Sheet Molding Compound (SMC) Processing

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SUMMARY: A spiral flow tool can bee used to gain insight into the dynamic interactions of the SMC during the compression molding process. In contrast to flat plate molding, the spiral flow tool simulates a very long flow; while collecting processing parameters during molding with respect to time. A mathematical model has been developed and experimentally verified for the spiral flow tool. A new method of determining the friction coefficient using the spiral flow tool is proposed, which yields similar results to flat plate molding.

KEYWORDS: Sheet Molding Compound, SMC, spiral flow tool, compression molding

INTRODUCTION

Sheet Molding Compound (SMC) is a fiber reinforced polymer matrix composite material that offers an array of beneficial properties that are demanded by many modern applications. Automotive, aerospace, marine, and industrial/consumer industries increasingly use SMC to take advantage of its performance. SMC is composed of polymerized or cross-linked resin, reinforcement fibers, filler, and various additives.
Throughout the years, the spiral flow tool has evolved in its design that would better accommodate the SMC, which included widening the flow channel and mimicking the actual compression molding process with shear edges.

THE SPIRAL FLOW TOOL

The spiral flow described in this paper is equipped with a data acquisition system that allows for collecting responses exhibited by the SMC, and a special hydraulic package that exerts a constant force on the material during the molding process, with the force specified by the operator.

The spiral flow tool's data acquisition system consists of 5 sensors that collect pressure and temperature inside the mold at 5 different positions. Besides the temperatures and pressures at these locations, the hydraulic force that is applied on the material is recorded as the material is molded. The LVDT provides data on the relative mold half's position during mold closing.

Lastly, the spiral flow tool provides a length value at which the material stopped flowing. A schematic of the spiral flow tool used in this research is shown in Fig. 1.

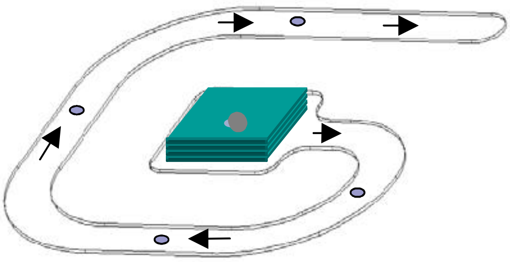

Fig. 1. Design of the spiral flow tool described in this paper. Dots represent the positions of temperature and pressure sensors. Arrows represent the direction of the material flow. The rectangles in the center represent the SMC charge.

MATHEMATICAL MODELING OF THE SMC INSIDE THE SPIRAL FLOW TOOL

Castro and Abrams [1] have proposed a model to represent SMC flow based on the pioneering work of Tucker [2, 3, 4, 5], Barone and Caulk [6, 7] and Marker and Ford [8]. The model consists of a material that flows by extension (bulk), with a thin lubricating layer on the surface (resin rich layer), which behaves as a power law fluid. They have also proposed a method to calculate the friction coefficient and resistance to extension. The model for the spiral flow tool is based on this model.

The spiral flow tool's molding process can be represented in three stages. Stage I starts when the SMC comes into contact with both halves of the mold and ends when the material fills up square section of the mold. Stage II picks up at the end of Stage I and ends when the hydraulic forces reaches maximum. Stage III is effective when Stage II ends and lasts until the flow stops [11].

Stage I could be described by the 2-directional SMC model, Eqn. 1.

$$F(t) = \frac{4\eta V U(t)}{h(t)^2} + M \frac{2U(t)V^{n+2}}{h(t)^{2n+3} W^{n+1} (n+2)(2^{n+1})} \tag{1}$$

F(t)=Force on SMC (compacted)
V=volume of SMC
h(t)=part thickness
U(t)=closing Speed
W=width of the part (6")
M=m/δn (lubricating layer)
η= resistance to extension
n= paste power law index

Stages II and III are based on a model that assumes a combination of one-dimensional flows, described by Eqn. 2 and illustrated in Fig. 2. This is a reasonable assumption to make, and has been verified by experiments where a small section of a colored charge maps out the flow of SMC [11]. Stages I and II occur in the first few seconds of the molding process, with not a very significant material flow, which means that Stage III is the most important stage to understanding the behavior of the material because Stage III lasts for more than 10 seconds and represents most of the material flow. The above model has been shown to represent the experimental data fairly well [11].

