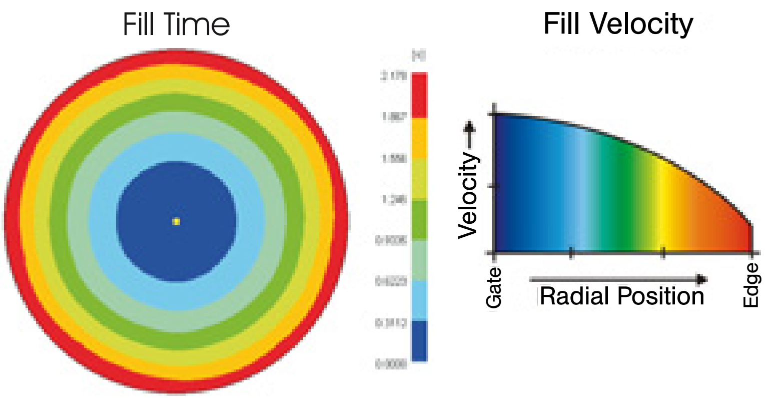


Figure 3.2 Moldflow plot of fill time and a graphical illustration of fill velocity as the melt radiates from the center to the perimeter of a center-gated disk. Note, velocity of the flow front decreases as the melt diverges from the gate as represented by spacing of the isochrones and by the velocity versus radial position graph

3.1.2 Development of a Frozen Boundary Layer

Both the viscosity of the plastic and the thickness of the flow channel affect the filling of a mold cavity. This is complicated by the fact that the actual thickness of the flow channel varies with the development of a frozen layer. The development of the frozen layer is affected by mold temperature and, particularly, by flow rate. Shear heating, at high flow rates, will minimize the growth of the frozen layer. This reduction in frozen layer development creates a larger flow channel cross section, which can have a significant effect on pressure drop. For example, the pressure drop at a given viscosity and flow rate through a cavity wall is inversely related to the thickness of the flow channel (h) to the third power. The effect of flow rate on the frozen layer can be seen in Fig. 3.3.

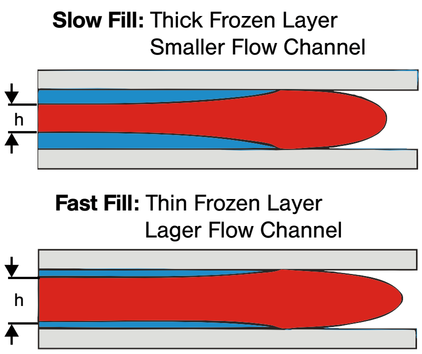


Figure 3.3 Frozen layer thickness as affected by flow rate

There are many factors that contribute to the development of the frozen layer thickness in a molded part. The primary factors are:

- The thermoplastic's thermal properties (thermal conductivity, specific heat, and no-flow temperature, or transition temperature);
- The melt and mold temperature;
- The mold material's thermal properties;
- The local flow rate; and
- The residence time of the melt.

Figure 3.4 shows a typical distribution of frozen layer thicknesses along the flow length of plastic in a cavity. The frozen layer near the gate can be very thin because of the high shear rates and the constant supply of molten thermoplastic through the region of the part nearest the gate. The frozen layer is at its maximum thickness between the gate region and the flow front, then again becomes relatively thin at the flow front due to the short time that the melt has been in contact with the cold cavity wall.

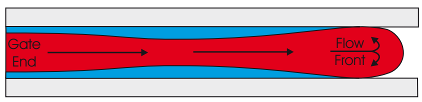


Figure 3.4 Development of frozen layer along the length of a polymer flow path

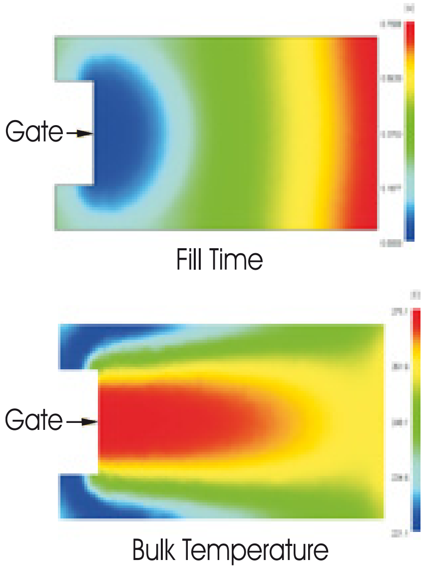


Figure 3.5 Mold filling analysis outputs of fill time and bulk temperature at the instant of fill. Note the rapid drop in melt temperature in the dead flow areas near the gate

In molds with unbalanced filling, areas that fill early develop a frozen layer much faster than areas equally distant from the gate that are still receiving continuous flow. Figure 3.5 shows an end-gated flat part with a constant wall thickness. The figure shows the fill time and bulk melt temperature distribution at the instant the part is filled. Note that the temperature distribution of the melt between the gate and the last place to fill on the right side of the part is relatively uniform as opposed to the temperature in the early filling regions near the gate. The gating location in this part causes the two tabs on the left side of the part to fill early. Once they are filled, flow into the tabs stop and the melt begins to quickly cool. Meanwhile the continuing flow in the main body of the part keeps the melt hot.

