Sheet Molding Compound Characterization Using Spiral Flow

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ABSTRACT: Sheet molding compound (SMC) is a fiber-reinforced polymeric composite. It is often used in automotive, marine, and industrial applications over other materials because of its high strength to density ratio, resistance to corrosion, and low cost. There is a demand in the SMC industry to be able to characterize SMC processability. This is particularly true for heavy truck body panels, one of the fastest growing applications of SMC. Because of their large size and high strength requirement, the molding forces have a major influence in the molding cycle. Also because of the long flow paths involved, the ability of the paste to carry glass needs to be properly characterized when developing new SMC materials. In this article, we demonstrate the benefits of using spiral flow as a processability tester. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 2465–2471, 2008

Key words: modeling; composites; SMC; spiral flow; processability

INTRODUCTION

Sheet molding compound (SMC) is a fiber reinforced polymer matrix composite material that is widely used in the automotive, aerospace, marine, and industrial/consumer industries. Its superior strength to weight ratio and corrosion resistance and relatively low cost make it favorable over steel in applications wherein weight savings is a major issue. For example, an SMC part of 0.1 in. [0.254 cm] thickness weighs 25% less than a steel part of 0.03 in. [0.08 cm] thickness, but provides the same stiffness. In addition, when compared with steel, SMC has better resistance to ''dings,'' is more corrosion resistant, and has lower tooling costs.[1] Because of the abovementioned properties, SMC is now the material of choice for heavy truck body panels.

SMC consists of resin, reinforcement fibers, filler, and various additives. Selection of the resin type, from the several available commercially, depends on the application of the finished products. Polyester resin is the most frequently used in SMC applications, as it offers fast reaction times, low cost, and good mechanical properties. The proper selection of initiators and inhibitors is essential to control the reactivity of the resin system.[2]

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Glass fibers, specifically E-type glass fibers, are the most common type of reinforcement used in the SMC industry. They provide dimensional stability and good mechanical properties at a favorable cost. Typically the glass fibers, which are bundles of individual filaments, occupy 25–35% by weight of the SMC composition.[2] If a large stiffness is desired, carbon fibers can also be used as reinforcements; however, because of their greater cost, their use is limited.

Fillers are necessary for the reduction of cost as well as the improvement of specific properties such as chemical resistance, heat resistance, dimensional stability, hardness, surface smoothness, and shrinkage. The most common fillers are calcium carbonate and alumina trihydrate, and 150–200 parts by weight based on 100 parts of resin is generally used in the composition of SMC.[2]

To begin the process of producing the SMC all of the ingredients, except for the fibers, are batch mixed prior to processing. The resulting paste is then poured into two doctor boxes on the SMC machine. The doctor boxes apply a thin layer of paste onto two separate polyethylene/nylon films. One film with a layer of paste is brought underneath a rotating cylinder with blades used to chop glass roving into lengths of typically 1 in. [2.54 cm]. The chopped fibers then randomly fall onto the paste. From there the second layer of polyethylene film is brought into contact with the chopped fiber/paste mixture, creating a sandwich with the film on the outside and the fiber/paste mixture in between. This product is known as SMC. The SMC is stored for a period of 2–3 days to give the paste time to thicken, or mature, after which it is ready to be molded.

When the SMC has matured sufficiently for molding, it is cut into pieces, called plies. Three or four plies are then stacked, creating a charge, weighed, and placed in a mold, which is typically heated to 300°F (150°C). To allow for enough flow and to eliminate air voids trapped in the SMC, the charge covers 50% or less of the mold surface.[3] Once the charge has been placed in the mold, the press is closed and a pressure of ~800 lbs/in^2 (5.52 MPa) is exerted over the projected part area. The mold then remains closed for about 45 s to 1 min, until the cure of the part is complete and it can be removed from the mold.[1]

