CARL HANSER VERLAG

Bruce Davis, Paul Gramann, Tim A. Osswald, Antoine Rios

Compression Molding

3-446-22166-2

www.hanser.de

3

Processing Fundamentals

The mechanical properties and dimensional stability of a compression molded polymer part are strongly dependent on the manufacturing process of the part. The structure of the final part is influenced by the design of the mold cavity, by the location of the charge, and by the various processing conditions such as compound temperatures, mold cooling or heating rates, as well as closing speeds, to name a few. The amount and type of filler or reinforcing material also has a great influence on the strength, dimensional stability, cosmetic appearance, and general quality of the final part.

This chapter discusses the various aspects that affect processing and the properties of the final part. This includes mold filling aspects, development of anisotropy, as well as solidification, residual stress build-up and warpage during compression molding of thermoset and thermoplastic parts.

3.1 Mold Filling

The heart of the compression molding process is mold filling. Along with part geometry and material properties, it dictates the quality of the final part. Orientation of reinforcement fibers and thermoplastic molecules is directly related to how mold filling occurs. This section will review how thermosets and thermoplastics flow through the mold during compression molding and how this influences some important characteristics of the final part.

3.1.1 Material Preparation

Before the mold filling process can begin certain procedures must be accomplished to prepare the material to be molded. This typically involves weighing, cutting, and placement of the compound. These are generally done by hand, however, robots are being utilized more often to reduce part-to-part fluctuations and cycle time. Slight changes in the amount of material and placement of it on the mold can evolve into an unacceptable part as a result of being overweight, creation of blemishes on the part surface, incorrect fiber orientation leading to a structurally unsound part, among many others. Depending on the complexity of the part and charge layout, material preparation has the potential to consume a majority of the cycle time. The processing engineer should be keen to the increase in cycle time that exists when specifying a charge layout that involves more than a few layers. A complex charge layout will make the operator's task difficult and lead to an increase in cycle time and chances for part variation. The placement of the charge on the mold and its influence on the final properties of the part should not be underestimated. Flow of material during molding is highly dependent on this, which in turn, dictates knitline formation and how fibers will orient throughout the part.

Utilization of the injection-compression molding process can help reduce human error and variation from part to part. This process involves two distinct phases: injection of the compound into the mold, and closing of the mold to complete the mold filling through compression. The injection process places the same quantity of material at the same location during every cycle prior to compression. However, it is essential that the placement of the injection gate be thoroughly investigated before the mold is cut. Changing the gate location after the mold has been made can be cost prohibitive.

Preheating the material before the compression phase is required when molding thermoplastics. At room temperature thermoplastics will not flow, hence, the material's temperature must be near or above the melt temperature prior to compression. Preheating is also used at times with thermosets to reduce cycle time. Curing of thermoset materials can consume a great deal of time and utilizing preheating essentially starts the curing outside of the mold, reducing the cure time while in the mold and thus shortening the overall cycle time. Careful analysis should be performed to assure that the material does not reach the gel point which hinders deformation during compression.

Though the material preparation step may seem trivial, it has the potential to be the root cause of problems that are carried throughout the whole molding process and eventually lead to flaws in the final part. Careful analysis and control of this step should be taken to assure that it does not create unnecessary problems down the road and cycle times are kept to a minimum.

3.1.2 Compression Molding of Thermoplastics

The mold filling phase of the compression molding cycle begins when the upper mold half comes in contact with the charge of material lying on the lower mold surface. As soon as contact is made, pressure from the downward movement of the upper mold forces material to flow. Ideally, this phase ends when upper and lower mold stops come in contact and the cavity is completely filled. Figure 3.1 illustrates the mold filling with GMT in an automotive grill-opening panel [1]. There are two areas in the part where flow anomalies occur, in this case, two knitlines.

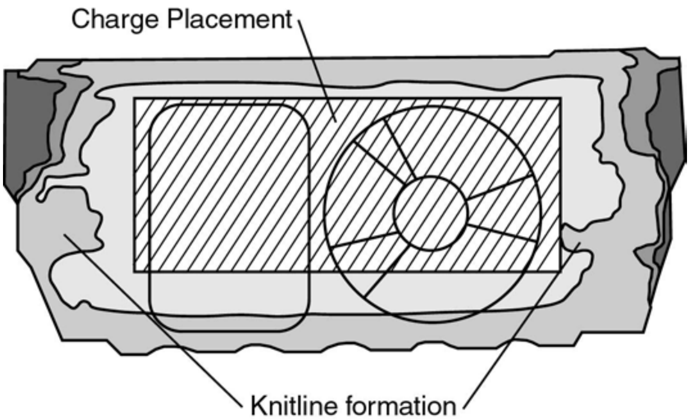

Figure 3.1 Mold filling of an automotive grill opening panel using GMT. Different shades of gray represent material flow over time.

Premature freezing of the thermoplastic through its thickness can bring about the end of filling. As material begins to flow outward it is simultaneously subjected to cooling. When processing GMT or LFT, the thermoplastic material is initially at a temperature above its melting point so that it can easily flow when the upper mold surface contacts it. The mold surfaces are kept relatively cold with cooling lines in the mold core to remove heat from the polymer during the crystallization process. For a polypropylene compound, the mold is typically between 50 ^{o}C (120 F) and 60 ^{o}C (140 F), well below the crystallization temperature of the resin. Heat transfer and material solidification phenomena influence material flow. At the instant hot thermoplastic compound comes in contact with the mold it starts to solidify. This occurs at the immediate layer of polymer that comes in contact with the mold surface. Thus, solidification starts when a charge is placed on the lower mold surface. Cooling and solidification of the charge upper surface occurs with the start of mold filling, when contact of the upper mold surface is made with the charge. Through the mold filling process the two solidification layers increase in thickness. Once the solidified layers from the top and bottom meet, the flow of material stops, which may stop the two mold halves from closing, creating a short shot in the mold. Figure 3.2 shows the velocity profile and solidification through the thickness during compression molding of a thermoplastic compound. The figure illustrates the fountain flow effect where the polymer melt between the two solidification layers is forced outward during compression, forcing the melt skin at the front to stretch and unroll onto the cool wall where it freezes instantly. The molecules of the polymer, and reinforcement fibers that may be in the compound, are oriented in the flow direction and laid on the cooled mold surface, which freezes them into place, though allowing some relaxation of the molecules after solidification [2].

