A Numerical Study of Filling Process in Resin Injection/Compression Molding

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ABSTRACT

Resin injection/compression molding (RI/CM) is a variant of resin transfer molding (RTM) process to produce advanced composites. In the present model a gap is present between the fibrous preform and the upper mold during the RI/CM filling process. The gap results in preferential flow path during resin injection. After the enough amount of resin is injected, the closing action of the mold initiates and forces the resin in the gap to penetrate into the fibrous preform. The resin flow in the gap is simplified by the Hele-Shaw flow model, while Darcy's law is used to calculate the flow field in the fibrous preform. Two modes of compression phase, either constant speed or clamping force, are discussed. Numerical results show that the process of resin penetrating into fibrous preform is a key factor in RI/CM cyclic period and clamping force. By comparing two compression modes, the compression time reduction can be made by applying the full capacity of the clamping force from the initiation of compression for the version of constant force compression. As compared to RTM, RI/CM process can significantly reduce the mold filling time using a low injection/compression pressure.

Key Words: Resin injection/compression molding, Resin transfer molding, Filling process

1. INTRODUCTION

Resin injection/compression molding (RI/CM) is a variant of resin transfer molding (RTM) process to produce fiber reinforced composites. The major motivation to develop this manufacturing technique is to improve the limitations of conventional RTM in making composite parts, particularly for the components having high fiber volume fraction. In addition, RI/CM process can also reduce the mold filling time by using low injection pressure.

Various stages in RI/CM are identical to RTM except the filling process. The filling process of the RI/CM is composed of two phases including resin injection and mold compression. During injection the preform is preplaced in the mold cavity and the cavity remains partially close. Two filling modes of RI/CM are often utilized because of the different situation of fiber mats in the cavity. One is a gap formed between the preform and the upper mold, and the other is loose fibrous preform fully occupied the cavity. The former is investigated in the present study. The RI/CM filling process is illustrated in Figure 1. The gap results in preferential flow path. Resin can quickly fill up the gap during injection. Once the necessary amount of resin is injected, the mold platens are brought together, driving the resin through the preform and
compacting the mold cavity to the final part thickness.

Han et al. [1] proposed a numerical code that can be used to simulate the flow and heat transfer in injection/compression liquid composite molding (LCM). They reported that the injection/compression LCM process could lead to more regular filling pattern and reduce the molding pressure significantly. Wirth and Gauvin [2] performed two series of experiment of compression resin transfer molding (CRTM). For the case of an open gap being present on the top of the preform, they reported that the resin injection time was extremely short and most filling and wetting time was elevated to the final closing of the cavity. Chang et al. [3, 4] developed a numerical study and conducted the flow visualization experiment of compression transfer molding (CTM). They reported that the gap resulted in a preferential flow during resin injection. Thus most resins entered the gap and merely few resins penetrated through the fibrous reinforcements. Chang [5] reported that using small gap size and high compression speed could achieve the minimum mold filling time for the simultaneous injection/compression molding process. However, the improper process parameters would cause the incomplete filling or reversed flow at the gate. Pham and Trochu [6] developed a two-dimensional finite element model (FEM) for the CRTM process. The model allowed studying the effect of compression on the filling of a composite part for different compression speeds and injection pressures. Kang and Lee [7] also proposed a numerical code to predict the resin flow, temperature, pressure and degree of cure distribution during resin transfer/compression molding (RT/CM). The compression force required for squeezing the impregnated preform can be calculated. Bickerton and Abdullah [8] utilized analytical solutions of simple flow geometries to explore the potential benefits of injection/compression molding (I/CM) relative to RTM. Their model, based on elastic preform deformation, was used to explore the effect of process design parameters on resulting filling times, and clamping force requirements. Shojai [9] developed a three-dimensional numerical code to simulate the CRTM filling process by using control volume/finite element method. Riche et al. [10] presented a methodology to study the effects of coupling the RTM and compression (RTCM) at early design stages. The model provided a clear description of how maximum mold pressure, injection times and final structures properties are trade-off. Chang et al. [11] investigated the effects of process variables, including injection pressure, mold opening distance, resin temperature, compression pressure, pre-heated mold temperature and cure temperature, on the quality of CRTM products by applying Taguchi’s method.

The objective of this study is to carry out an investigation for resin flow behavior in RI/CM filling process by numerical simulation. A gap is present between the fibrous preform and the upper mold in the model. The gap results in preferential flow path during injection. Therefore, the flows in the gap and in fibrous preform are treated separately in this article. Moreover, two modes of compression phase, either constant speed or clamping force, are discussed. The compression operation of constant force is difficult to implement numerically, and little information is available [8]. A numerical technique, body-fitted FEM, is used to deal with irregular front surface of resin and to calculate the other relative properties in the RI/CM mold filling process. Simulations are also applied in RTM for comparison purposes.