Research background and objectives

The need to characterize the flow of SMC materials is evident in the literature. There are at least three aspects considered in regard to this objective: (a) rheology, (b) glass carry, and (c) fiber orientation. The importance of rheological measurements and proper rheology equipment is underlined in Refs. 4, 5. In fact, the latter utilizes a spiral mold to elicit thermosetting resins viscosity functions focused on low pressure processes. On the other hand, glass carry and fiber orientation are also discussed in many publications as major material flow issues.[6–9]

As previously mentioned, the heavy truck industry, being an industry where weight savings is critical, offers the largest potential for SMC growth. The trucking industry requires parts with high strength and stiffness, yet surface quality is important. Because of the large size of heavy truck parts, SMC characterization is critical. Molding forces occurring during the molding process are large enough to have a major influence in the cycle time. If the press capacity is low, the time needed to compress the SMC to its final shape is large, requiring the use of

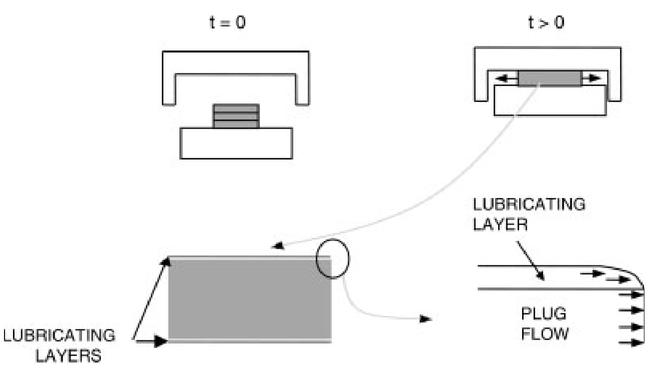

Figure 1 Schematic representation of the SMC flow field.

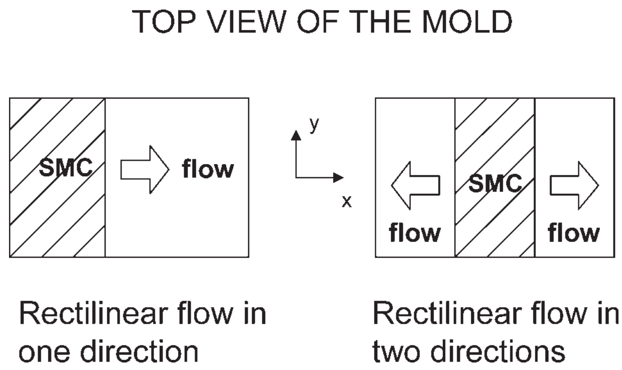

Figure 2 Schematic representation of one-dimensional flow in either 1 or 2 directions.

lower reactivity materials which greatly impact the cycle time. The ability of the SMC paste to carry glass because of the long flow paths encountered must be evaluated and is a critical performance measure when developing new SMCs.[10–14]

Previous work in our group[15–17] demonstrated that there are two material parameters critical to predicting molding forces. One parameter represents the resistance to extension in the SMC core and the second, the friction resistance at the mold wall interface. We also developed a method using flat plate moldings to measure these two parameters. For large parts such as the ones encountered in the heavy truck industry, the friction at the wall is the dominant flow resistance.

The main objectives of this article are twofold: first, to present a method to measure the friction parameter using the spiral flow tool, and second, to demonstrate the use of the spiral flow tool as a processability tester. Values of the friction parameter measured using spiral flow are compared with previous results obtained using flat plate moldings.

Predicting molding forces

Castro and coworkers[15–18] proposed a model to represent the flow of SMC based on the pioneering work of Tucker, Barone and Caulk, and Marker and Ford.[18–23] The model consists of an SMC core with lubricating layers at both mold surfaces. The lubricating layer is assumed to contain only paste whose rheology is assumed to be represented by the power law. Figure 1 shows a schematic representation of the model.