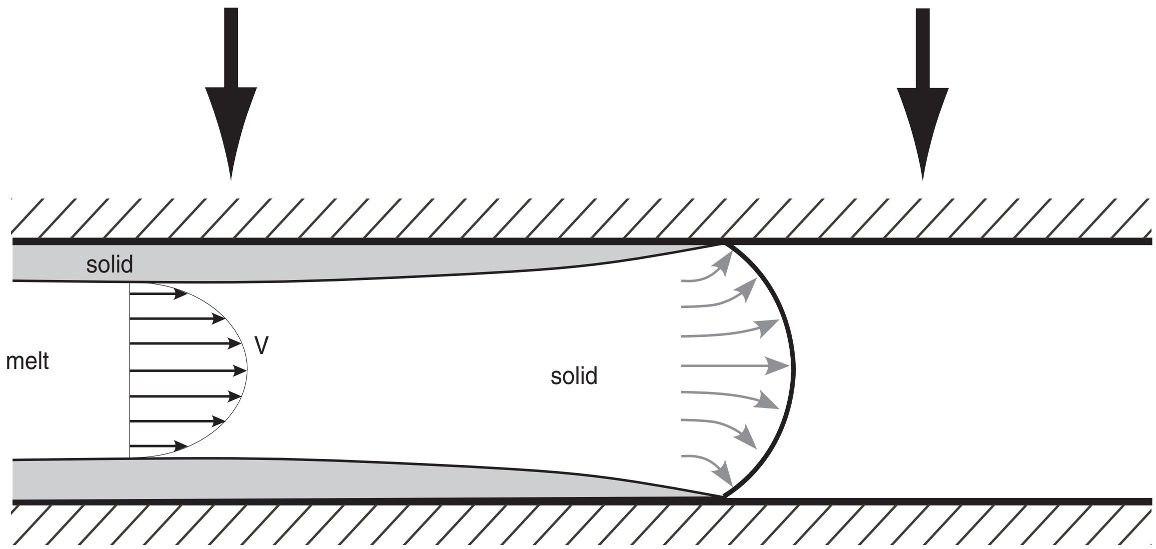

Figure 3.2 Fountain flow and solidification during compression molding of a thermoplastic.

The force required to mold an article is of great interest, especially when sizing the press required for the process. In general, the force that is needed to mold a GMT or LFT part is approximately 1.5 ton (200 bar) per square inch of surface area, which is less than what is typically required for injection molding [3]. Certainly, there are many factors that influence the amount of force required, such as the temperature of the charge, mold temperature, fiber content, and mold closing speed, to name a few. The graphs shown in Figs. 3.3 – 3.6 illustrate the measured closing force as a function of the mold opening [4]. The experimental data is for the compression molding of a 30 cm x 30 cm polypropylene GMT plate. Figure 3.3 illustrates the mold closing force at different initial charge temperatures. As expected, it takes significantly less force to mold a charge that was heated initially to 230 ^{o}C than one that is at 170 ^{o}C. The downside to the hotter initial charge temperature is the longer processing time that results due to the increase in solidification time.

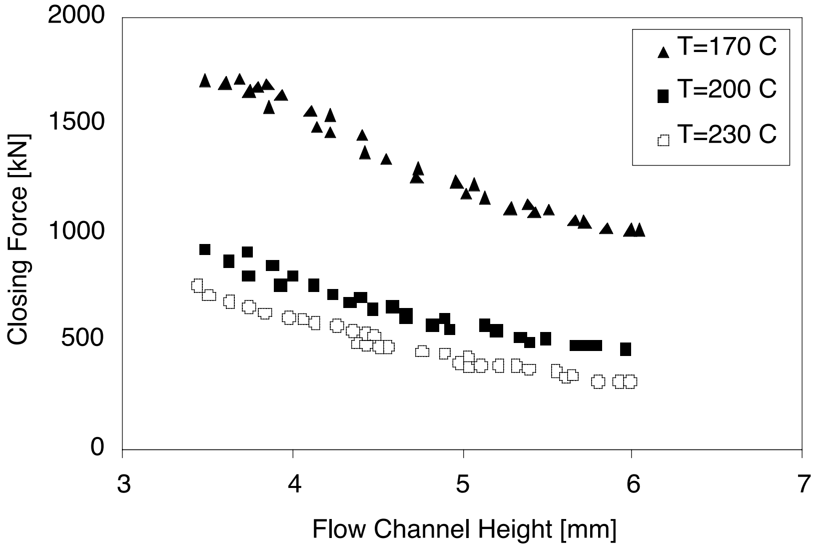

Figure 3.3 Influence of initial GMT charge temperature on mold closing force. $T_{mold} = 120^{o}C, \quad \dot{h} = 3\mathrm{mm/s}$

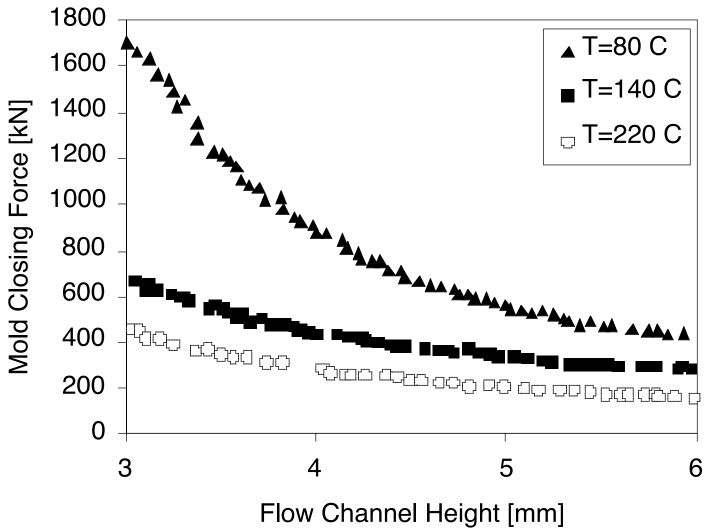

Figure 3.4 Influence of mold temperature on mold closing force. $T_{GMT} = 220^{o}C, \quad \dot{h} = 1\mathrm{mm/s}$

The effect of mold temperature on the mold closing force is shown in Fig. 3.4. An increase in mold temperature greatly reduces the closing force requirement. Similar to the initial charge temperature, the downside of a hotter mold surface is the longer solidification time.