$$F(t) = 2 \cdot \left[\begin{array}{l} \dfrac{4 \cdot \eta \cdot U(t)}{h(t)} \cdot L_m(t) + \dfrac{M \cdot 2 \cdot U(t)^n}{h(t)^{n+1} \cdot (n+1)} \left(L_m(t)^{n+2} - \dfrac{L_m(t)^{n+2}}{n+2} \right) + \\ + \left(\dfrac{16 \cdot \eta \cdot U(t)}{h(t)} + \dfrac{2 \cdot M \cdot U(t)^2}{h(t)^{n+1} \cdot (n+1)} \left(2^{n+2} - \dfrac{2^{n+2}}{n+2} \right) \right) \cdot 6 + \\ + \dfrac{4 \cdot M \cdot U(t)^n}{h(t)^{n+1} \cdot (n+1)} \left(6 \cdot L_m(t)^{n+1} - \dfrac{6^{n+2}}{n+2} \right) \end{array} \right] \quad (2)$$

Lm(t)=Flow length, calculated from the conservation of mass assumption

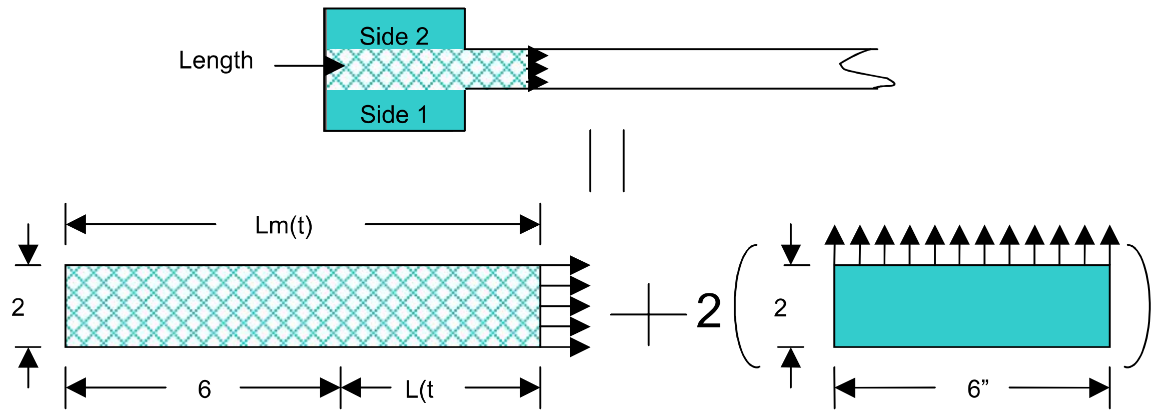

Fig. 2. Breakdown of the geometry used to model Stages II and III.

The data from the pressure transducers can be used to calculate the lubricating layer parameter ($M=m/\delta^n$) by using the LVDT data and pressure readings [11].

$$\frac{m}{\delta \cdot n} = M = \frac{(p_i - p_{i+1})\left(h(t)^{n+1}(n+1)\right)}{\left(2 \cdot (U(t))^n\right)\left(x_{i+1}{}^{n+1} - x_i{}^{n+1}\right)} \quad (3)$$

p=pressure from the transducer
x=position inside the mold

SPIRAL FLOW TOOL VERSUS FLAT PLATE MOLDING FOR OBTAINING MATERIAL PARAMETERS

Previous work has been done using flat plate molding for determining the material flow parameters. Flat plate molding has the advantage over the spiral flow tool with its simpler geometry, but the spiral flow tool has the advantage of simulating an extensive flow of the material.
Equation 2 could be solved by iterations for the part thickness (h) and the closing speed (U), from which the length of flow could be calculated. Fig. 3 shows a plot where the predicted length of flow values is compared to the experimentally measured values. The predictions were made using the material parameters measured with the flat plate molding, done by Boylan and Castro [10].