Considering unidirectional flow in either one or two directions as shown in Figure 2, they derived the following relationship to represent the pressure during the compression stage:

$$P(t) = \frac{4 f_C U(t)}{h(t)} + \frac{2 f_L U(t)^n}{h(t)^{n+1}(n+1)} (L_m(t)^{n+1} - x^{n+1}) \quad (1)$$

TABLE I
SMC Paste Make-Up

Component	Weight	Weight (%)
Unsaturated polyester and styrene monomer resin (including low profile additive)	100	32
Mod E (inhibitor)	0.24	0.0076
TBPB (catalyst)	1.5	0.47
PDO (catalyst)	0.2	0.0063
VR 3 (mold release)	3.0	0.95
Calcium stearate (mold release)	1.0	0.32
$CaCO_3$ (63% filler of SMC paste)	200	63
Thickener (magnesium oxide)	10.2	3.2

where *P(t)* is the pressure; f_c is the coefficient of resistance to extension in the core, $(\text{tons s})/\text{in}^2$ $[(\text{N/s})/\text{cm}^2]$; f_L is the lubricating layer parameter, $(\text{tons/s})/^n\text{in}^{n+2}$, $[(\text{N s})^n/\text{cm}^{n+2}]$, defined as m/δ^n, with m as the power law consistency index for the paste, n the power law exponent, and δ as the lubricating layer thickness; *U(t)* is the instantaneous press closing speed; *h(t)* is the instantaneous part thickness; $L_m(t)$ is the instantaneous flow length; and x is the position in the charge. Both L_m *and* x are measured from the center of the mold if the flow occurs in two directions or form the end of the charge in contact with the mold if the flow is in one direction.

They also developed the following expressions to predict the molding forces[15–17]:

$$F_L = \frac{4 f_C VU}{h^2} + f_L \frac{2U^n V^{n+2}}{h^{2n+3} W^{n+1}(n+2)} \quad (2)$$

$$F_C = \frac{4 f_C VU}{h^2} + f_L \frac{2U^n V^{n+2}}{h^{2n+3} W^{n+1}(n+2)(2^{n+1})} \quad (3)$$

where V is the volume of part, and W is the width of mold.

Equation (2) represents the force required to mold a part when the charge is placed in the left side of the mold. Similarly, eq. (3) provides the force required when the charge is placed in the center of the mold (i.e., one-dimensional flow in two directions).

Examining both equations, it becomes clear that for large parts (large volume), the second term dominates. Also as the mold closes, the required molding force increases (h decreases) and the influence of the second term becomes increasingly larger. Thus, when sizing a press, except for very small parts, the friction resistance (second term) dominates the required molding force.

MATERIALS AND METHODS

SMC composition

With the assistance of Ashland Chemical in Dublin, Ohio, SMC formulations with varying amounts of glass and filler were produced. Each SMC sheet was 36 in. wide, was compacted at 450 g/ft^2, and utilized the same paste make-up except for the amount of filler. The paste make up is shown in Table I. After the SMC was made, it was allowed to mature for at least 1 day and it was used within 3 days of being made. The levels of filler and glass were kept within the commercial ranges for automotive SMC. The charge was 12.7 cm by 12.7 cm and it was located in the center of the square cavity.

Spiral flow tool

The spiral flow tool has evolved in its design and application in the past 30 years. The concept behind the spiral flow tool is to use a relatively small amount of material to represent the actual molding process. The initial spiral flow tool's design was taken from the injection molding industry, where the SMC paste was injected into a small channel in a hot mold. The dimensions of the channel were 0.25 in. × 0.125 in. × 48 in. [0.635 cm × 0.3175 cm × 121.92 cm], and the tool was intended to be used only to obtain relative comparisons of the final length for different materials. The biggest disadvantage of the early spiral flow tool designs was that the fiber reinforcements prevented the SMC from flowing in the channel.[24,25] To use the early spiral flow tool, the SMC had to be chopped up into small pieces. These experiments were inconsistent and unrepeatable. The main application for the early spiral flow tool was to test the paste without the glass. The spiral flow tool's geometry was later improved to accommodate for the flow of glass fiber during molding.