The increase in fiber reinforcement content affects the closing force due to the change in rheological properties. An increase in fiber content in the compound will result in higher deformation resistance, leading to higher mold closing forces. Figure 3.5 shows this effect with two GMT compounds that have 30%(wt) and 23%(wt) fiber loading. The compound with higher fiber loading requires approximately 20% more closing force.

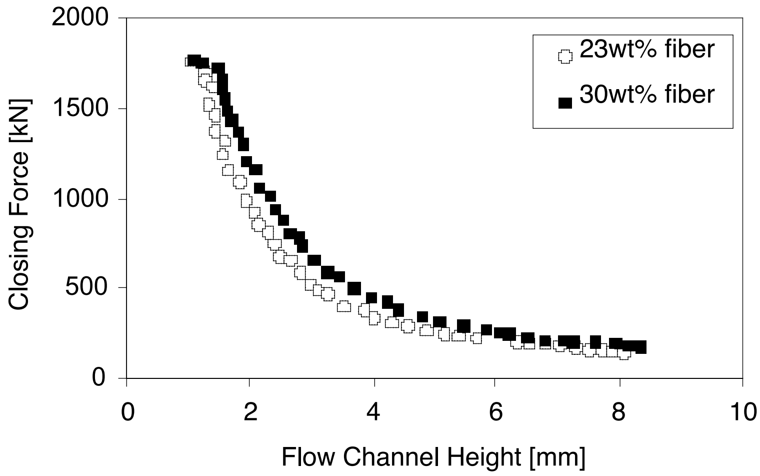

Figure 3.5 Influence of GMT fiber loading on mold closing force.

The mold closing speed has a profound effect on the mold closing force. Figure 3.6 illustrates this well using three different closing speeds. A 6 mm/s closing speed requires nearly three times the force of a 1 mm/s speed. Clearly, the faster closing speed fills the mold quicker, however, this will not translate into faster cycle times since solidification is not influenced by the closing speed. On the other hand, as will be discussed later, faster mold closing speeds will result in higher drag forces between the flowing resin and the reinforcing fibers, which will reduce fiber matrix separation effects.

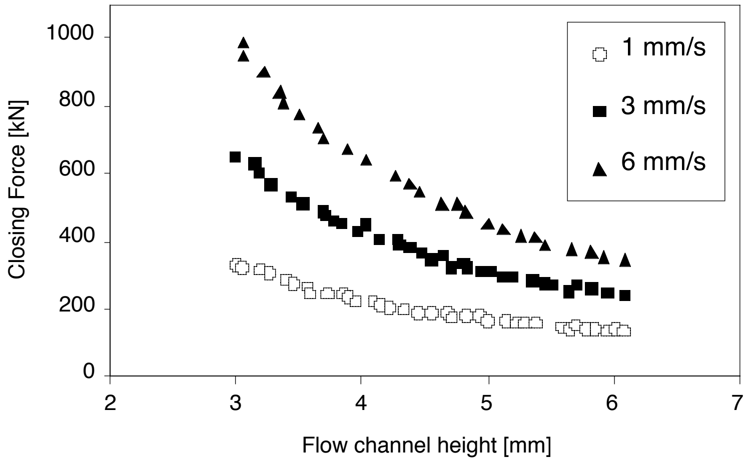

Figure 3.6 Influence of the mold closing speed on the closing force. $T_{GMT} = T_{mold} = 200\ ^oC$

3.1.3 Compression Molding of Thermosets

As will be discussed in more detail later, the mechanism of solidification of thermosets is a curing reaction, which creates a network of tightly connected molecules. Thermoset charges are typically placed on the mold at room temperature, or after being heated for several seconds. The mold surface is at an elevated temperature to initiate and carry through the curing reaction process. Once in contact with the mold, the resin in the compound softens and creates a thin viscous layer at the mold surface. The compound begins to flow because of pressure applied as the top mold surface moves downward. Figure 3.7 [5] shows an example of mold filling patterns that develop while squeezing a relatively thick SMC charge. The different shades of gray represent how the material flowed during a set amount of time. In order to obtain the filling patterns or "short shots," the mold closing was arrested using brass shims.

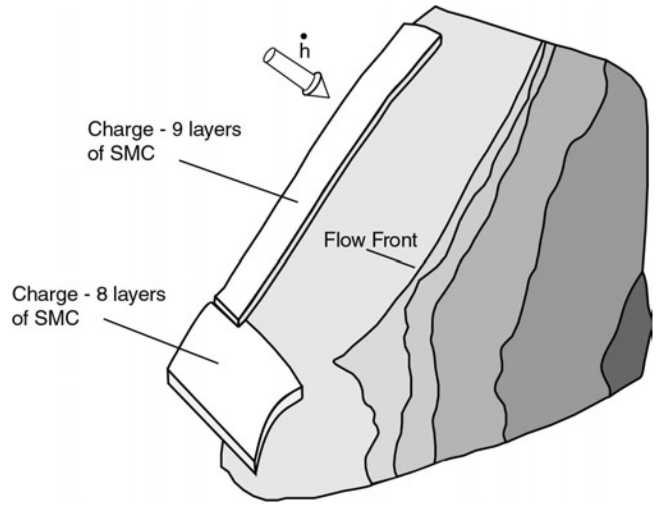

Figure 3.7 Mold filling pattern of a truck wind deflector generated by shimming the mold.

During compression molding the compound deforms uniformly through the thickness due to the slip condition that exists between the mold surface and the compound. This slip condition is a consequence of the viscous layer that forms shortly after heating begins. As a result, the compound moves in plug motion and the fountain flow seen with thermoplastics is not present. The center of the material experiences very little shear and deforms primarily in biaxial extension. Figure 3.8 shows the kinematics of flow that is created from slip between the compound and mold surface during compression molding.