3.2 Factors Affecting Plastic Material Degradation

Degradation of a polymer will affect different polymers in different ways. Degradation of a polymer can manifest itself as a reduction in molecular weight, separation of polymer and additives, or it may result in a chemical reaction. Under high shear, a thermoplastic elastomer will experience a separation of its polymer matrix and its rubber additive. Excessive heat (time and temperature) will cause a rigid PVC to go through a chemical reaction, which includes the formation of hydrochloric acid that can attack and degrade the steel components of the screw, barrel, and mold.

During the injection molding process, material degradation occurs when the plastic material reaches too high a temperature or is forced to remain at an elevated temperature too long. Additionally, a material may experience excessive shear rates. Processing conditions leading to material degradation can be caused by:

- Poor venting,
- Increasing melt temperature or injection velocity,
- Dead areas or hang-ups in hot runners, and
- Long residence times in a hot runners or the molding machine's barrel.

Over drying of hygroscopic material can also lead to degradation. With some materials, such as polyurethane, under-drying can result in degradation as a result of hydrolysis.

3.2.1 Excessive Shear

During the injection molding process, excessive shear rates and temperatures are normally associated with degradation of the plastic material. Some materials, such as rigid PVC, acetal, and polyurethane are much more shear-sensitive than others. Also, some thermoplastic elastomers are highly shear sensitive. With excessive shear, melt fracture can occur. Melt fracture is the separation between the polymer matrix and the rubber additives. This degradation of the polymer is theorized to result from molecules being physically torn apart due to the velocity variation across the flow channel.

However, there are some thermoplastic elastomers that require high shear rates to be processed. One such thermoplastic elastomer is Santoprene®, which is actually a thermoplastic vulcanate (TPV). These TPVs are made up of small rubber particles dispersed in a polymer matrix that have been vulcanized to crosslink. Unlike some other types of TPEs, Santoprene exhibits excellent flow characteristics when subjected to high levels of shear during the injection molding process. Santoprene is a shear dependent elastomer that prefers high injection velocities to increase the shear to reduce its viscosity.

Highest shear rates are commonly expected at a restrictive gate. Of particular concern are tunnel gates, cashew gates, pinpoint gates on three plate cold runner molds, and restrictive gates commonly used with hot runners. The nozzle tip of the injection molding machine is another location of potential excessive shear rates. This location is not commonly recognized as a threat as it is much larger than most restrictive gates. However, in a 32-cavity mold, the flow rate will be 32 times higher through the nozzle tip than at each of the 32 gates.

Shear rate limits of most materials are poorly defined, if not unknown. Many companies and individuals have adopted shear rate guidelines established by Colin Austin in the early stages of Moldflow Inc. However, these guidelines had little scientific foundation. Numerous studies over the years have attempted to define shear rate limits by studying molded parts and materials following their exposure to high shear. Most of these data are questionable because they do not clearly separate the effects of other influencing factors experienced when the high shear rate is experienced. A part being evaluated for shear rate degradation by molding it through various gate diameters or injection rates will also experience variation in shear stress, molecular orientation, and packing. However, all studies to date appear to indicate that most materials can experience far higher shear rates than the limits established by Austin and Moldflow.

A credible ANTEC proceeding in May of 2003 from Astor and Cleveland provided some insight on ultra high shear rates and their actual effects on the mechanical and melt properties of injection molded parts molded from polypropylene and polystyrene [3]. This study involved a molding process, which introduced very high shear rates (on the order of 940,000 s^{-1}) to the materials during injection. Moldflow identifies shear rate limits for the polypropylene as 100,000 s^{-1}, and only 40,000 s^{-1} for the polystyrene. Melt flow rate and tensile tests were performed after the highly sheared material was molded into parts. The study found that these ultra high shear rates had very little effect on the actual mechanical properties of the injection molded parts. As shear rates approach extremely high levels, the mechanical properties tended to remain constant. It is theorized that these shear rates are only affecting a very small percentage of the overall material near the perimeter of the flow channel, leaving a majority of the polymer's original properties intact. The study did find that the flow characteristics of the highly sheared material were somewhat affected. Melt flow rates for the high shear material increased by up to 19% form the original virgin resin. This indicates some loss in molecular weight.