Even though the spiral flow mold has a more complex geometry than the previously used flat plate, its long flow channel allows for evaluation of the paste's ability to carry the reinforcement. This long channel also holds another advantage over the flat plate since the material's ability to flow can be quantified by simply measuring the flow length.[25] The spiral flow used in this research has been designed to better represent the actual molding process than does the early spiral flow tool, by accom-

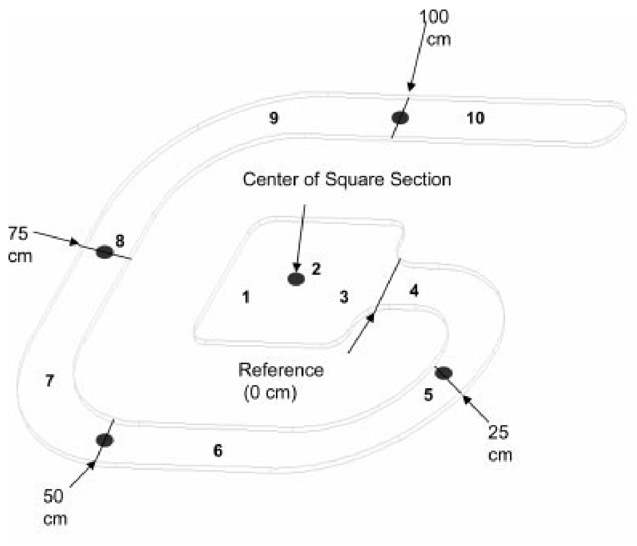

Figure 3 Schematic representation of the Spiral Flow Tool. The position of the pressure and temperature sensors (25 cm, 50 cm, etc.) is indicated. The numbers (1–10) indicate the positions where samples were taken to test for glass content.

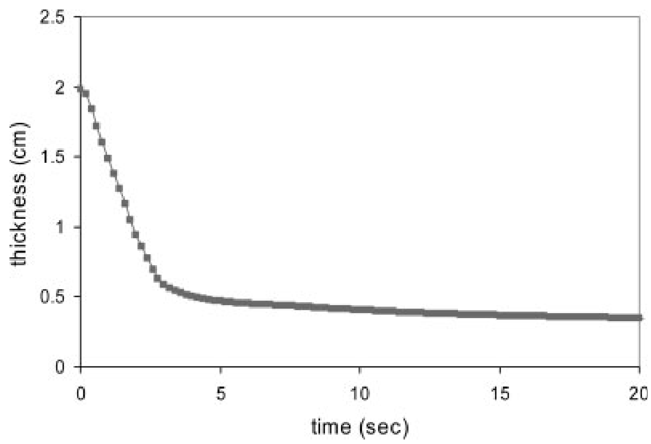

Figure 5 Mold separation as a function of time for the same run as Figure 5.

modating for the long glass fibers and shear edges.[24,25] Its dimensions were increased to a 6-in. × 6-in. [15.24-cm × 15.24-cm] square charge cavity, with a 2-in. [5.08-cm]-wide channel that is 48 in. [121.92 cm] in length. The spiral flow tool is equipped with a data acquisition system that uses LABVIEW from National Instruments to collect temperature and pressure readings along the channel, hydraulic force, and mold separation all with respect to time. Figure 3 shows the positions of temperature and pressure sensors. The data were collected at the rate of 5 readings/s. All sensors were calibrated before using. The details can be found in reference [25].

Significant effort went into setting the hydraulic press used in these experiments so that the desired molding force is reached quickly and kept at a constant value. Figure 4 shows the hydraulic pressure versus time for a run using SMC with 56% filler and 33% glass by weight. Figure 5 shows the mold separation versus time and Figure 6 shows the responses of the pressure sensors located at 25, 50, and 75 cm from the start of the constant width channel (Fig. 3) for the same run. Notice that by the time the SMC reaches the first pressure sensor, the desired molding force has been reached.