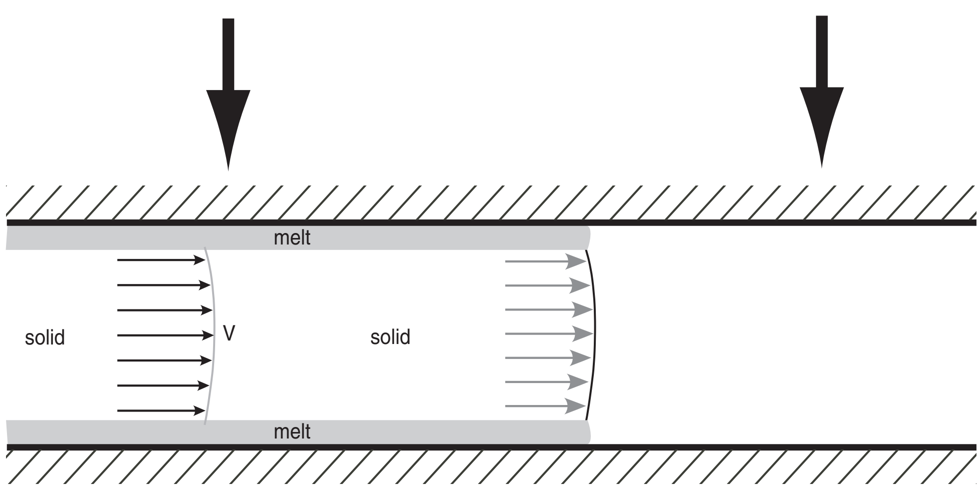

Figure 3.8 Velocity distribution during compression molding with slip between material and mold surface.

The amount of energy required to heat a mold can be approximated at 1000 W for every 45 kg (100 lb) of mold steel [6]. In general, the force that is needed to mold an SMC part is approximately 1.0-3.0 ton (135-405 bar) per square inch of surface area. Similar to molding GMT or LFT, many factors control the force required to mold SMC, such as the type of fiber reinforcement, fiber length, and fiber content, to name a few. The graphs shown in Figs. 3.9-3.11 illustrate the measured closing force as a function of the mold opening for these factors [7]. The graphs were generated while molding a 3.18 mm thick 43 cm x 56 cm plate in a 400 ton press and a closing speed of 2.5 mm/s and a mold temperature of 150 ^{o}C.

The fiber reinforcement used in the thermoset compound can influence the force needed to mold the part. Figure 3.12 shows that for the two types of glass analyzed, the hard glass required slightly more force than the soft glass. The stiffer carbon fibers required even higher forces to mold.

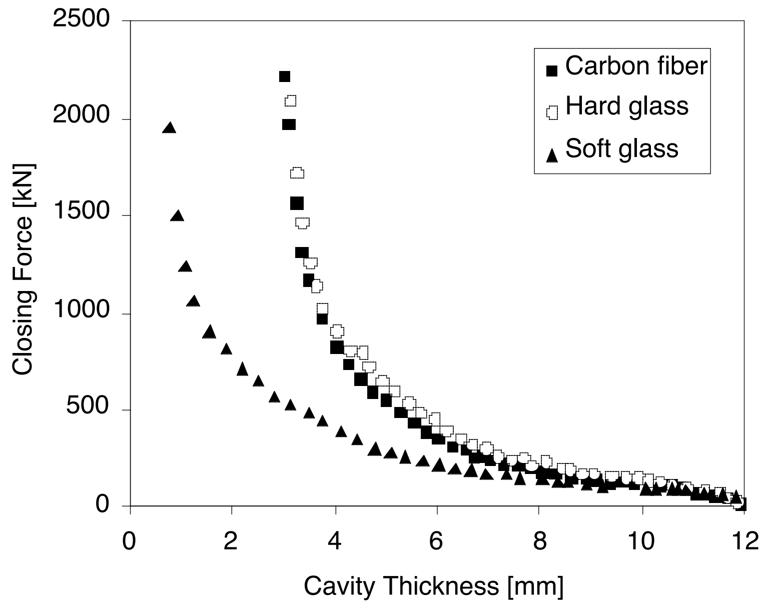

Figure 3.9 The measured molding force for three different fiber types.

The ease of flow and its effect on the required molding force is also influenced by fiber length. As Fig. 3.10 illustrates, longer fibers require a higher molding force. Longer fibers have a higher flow resistance, which leads to a higher overall viscosity of the compound.

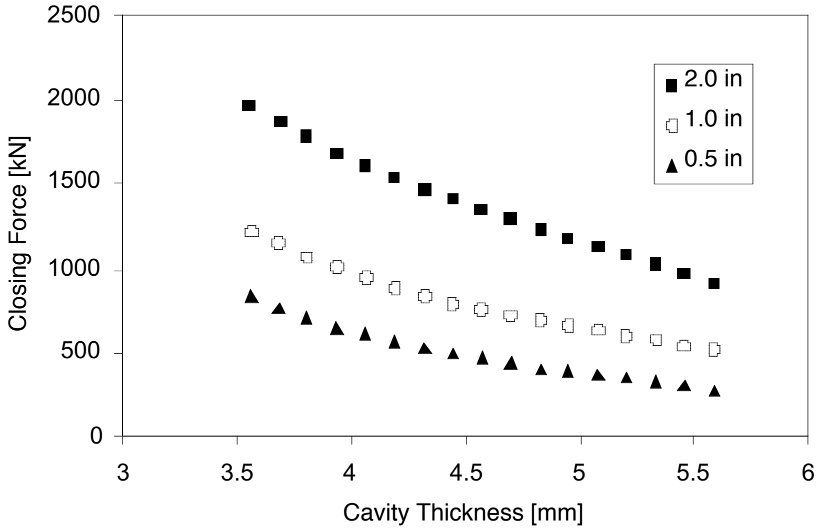

Figure 3.10 The measured molding force for various fiber lengths.

The fiber content in the compound is also an important factor that affects the force required for molding. As the fiber content is increased the forces required for molding also increase, as shown in Fig. 3.11.