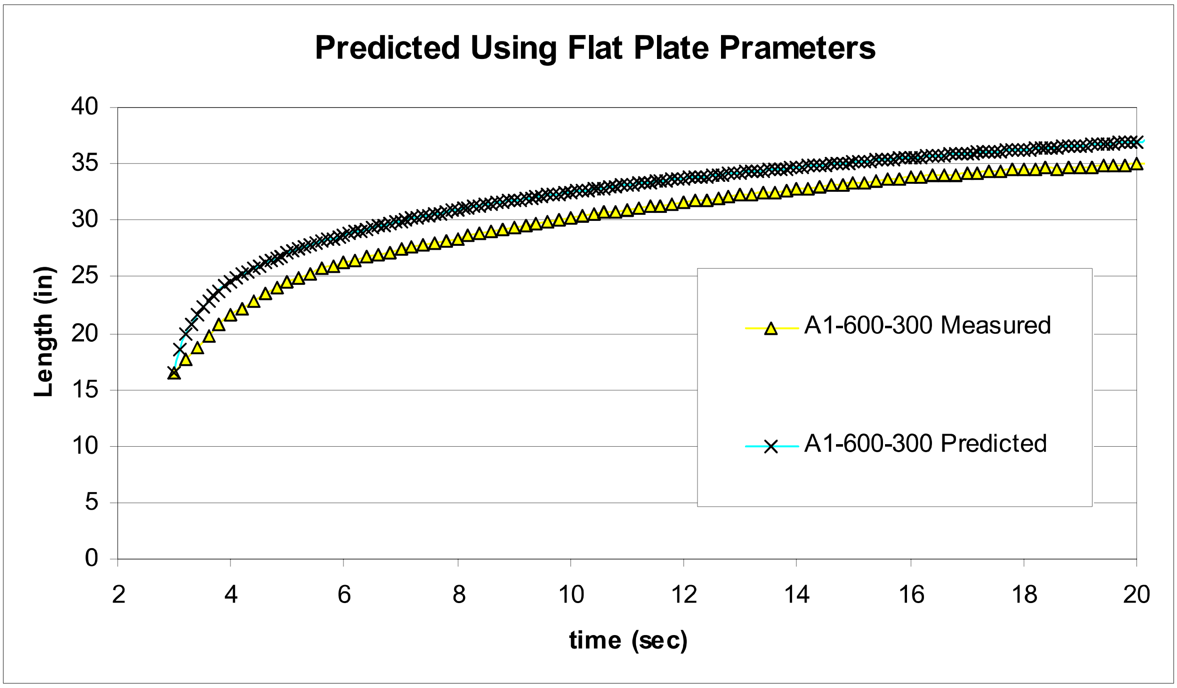

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Fig. 3 Predicted flow length in the spiral flow tool using flat plate measured material parameters.

It should be noted that the spiral flow tool experiments are only repeatable within one inch of the final flow length. The model predictions using the flat plate parameters produce values that are close to the actual experiments.
A comparison between the lubricating parameters from the spiral flow tool using Eqn. 3 and the flat plate molding is displayed in Table 1.

Table 1. Comparison of the lubricating layer parameter from two different methods.

	Spiral Flow	Flat Plate
Low Filler – Low Glass	1.3	1.27
Low Filler – High Glass	4.1	4.36
High Filler – Low Glass	1.5	2.17

The lubricating layer parameter (M) obtained from the spiral flow tool closely matches to the values obtained from the flat plate molding. However, efforts to determine the resistance to extension parameter (η) with the spiral flow tool produced inconsistent results.

CONCLUSIONS

The spiral flow tool which was previously used as a qualitative tool to evaluate SMC can also be used to determine the lubricating layer parameter M, with similar results to flat plate molding. The flow of SMC inside the spiral flow tool could be predicted with the material parameters obtained from flat plate molding. The resistance to extension parameter (η) cannot be obtained from the spiral flow tool easily and needs to be investigated further.

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REFERENCES

1. Abrams, L. and J. Castro. *Predicting Molding Forces in SMC Compression Molding.* In ANTEC 2000. 2000. Orlando, Florida.
2. Advani, S.G. and C.L. Tucker, *A Numerical Simulation of Short Fiber Orientation in Compression Molding.* Polymer Composites, 1990. p.164.
3. Tucker, C.L and E.W. Liang, Polymer Composites, 1995. p.70.
4. Osswald, T.A. and C.L. Tucker, *Compression Mold Filling. Simulation for Non-Planar Parts*. International Polymer Processing, 1990. p.79.
5. Lee, C.C. and C.L Tucker, *Flow and Heat Transfer in Compression Mold Filling.* Journal of Non-Newtonian Fluid Mechanics, 1987. p. 245.
6. Barone, M.R. and D.A. Caulk, *A Model for the Flow of a Chopped Fiber Reinforced Polymer Compound in Compression Molding.* Journal of Applied Mechanics, 1986. p. 361.
7. Barone, M.R. and D.A. Caulk, *The Effects of Deformation and Thermoset Cure on Heat Conduction in a Shopped Fiber Reinforced Polyester During Compression Molding.* Int. J. Heat Mass Transfer, 1979. p. 1021-1032.

8. Marker, L. and B. Ford. *Rheology and Molding Characteristics of Glass Fiber Reinforced Sheet Molding Compounds.* In Reinforced Plastics/Composites Institute. 1977.
9. Lee, L. J., Marker, L. F., and Griffith, R.M *The Rheology and Mold Flow of Polyester Sheet Molding Compound.* Polymer Composites, 1981.
10. Boylan, Sarah *Applications in Sheet Molding Compound Compression Molding.* M.S. Thesis, The Ohio State University, 2002.
11. Castro, J., Rabinovich, M., and Leach, B. *Mathematical Modeling of the Spiral Flow Tool for Sheet Molding Compound (SMC).* Numiform, The Ohio State University, 2004.