RESULTS

Measuring the friction coefficient using the spiral flow tool

Assuming that the flow in the channel is equivalent to one-dimensional flow, the pressures at the position of the transducer, are given by eq. 1, where x is the position of the transducer. Rabinovich[25] using flow visualization experiments with colored charges

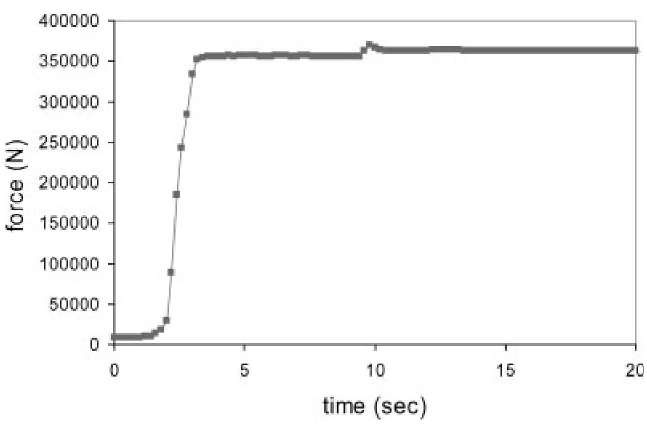

Figure 4 Molding force as a function of time for SMC with 56% filler and 33% glass.

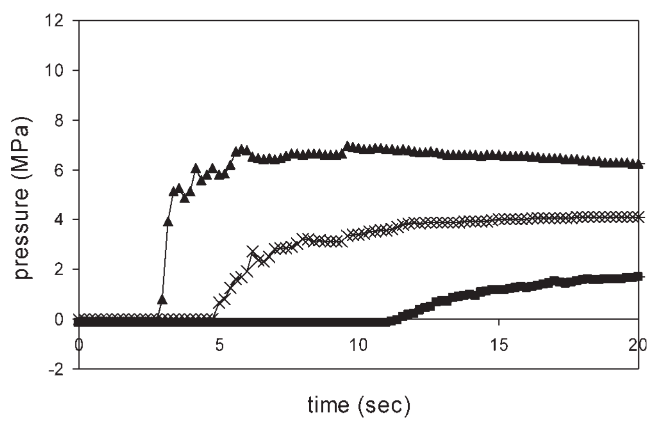

Figure 6 Pressure as a function of time for transducers located at 25 cm (▲), 50 cm (×), and 75 cm (■) along the spiral flow channel for the same run as Figure 5.

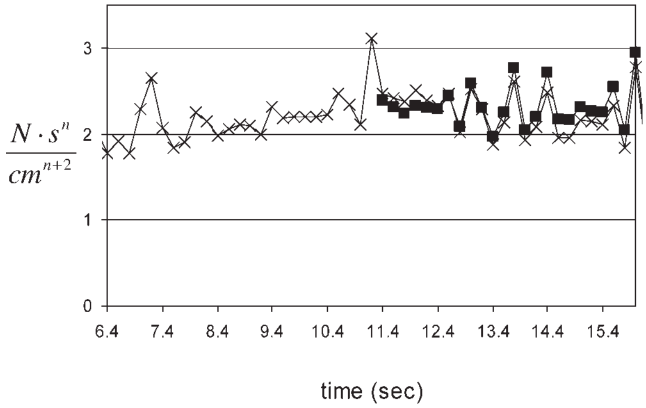

Figure 7 Calculated friction coefficient form pressure differences for the SMC with 56% filler and 33% glass. The thick horizontal line represents the best fit constant value. The pressure differences used are from transducers located at 25, 50, and 75 cm.

demonstrated that this is a good assumption. By taking the difference between two consecutive pressure transducers, the resistance to extension coefficient is eliminated and the resultant expression shown in eq. 4 can be used to determine the lubricating layer parameter.

$$f_L = \frac{m}{\delta^n} = \frac{(p_i - p_{i+1})(h(t)^{n+1}(n+1))}{(2U(t)^n)(x_{i+1}^{n+1} - x_i^{n+1})} \tag{4}$$

Using the pressure sensors and the displacement transducer in the in the spiral flow tool, we can evaluate the terms in the right hand side of eq. 4, which when plotted should give a straight horizontal line centered on the value of the friction coefficient. The effect of varying the amounts of filler and reinforcement on the lubricating layer parameter was studied. The percentages of filler by weight of paste used were 56 and 65, and the percentage of glass by weight of the total SMC was 18 and 33. These are the same ones used by Boylan,[17] which will allow us to compare the values using spiral flow with the ones from flat plate molding.

