In-Mold Coating of Thermoplastic Substrates-Wall Slip and Improved Rheological Model

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SUMMARY: For thermoplastic parts like automotive body panels, the current industrial practice is to paint them for protection against outdoor exposure or to improve surface appearance. Painting is environmentally unfriendly and costly. Furthermore, a non-environmentally friendly adhesion promoter typically needs to be used before painting. In-mold coating (IMC) is a cost effective and environmentally benign alternative to painting. IMC is carried out by injecting a liquid low viscosity thermoset material onto the surface of the thermoplastic part while still in the mold. The coating then solidifies and adheres to the substrate. A Hele-Shaw based mathematical model and a corresponding computer code based on the Control Volume Finite Element Method (CV/FEM) has been developed to simulate the flow during the IMC process assuming the coating to be a power law fluid [5]. The continuous deformation of the thermoplastic substrate caused by the coating injection is analyzed by means of the PVT relationship of the substrate. Although the simulation works well for predicting fill patterns as discussed in [5], pressures were found to deviate from experimentally recorded results. A one-dimensional simulation is presented in this paper to show that including wall slip and using an improved rheological model better predicts the pressure distribution.

KEYWORDS: In-mold Coating, Wall slip, Sisko Model, Power law model.

INTRODUCTION

In-mold coating (IMC) has been successfully used for many years for exterior body panels made from a fiber reinforced polymeric composite material named Sheet Molding Compound (SMC) by compression molding. The coating is a thermoset liquid, used to fill the surface porosity typical in these composites and to improve their surface quality in terms of functional and cosmetic properties [1]. When injected onto a cured SMC part, IMC cures and bonds to provide a paint-like surface [2]. Because of its distinct advantages, IMC is now being considered for injection molded thermoplastic parts. Similar to IMC for SMC, IMC for thermoplastics could be used either as a topcoat or as a primer. As a primer, it will replace the currently used adhesion promoter. The long term goal is to completely eliminate both the priming and painting operation altogether. With current materials, the potential to eliminate the adhesion promoter is large [3, 4]; however, more research is needed to completely eliminate painting. For a successful IMC operation, there are two key concerns that need to be addressed. The first one is the location of the injection nozzle. It should be located such that the thermoplastic part is totally covered and the potential for air trapping is minimized. The selected location should be cosmetically acceptable and should also be accessible for ease of maintenance. The second one is that the clamping force available needs to be higher than the hydraulic force generated by the coating so that the mold does not open during IMC injection. For IMC for SMC, this is not a key issue since SMC molds have shear edges that act as a seal in case the mold opens. The goal of this research work is to develop a computer simulation tool to predict the pressure distribution and the fill pattern to enable the identification and screening of potential IMC nozzle locations and to determine the required clamping force. In a previous paper [5], we presented a two-dimensional model based on the Hele-Shaw approximation to predict the flow of IMC, assuming the coating to be a power law fluid. Though the simulation tool predicts experimental fill patterns reasonably well, the pressures were not properly predicted. This could be due to wall slip as often found in flow through micro channels. To demonstrate this effect, we introduced a slip boundary condition into the 1-D pressure governing equation presented in [6]. It was shown that as we introduce a non-zero value to the slip coefficient β, the simulated pressures move towards the experimental values as shown in Fig.1. Thus slip at the wall during filling of the mold could be one of the reasons we obtain lower than predicted pressures [7]. Additionally, the coating material has shown evidence of an upper Newtonian plateau at the high shear rates encountered during coating. Thus, an improved rheological model instead of the power law would also help in predicting pressures more accurately. In this paper, we use an improved rheological model, namely, the Sisko model, in conjunction with the slip boundary condition in a 1-D flow case to illustrate how the introduction of additional modeling parameters is a step in the right direction towards predicting pressures more accurately.

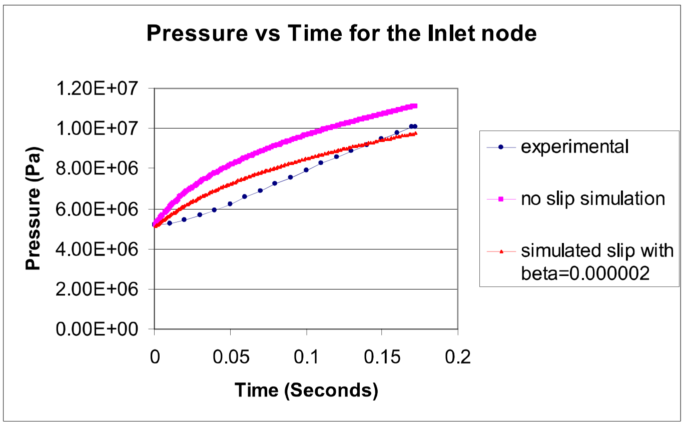

Fig.1. Numerical vs. Experimental Pressures

MATHEMATICAL MODELING

For a simple rectangular part, the coating flow from a line injection port can be approximated as a one-dimensional flow as shown schematically in Fig. 2. The following assumptions are made:

1) Isothermal flow, since, due to the very thin gap, the coating reaches the wall temperature in a very short time [4];
2) Quasi-steady-state flow with inertial terms neglected;
3) Lubrication approximation: $v_x = v_x(z, h(x))$;
4) The gap available for IMC flow can be expressed as [4] :

$$h = h_S(1 - \frac{V}{V_0}) \tag{1}$$

where h_S is the thickness of the thermoplastic substrate, V is the specific volume of the thermoplastic substrate and is a function of the IMC pressure under the assumption of isothermal flow, V_0 is the specific volume of the thermoplastic substrate at the average (bulk) temperature just before the coating injection starts.