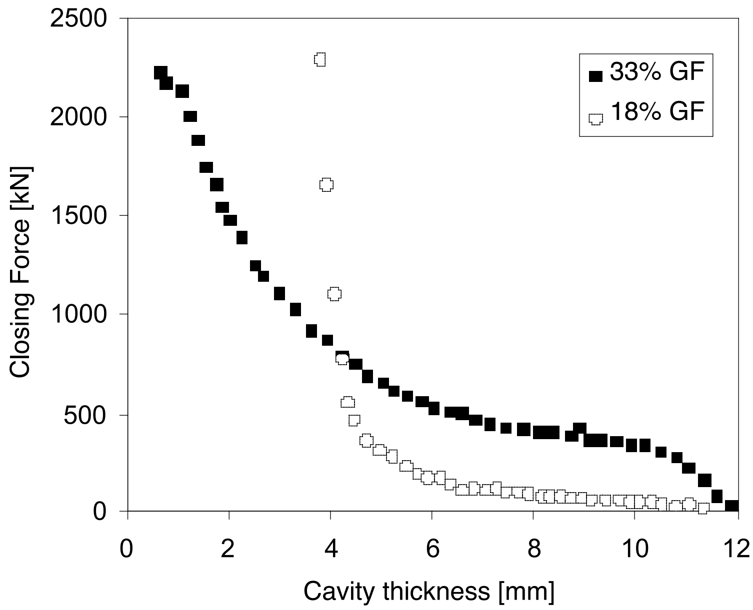

Figure 3.11 The measured molding force for 18%(wt) and 33%(wt) hard glass fiber.

There are many other factors that control the required molding force. The viscosity of the compound is one factor that has a strong effect on the mold force. The viscosity, in-turn, is directly related to the reaction or cure that has taken place. As the level of cure increases, the viscosity of the compound rises, requiring a higher molding force. This can be seen at times when the flow length of the compound is increased. Here, the cure of the compound reaches a higher level at the end of fill due to the increase in time to mold the part. Also affecting the viscosity of the compound, and as a result the mold force, is the filler (non-reinforcement) content. In general, a greater quantity of filler will require a higher molding force. This again, is due to the increased viscosity that is realized when more filler is added. The model proposed by Gutt and Simha[8], which can be used to predict the viscosity rise when a filler is added to a resin, is as follows

$$\frac{\eta_f}{\eta_0} = 1 + 2.5\phi + 14.1\phi^2 \tag{3.1}$$

Figure 3.12 compares Geisbüsch's experimental data to Eq. 3.1. The data and Guth and Simha's model seem to agree well.

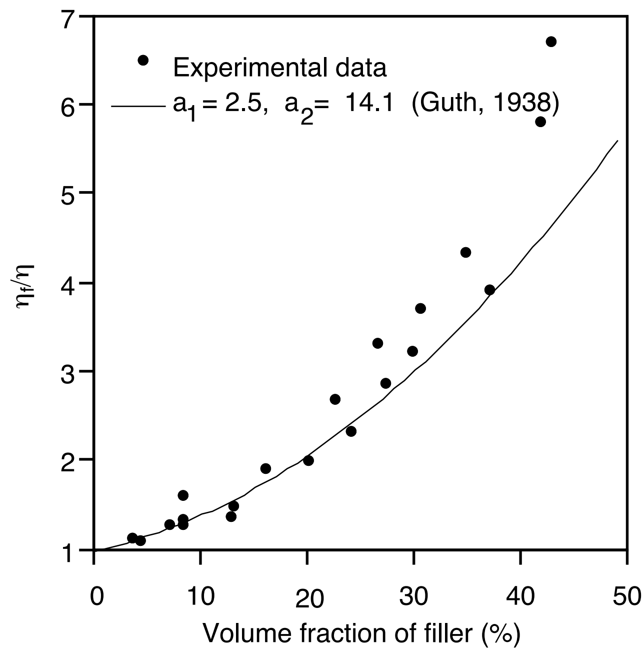

Figure 3.12 Viscosity increase as a function of volume fraction of filler for polystyrene and low density polyethylene containing spherical glass particles with diameters ranging between 36 μm and 99.8 μm.

3.1.4 Anomalies During Mold Filling

The properties of the final part are strongly influenced by the mold filling process. Certain anomalies may occur during mold filling, such as preferential flow, knitline formation, race tracking, and fiber-matrix separation.

3.1.4.1 Fiber-Matrix Separation

During the mold filling process material must flow around sharp corners and into areas that are difficult to access by the molding compound, such as ribs and bosses. As the material is forced to flow into these areas the resin is often squeezed out of the bed of fibers leading to a resin rich flow front. This fiber-matrix separation phenomenon results in local differences in fiber content throughout the part, particularly in ribs, the last places to fill and other difficult areas to fill. This variation affects the mechanical properties of the finished part, as well as the surface finish where surface waviness, sink marks, and "orange peel" effects can result. Figure 3.13 illustrates fiber-matrix separation in a simple contraction. As the compound approaches the restriction the fibers are reluctant to flow forward with the resin. The fibers dam-up at the contraction as the resin flows through the fibers.

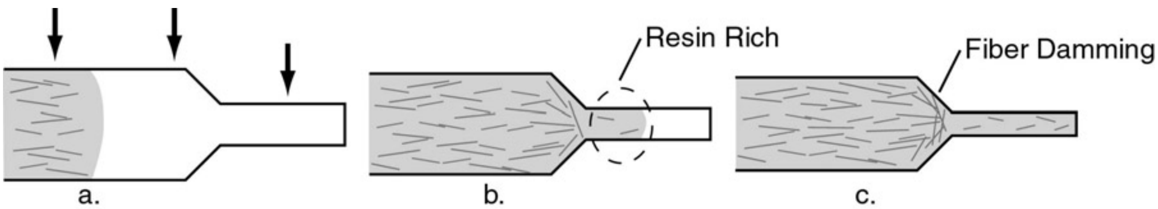

Figure 3.13 Fiber-matrix separation during mold filling.

This results in a decrease in mechanical properties within the rib, for example, in cracks at the bottom of the rib at much lower stress levels than expected. The flow of fibers into ribs is difficult since it generally involves bending of the fibers. Figure 3.14 illustrates the filling of a rib in a simple plate for two different charge layouts. The layout in the top figure has both charge layers stacked over the rib. Here, the fibers bridge across the rib opening causing them to bend downward and eventually stop flowing into the rib. At this point, the resin flows through the fibers to complete the filling. The bottom figure in Fig. 3.14 illustrates a better method for placing the charge on the mold surface.