3.2.2 Excessive Temperature

Excessive temperature will also degrade polymeric materials. Temperature related degradation can occur prior to molding during material drying, from excessive heat in the injection unit, from excessive heat experienced in a hot runner, and potentially excessive frictional heating developed during flow in a runner.

Thermal degradation of a polymer is a function of time and temperature. The longer a polymer is exposed to an elevated temperature, the less tolerant of the temperature it is. Drying temperatures are quite low and will show no negative effects if the duration of exposure at the temperature is not excessive. However, commonly a material may be left in a dryer for days. This prolonged exposure to heat can degrade some polymers, affecting processing characteristics and mechanical properties. Spiking the temperature of the melt through a high shear runner is not expected to thermally degrade a material as the material is exposed to the high temperature only for a matter of seconds.

Some commonly used materials that exhibit degradation when exposed to excessive temperatures, or left at elevated temperatures for extended periods of time, are PVC, acetal, polyurethane, and polystyrene. Materials such as nylon, polycarbonate, and polyurethane may also experience degradation simply from over-drying.

An over-sized injection unit, or excessively long cycle times, can also cause the degradation of a polymer during molding, because they will extend the residence time of the material in the injection barrel.

Hot runner systems extend the thermal history of a polymer beyond that of the dryer and the injection unit. Ideally, the hot runner system will contain a minimum of material, which is purged with every shot. However, concerns regarding excessive pressure and shear, particularly when small thin-walled parts are molded, commonly will result in designs with relatively large channels. These large channels may take numerous cycles to flush with fresh polymer. In addition, it should be realized that even a runner channel volume that is the same as, or less than, the cavity volume will not actually be purged every cycle. The non-plug flow conditions, resulting from the pressure driven flow and the zero flow conditions at the wall, will result in melt near the perimeter of the flow channel experiencing extended residence time. Additionally, hot runners can contain dead or low flow regions where material can collect and degrade. This is highly dependent on the design and manufacture of the system. A full round flow channel with well-aligned components throughout the flow channel will minimize the thermal degradation concerns.

During injection molding, significant heat from friction can be developed in a polymer. This heat is generated in thin laminates near the outer wall of the flow channel where shear rates are highest. Close analysis of this phenomenon with computer flow analysis programs have predicted the temperature in this area to rise by over 200 °C at very high injection speeds and with very small runner cross sections in some cold runners. However, this heat is rarely considered a problem as it is usually generated and lost to the cold mold in less than a few seconds.

3.3 Effects of Mold Fill Rate on Fill Pressure

The mold filling rate of the polymer is the most recognized direct contributor to the pressure required to fill any particular mold. The pressure required to push a polymer melt is directly proportional to the local velocity of the polymer in the melt channel and its viscosity. The following relationship of fill pressure to the melt flow velocity is shown in the common slab flow and is based on Hagen Poiseuille's Law:

$$\Delta P = \frac{12Q\,\eta l}{wh^3} \tag{3.1}$$

Where:

P = Pressure Q = Flow rate

η = Viscosity l = Flow length

w = Flow width h = Flow channel thickness

Without close review, this basic relationship can mislead a molder to assume that reducing flow rate will decrease fill pressure. However, the results can be completely opposite.

Figure 3.6 contrasts the expected behavior of a common Newtonian fluid with that of a thermoplastic during injection molding. With a common Newtonian fluid, the pressure required to flow through a flow channel will continually decrease with decreasing flow rate. In contrast, a thermoplastic material's pressure profile will initially decrease but will then increase. The result is the characteristic "U" shaped curve seen here.

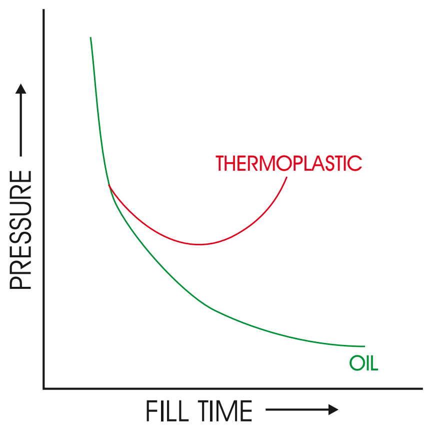


Figure 3.6 Comparison of effect of fill time on pressure development of a non-Newtonian plastic material and a Newtonian fluid

Initially, as flow is slowed, there is a corresponding reduction in pressure as experienced by a Newtonian fluid. However, as the flow rate continues to slow, the polymer viscosity begins to increase as it loses the benefits of non-Newtonian shear thinning. In addition, some of the frictional heating