The viscosity of the coating liquid is modeled using the Sisko model:

$$\eta = \eta_\infty + m\dot{\gamma}^{n-1} \tag{2}$$

where η_∞ is the upper Newtonian Viscosity, *m* and *n* are constants.

Fig.2. Schematic of 1D IMC flow

With the above assumptions, the momentum balance equation can be simplified to:

$$\frac{\partial p}{\partial x} = \frac{\partial}{\partial z}[\eta(\frac{\partial v_x}{\partial z})] \tag{3}$$

where p is the pressure of the coating and v_x is the velocity of the coating. The boundary conditions are given by:

$$v_x = v_s = \beta\left(\frac{\partial v}{\partial z}\right)\Big|_{z=0}; \qquad \text{at } z = 0 \tag{4}$$

$$\frac{\partial v_x}{\partial z} = 0; \quad \text{at } z = h/2 \tag{5}$$

where β is the slip coefficient.

Integrating Eqn. 3 using the boundary conditions, and substituting Eqn. 2 in the resultant equation, we obtain an expression for the pressure gradient in terms of the velocity and viscosity parameters:

$$\frac{\partial p}{\partial x}\left(z - \frac{h}{2}\right) = [\eta_\infty\left(\frac{\partial v_x}{\partial z}\right) + m\left(\frac{\partial v_x}{\partial z}\right)^n] \tag{6}$$

This equation needs to be solved numerically since the pressures cannot be calculated explicitly in terms of flow rate. Further, the coating thickness is a function of the specific volume of the thermoplastic that is related to pressure and needs to be solved numerically. Finite Difference Method (FDM) was used to solve the equations numerically. Nested iteration loops were used to solve for pressures. At a fixed spatial step, that is used to track the flow front location, using the inner loop, the pressures were obtained for using iterative solutions for velocity and pressure at a particular coating thickness. For each time step, the flow front is advanced by one spatial step, and then the pressure distribution and the coating thickness distribution are obtained by iterative solution of Eqn.1 and PVT relationship as defined in [5]. The whole procedure is repeated until filling is completed.

RESULTS AND DISCUSSION

Fig.3 shows the comparison between the experimentally observed pressures (at transducer location) and various numerically obtained results for coating a thermoplastic (ABS) flat plate of dimensions 0.152m x 0.152m x 0.002m. The flow rate used was 3.679E-07 m^2/s. n and $m0$ values were 0.3085 and 0.0935 respectively. It can be seen that the experimental results are not adequately predicted by the available filling simulation codes. Based on the preliminary experimentally determined viscosity values, η_∞ was found to be approximately 0.075 Pa-s. Using this value in the 1-D flow case and checking for various values of slip coefficient β, it was observed that at a particular value, the predicted pressures adequately match the experimentally observed values. The general trend seen is that increasing η_∞ increases the slope of the curve whereas decreasing β, the slope decreases.

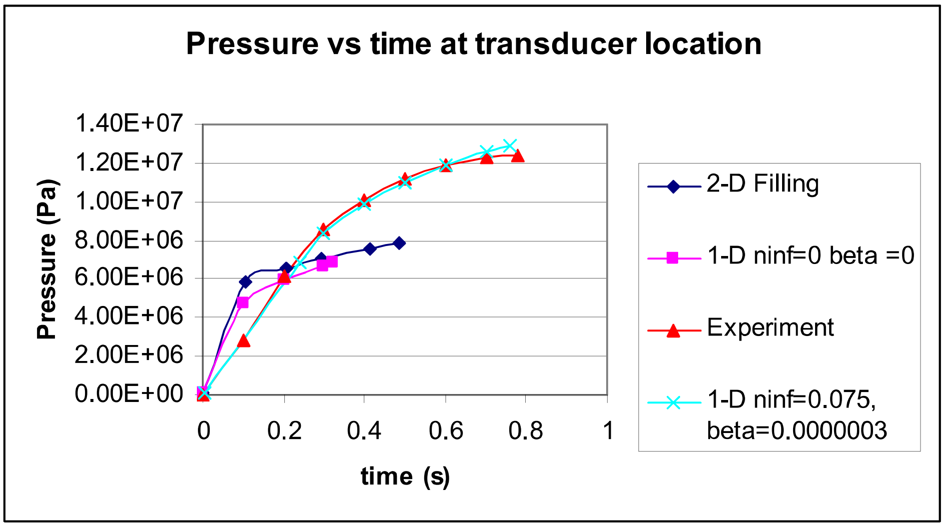

Fig.3 Comparison between the experimentally observed pressures (at transducer location)

CONCLUSIONS AND FUTURE WORK

A computer code has been developed for coating flow in one direction. The code includes an improved viscosity model, namely, the Sisko model and boundary condition allowing slip at the wall. Preliminary results indicate that these are steps in the right direction towards being able to predict the pressure distribution during coating flow. More work is needed to properly characterize the coating materials at high shear rates and to evaluate the slip coefficient. The computer code also needs to be extended to 2-D cases so that the coating of actual parts can be simulated.

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