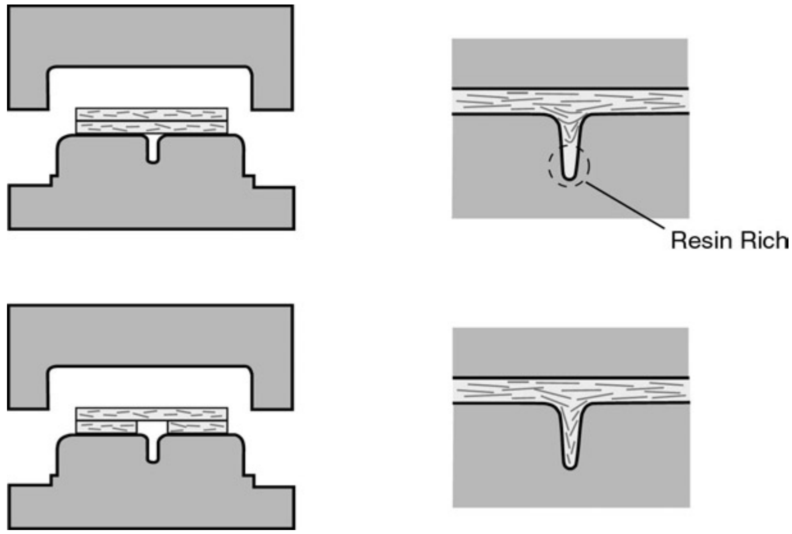

Figure 3.14 Alternative charge patterns with resulting rib filling.

The bottom charge is divided into two charges that are separated at the top of the rib. This allows the compound to flow more easily into the rib, helping eliminate the bridging of fibers that created fiber-matrix separation in the previous charge layout. Figure 3.15 shows a mold filling short shot that reflects fiber matrix separation as the material enters the rib. The part presented in the figure is being compression molded with a polypropylene GMT. The flow front inside the rib is nearly all resin. A flow front where fiber-matrix separation does not occur can be seen of the same figure, where the fibers are clearly visible.

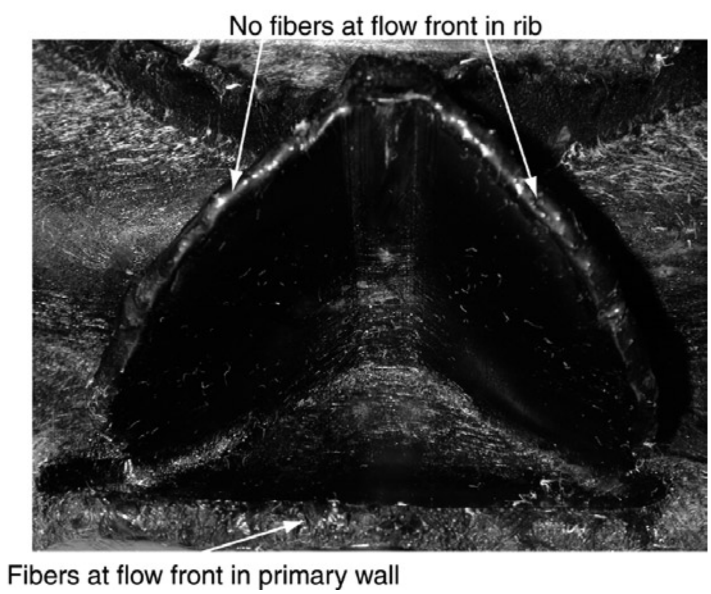

Figure 3.15 Short shot illustrating fiber-matrix separation occurring at a rib.

Christensen et al. [9] measured the fiber density distribution in an SMC compression molded breaker switch box using a burnout procedure[1]. Their results shown in Fig. 3.15 clearly indicate a large difference in fiber density throughout the part, with a much lower fiber content at the bottom of the rib. Osswald et al. [10] developed a model to serve as a tool to help understand the parameters that lead to fiber-matrix separation during compression molding of SMC and GMT. The model is based on a flange and rib geometry and considers two competing forces responsible for fiber-matrix separation: the force required to squeeze the resin through the bed of fibers (D'arcy effect), F_D, and the fiber deflection force (Fiber bending), F_f. The ratio of the two gives

$$D = \frac{F_D}{F_f} \tag{3.2}$$

Here F_D is a function of the viscosity, the fiber density, and the closing speed, as well as the rib and flange dimensions. The forces required to bend the fibers into the rib are a function of the product of fiber stiffness and area moment of inertia, EI. The parameter D is a measure of the ability of a bed of fibers to flow or be dragged with the deforming charge. When D << 1 fiber-matrix separation occurs since the force to squeeze the resin out of its fiber bed is much lower than to bend the fibers into the rib. A good distribution of fibers throughout the rib occurs when D >> 1.

Figures 3.16 -3.19 illustrate the influence material and processing conditions have on fiber-matrix separation. The graphs shown assume a random fiber orientation with a fiber reinforcement that has a length of 25 mm. The stiffness of the fiber bundles, determined experimentally, is $EI = 6.1093 \times 10^{-8}\ \mathrm{Nm}^2$, a rib thickness of $L_r = 3\,\mathrm{mm}$, a closing speed of $\dot{h} = 1\mathrm{mm/s}$ and the viscosity at $\eta = 3000\,\mathrm{Pa\text{-}s}$ and a flange thickness of 5 mm are used. Figure 3.16 shows that when using low stiffness fibers more fibers will reach the bottom of the rib. This is because the fibers are less likely to bridge across the top of the rib since they bend into the rib with more ease.

1 If a burnout procedure is used instead of acid washing, the 44% loss of calcium carbonate must be accounted for due to the burning of its organic components. The fiber content after burnout can be determined by using the following $\phi_N = 1 - \left(\frac{1+\kappa}{1+0.44\kappa}\right)\frac{m_s - m_a}{m_s}$ where, m_s is sample weight before burnout, m_a is sample weight after burnout, and k is the ratio of mineral to organic mass content in the resin.