The power law exponent needed in eq. 4 has been measured by Boylan[17] and is 0.42 for the paste with 56% filler and 0.33 when the filler level is 65%. The results for the SMC with 56% filler and 33% glass are shown in Figure 7. The pressures used to evaluate the pressure difference are from the transducers located at 25, 50, and 75 cm and are the ones shown in Figure 6. The thick horizontal line represents the best fit constant value. Table II shows a comparison of the friction coefficient for both the flat plate and the spiral flow tool. The values from both methods are close and follow the same trend, which means that the spiral flow tool can be used to obtain the lubricating layer parameter. More details can be found in.[25] The friction coefficient value for high filler/high glass is lower than anticipated. The filler level within the ranges used commercially has little effect on the molding forces. Glass level on the other hand has a larger effect. Increasing the amount of glass decreases the lubricating layer thickness, which then increases the friction coefficient. This observation is consistent with the flow length study in the next section.

Rabinovich[25] also discusses a method to obtain the resistance to extension using the spiral flow tool. However, the results for the resistance to extension by this method are not as reliable as the ones from our previous flat plate molding approach.

Using the spiral flow tool to evaluate processability

Evaluating glass carrying ability of the SMC

One of the important factors in SMC manufacturing is the ability of the paste to carry glass, which is vital to achieving uniform physical properties in a part. The spiral flow tool can be used to evaluate the SMC's ability to carry glass because the material is forced to flow for a long distance. To demonstrate this, an experiment was performed in which 1-in. circular samples were drilled out of the molded part and measured to check for glass contents at various locations, shown in Figure 3. The glass burnout method was used to determine glass compositions.[25] This method involves placing the samples in an oven

TABLE II
Friction Coefficient Evaluated with the Flat Plate and Spiral Flow Tool

		Flat plate, f_L		Spiral flow, f_L	
Filler in paste (%)	Glass (%)	$\left(\frac{\text{lbs s}^{0.33}}{\text{in}^{2.33}}\right)$	$\left(\frac{\text{Ns}^{0.33}}{\text{cm}^{2.33}}\right)$	$\left(\frac{\text{lbs s}^{0.33}}{\text{in}^{2.33}}\right)$	$\left(\frac{\text{Ns}^{0.33}}{\text{cm}^{2.33}}\right)$
56	18	1.27	0.65	1.3	0.66
56	33	4.36	2.21	4.1	2.08
65	18	2.17	1.10	1.5	0.76
65	33	3.96	2.01	3.4	1.72

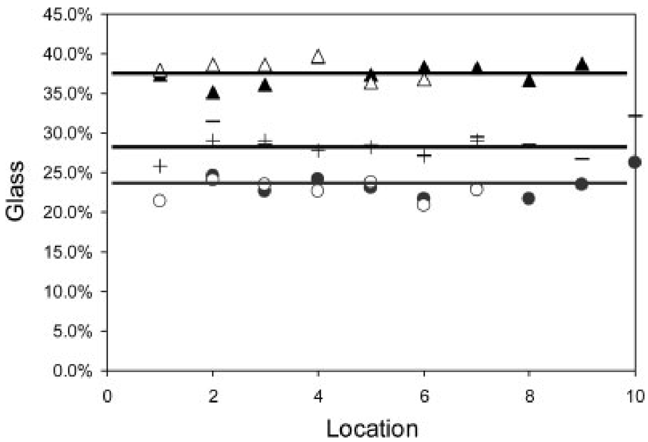

Figure 8 Glass percent for the locations shown in Figure 1, for SMC made with different glass weight percent (38, 28, and 23) molded using two different molding forces.