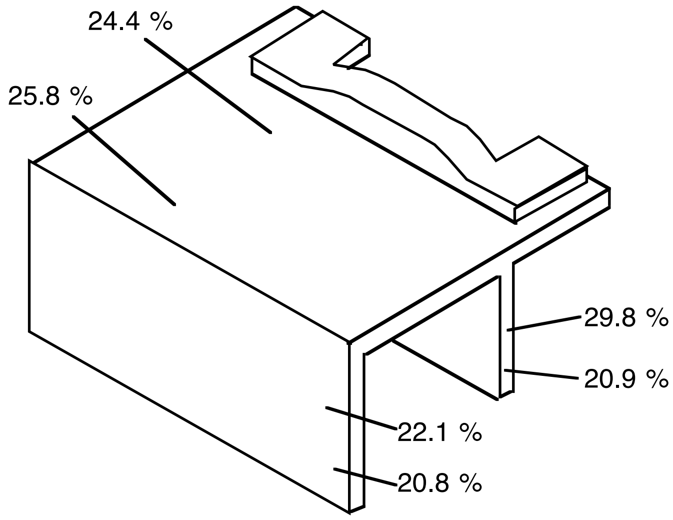

Figure 3.16 Schematic of a breaker switch box with the fiber content.

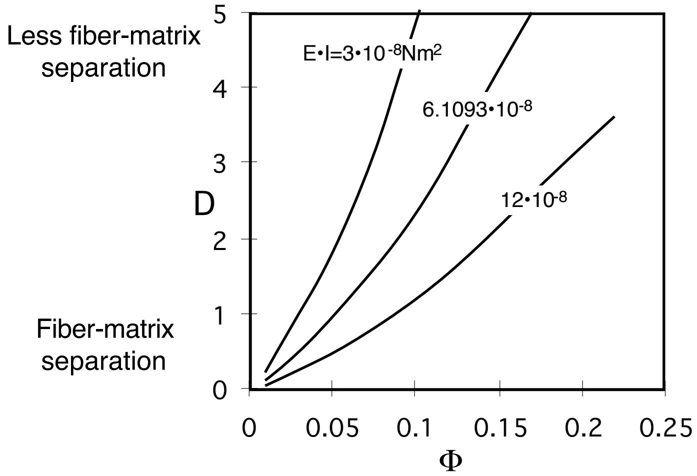

Figure 3.17 Influence of fiber stiffness on fiber matrix separation.

The graph shown in Fig. 3.18 illustrates that a more viscous resin will result in less fiber-matrix separation. This is due to the fact that it is more difficult for a viscous resin to flow through the fibers and the resin will therefore carry the fibers more effectively throughout the part.

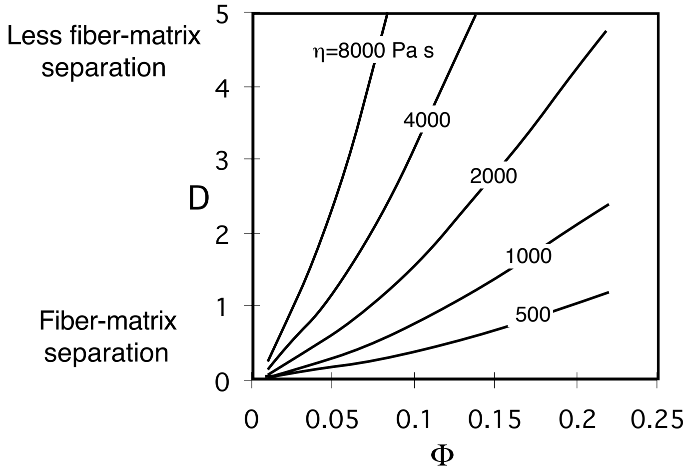

Figure 3.18 Influence of resin viscosity of fiber-matrix separation.

The effect of mold closing speed on fiber-matrix separation is shown in Fig. 3.19. A faster closing speed will reduce fiber-matrix separation, because a slow closing speed will allow the resin to seep through the bed of fibers, while a faster closing speed will carry the fibers better with the flow.

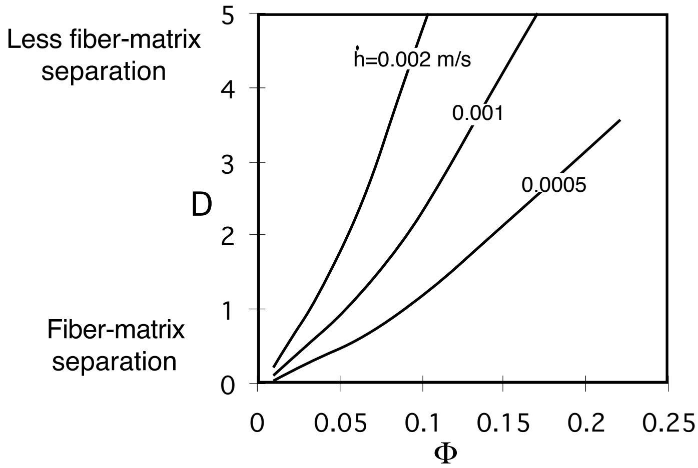

Figure 3.19 Effect of molding closing speed on fiber-matrix separation.

In addition, the thickener that keeps the viscosity of the material at a high level reduces the amount of fiber-matrix separation. Low viscosity can be caused by preheating the charge too long.

3.1.4.2 Preferential Flow

A phenomenon often encountered during compression molding of thermoset charges is preferential flow. Preferential flow occurs when the heated layer with the lower viscosity, near the mold wall, is squeezed out from the charge [11]. This is sometimes also referred to as reverse fountain flow and will lead to a flow front that is resin-rich and therefore low in fiber content. In addition the "rolling" front caused by the preferential flow will lead to voids in the finished product. Because the edge of a part often experiences much higher stresses and can be exposed to higher impact this phenomenon should be avoided. Figure 3.20 illustrates preferential flow during compression molding. As can be seen, a thick viscous layer develops near the surfaces that touch the hot mold. The figures illustrate this viscous layer flowing preferentially ahead of the flow front and eventually creating a resin rich, porous edge.

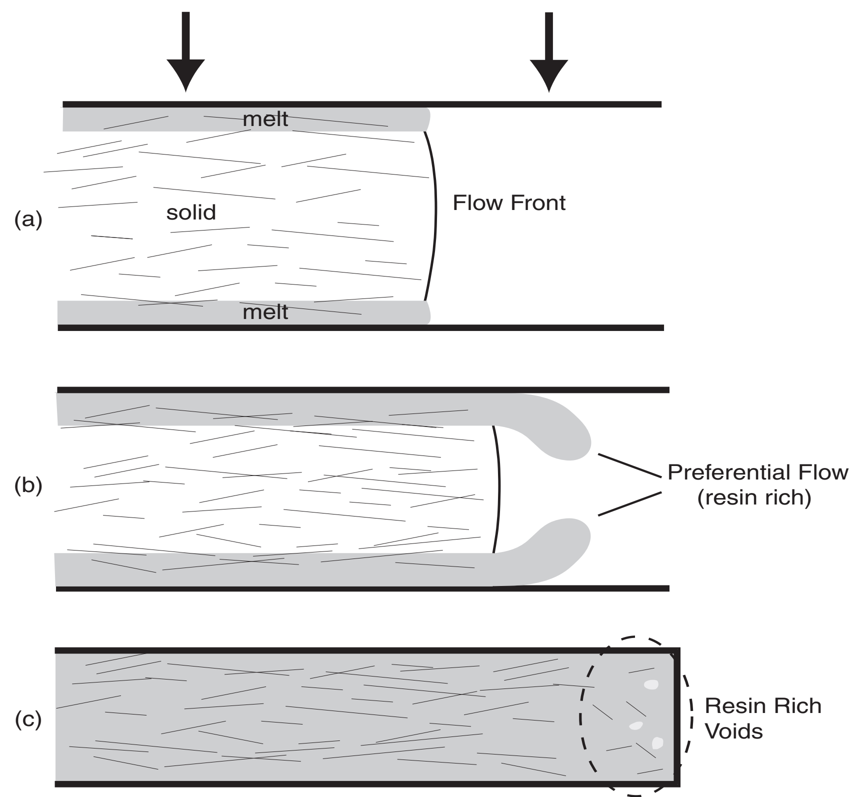

Figure 3.20 Preferential flow of resin rich material flowing ahead of flow front.

This flow phenomenon has been seen experimentally by Marker and Ford [12] and Schmelzer [13]. Figure 3.21 presents a series of photographs showing the progression of preferential flow of a 7-layer SMC charge after a 20 second one-sided heating period [13]. Due to the one-sided heating that occurs after depositing the charge on the lower mold surface and before the upper mold surface comes in contact with the material, preferential flow occurs at the bottom side of the charge. The material is clearly seen traveling ahead of the charge and curling upward. Figure 3.22 presents a schematic of the experimental set-up used to perform the experiments.

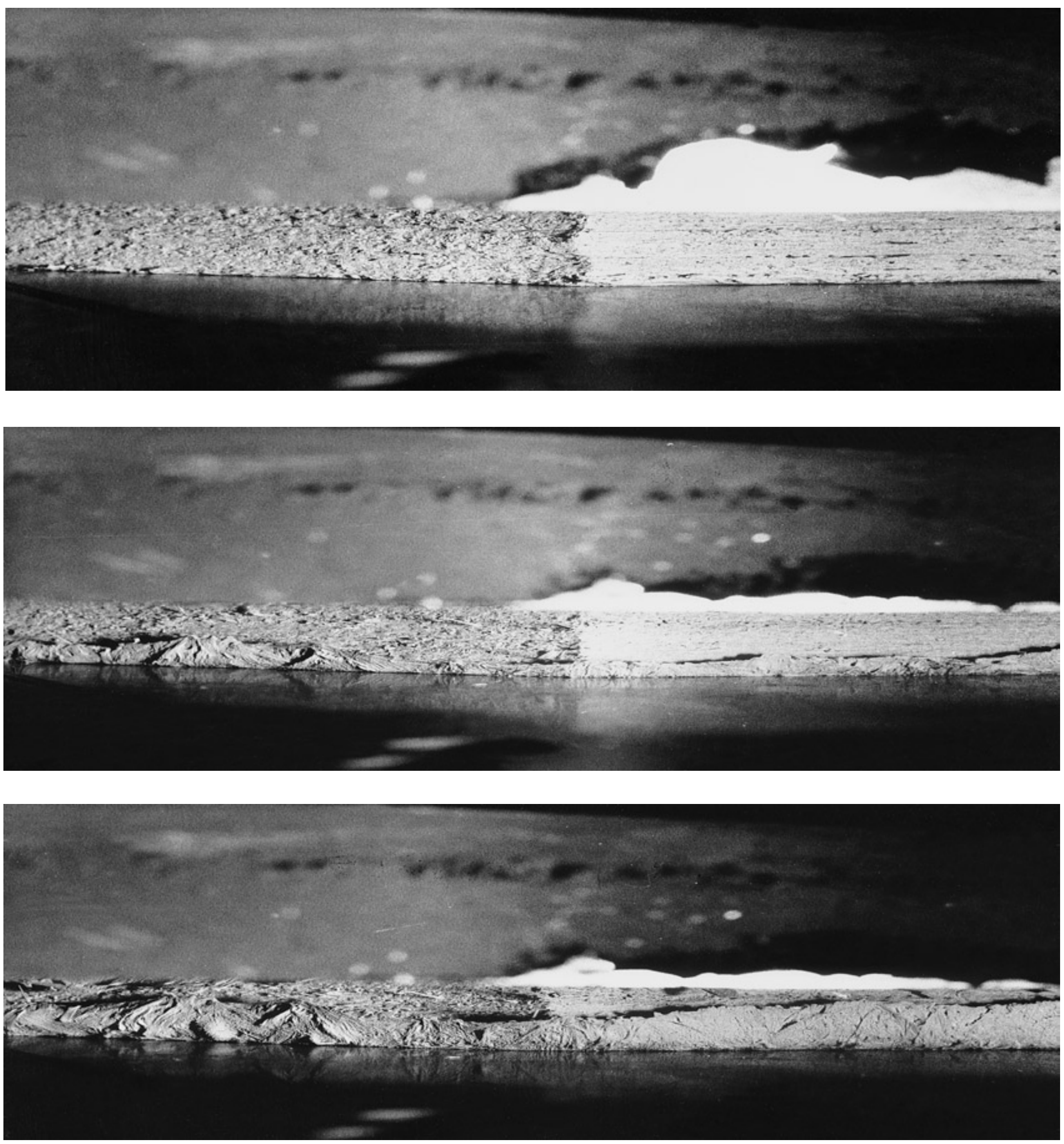

Figure 3.21 Series of photographs showing the progression of preferential flow of a 7-layer SMC charge.