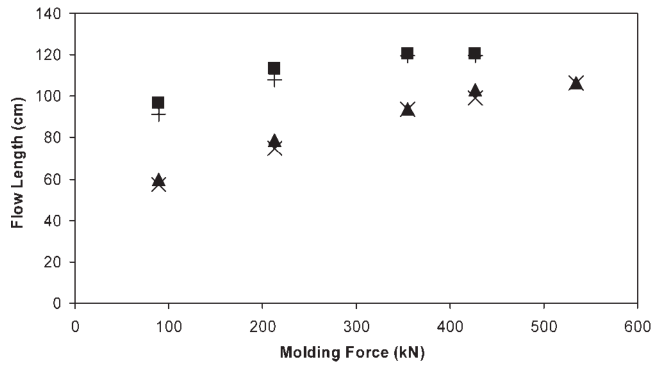

Figure 10 Flow length versus molding pressure for SMC with different glass and filler contents. 18% glass and 56% filler (■), 18% glass and 65% filler (+), 33% glass and 56% filler (▲), 33% glass and 65% filler (×).

and baking them overnight at 450°C. The organics, including the polymer matrix, reacted with the oxygen in the oven to form carbon dioxide, leaving the filler and glass. The filler was reacted away with acid, leaving the glass fibers, which were then washed and dried before measuring the amount of glass in the sample. Three different materials with glass content of 38%, 28%, and 23% molded at high (450 kN) and low molding force (225 kN) are shown in Figure 8. The low variation of the glass amounts at each of the samples' locations shows that the materials tested are very good at carrying the glass reinforcement. This was the expected result as the formulations were designed for commercial use.

Using the flow length to evaluate processbility

As previously mentioned, one of the advantages of the spiral flow tool with respect to flat plate moldings is that the final flow length could be used empirically to judge the material's ability to flow. That is, the spiral flow tool can be used as a processability tester for SMC. For example, trends could be observed in Figure 9 as to how the temperature and molding force affect the final flow length for a material with 56% filler and 33% glass. The larger the molding force the more the material flows. Increasing the molding temperature decreases the flow length since the chemical reaction is accelerated with temperature. The higher the temperature, the earlier the material solidifies and stops flowing.

Figure 10 shows the flow length as a function of the molding force for several glass and filler compositions at a molding temperature of 150°C. The results show that the filler level within the range used has a negligible effect on the flow length. The glass percent does have a larger effect on flow length. This agrees with the friction coefficient results where the effect of filler is negligible but increasing the glass percent, increases the friction coefficient.

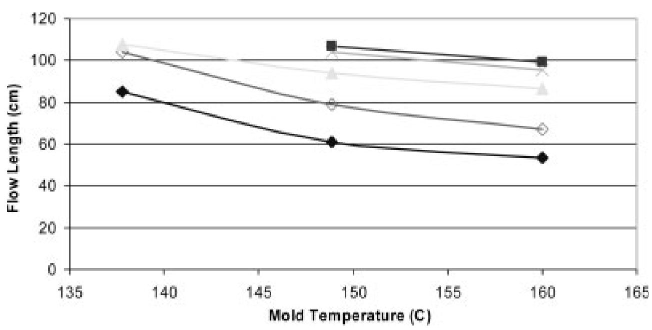

Figure 9 Flow length as a function of molding temperature for SMC with 33% glass and 56% filler, molded at different molding forces: 89 kN (◆), 213 kN (×), 355 kN (■), 425 kN (+), and 534 kN (●).

CONCLUSIONS

The spiral flow tool can be used as a qualitative tool to evaluate SMC processability. By examining the flow length, one can get an idea of the amount of flow the material can undergo before solidification occurs because of chemical reaction. The ability of the paste to carry glass can also be established. This can be very useful when developing new SMC formulations. Using the pressure sensors in the spiral flow tool, the friction coefficient can be evaluated. This is the parameter controlling the molding forces for larger parts and is critical in selecting press size. Within the levels tested, the amount of glass has a larger effect than does the amount of filler on the SMC ability to flow.

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