2. THEORY

In the present model a gap forms between the preform and the upper mold by mobile mold compacting the preform before filling process. The gap results in
preferential flow path since the flow resistance offered by the gap is much less than that by the fibrous preform. Thus, two types of filling mode, the resin flow in the gap and the resin penetrating into the fibrous preform, are investigated separately during the RI/CM filling process. The sketch is depicted in Figure 1. To simplify the problem, the assumption of the negligible amount of resin penetrating into the reinforcements is adopted during injection. For the resin flow in the small channel, the relevant governing equations, based on the Hele-Shaw flow model, under isothermal condition are

\[
\frac{\partial P}{\partial x} = \frac{\partial}{\partial z} \left( \mu \frac{\partial u}{\partial z} \right) \tag{1a}
\]

\[
\frac{\partial P}{\partial y} = \frac{\partial}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right) \tag{1b}
\]

where \( P, u \) and \( v \) represent pressure and resin velocities in the x and y directions, respectively, \( \mu \) is resin viscosity. A thickness-averaged continuity equation is applied.

\[
\frac{\partial}{\partial x} (hu) + \frac{\partial}{\partial y} (hv) = -\dot{h} \tag{2}
\]

where \( \bar{u} \) and \( \bar{v} \) are averaged velocities gapwisely for \( u \) and \( v \), correspondingly. \( h \) is the gap size and \( \dot{h} \) is the compression speed. Equation (2) can be applicable to both injection and compression phases. The compression speed is null during the injection phase.

By applying the no-slip boundary conditions in the channel flow, the gap-averaged velocities for \( u \) and \( v \) can be obtained

\[
-\bar{u} = -\left( \frac{h^2}{12} \right) \frac{1}{\mu} \frac{\partial P}{\partial x} \tag{3a}
\]

\[
-\bar{v} = -\left( \frac{h^2}{12} \right) \frac{1}{\mu} \frac{\partial P}{\partial y} \tag{3b}
\]

Equations (3) are in the same form as Darcy’s law. Therefore, the term of \( h^2/12 \) can be regarded as equivalent permeability of the gap. The inverse of permeability describes the resistance offered by a fibrous preform to the flow of fluid. The permeability of the gap is much larger than that of fibrous preform in the present study. It is reasonable to neglect the resin penetrating into fibrous preform during the period of resin flow in the gap.

Substituting Equations (3) into (2), the pressure equation can be obtained

\[
\frac{\partial}{\partial x} \left( -\frac{h^2}{12 \mu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left( -\frac{h^2}{12 \mu} \frac{\partial P}{\partial y} \right) = -\frac{\dot{h}}{h} \tag{4}
\]

For a rectangular mold cavity, the physical domain is symmetric for x, y-axis and only quarter of the cavity needs to be concerned in the numerical simulation. The corresponding boundary conditions applicable to Equation (4) are

\[
P = 0 \quad \text{along the flow front,} \tag{5a}
\]

\[
\frac{\partial P}{\partial n} = 0 \quad \text{along the center lines and solid side-wall,} \tag{5b}
\]

\[
P = P_{nj} \quad \text{or} \quad \frac{\partial P}{\partial n} = 0 \quad \text{at inlet gate,} \tag{5c}
\]

Equation (5a) shows that the gauge pressure is adopted in the numerical simulation.
Equation (5b) interprets the symmetrical condition along the center lines and no fluid flowing through solid side-wall. Equation (5c) represents a constant applied pressure at inlet gate during injection. After the necessary amount of resin is injected, the gate is closed and no resin is injected into the mold cavity. Thus the constant injection pressure is switched to null flow rate at the gate. The switch time \( t_s \) from injection to compression can be deduced by mass conservation.

\[
\int_0^{t_s} Q_{\text{inj}} \, dt = \phi A h_{\text{fiber}}
\]

where \( Q_{\text{inj}} \) is the resin injection flow rate. \( A \) is the area of the cavity. \( \phi \) and \( h_{\text{fiber}} \) are the porosity and height of the fibrous preform, respectively. The resin injection flow rate depends on the applied injection pressure.

Note that an excessively small gap can cause the incomplete filling in the RI/CM filling process, i.e. all the pores of fibrous preform can not be filled with the resin in the gap. An admissible minimum gap size \( h_{\text{min}} \) exists and can be expressed as below.

\[
A h_{\text{min}} = \phi A h_{\text{fiber}}
\]

As the compression phase initiates two modes of compression is considered, either constant speed or clamping force in this paper. For the case of constant clamping force, the numerical treatment is difficult due to variable compression speed. The clamping force is calculated by integrating fluid pressure across the wetted portion of the mold as follows.

\[
F_{\text{clamp}} = \int P(x, y) dA
\]

By numerically iterative predicted compression speed, the condition of constant clamping force can be achieved.

After the gap is fully filled with resin, the resin in the gap begins to be forced to penetrate into the fibrous preform by mobile mold. The process of resin penetration can be regarded as liquid flowing through the porous medium. Since the fibrous preform is pre-pressed, the preform is assumed no further deformation during the mold filling. A uniform compression process makes the resin flow be one-dimensional. The friction of the fluid flow in the gap is negligible compared to that in fibrous preform. Under the assumptions, the momentum equation of fluid flow is then described by Darcy's law as

\[
w = -\frac{K_z}{\phi \mu} \frac{dP}{dz}
\]

where \( w \) and \( K_z \) are the z-directional resin interstitial velocity and permeability of the fibrous preform, respectively. Combination of Equation (9) and mass equation yields

\[
\frac{d}{dz} \left( \frac{K_z}{\phi \mu} \frac{dP}{dz} \right) = 0
\]

The corresponding boundary conditions applicable to Equation (10) are

\[
P = P_{\text{comp}} \quad \text{along the mobile mold,} \quad (11a)
\]
\[
P = 0 \quad \text{along the flow front,} \quad (11b)
\]

Equation (11a) shows the compression pressure resulting from mold closing action. It is a function of filling time. Since the decreasing resin amount in the gap must be equal to the increasing resin amount in the preform, the relationship between the mobile mold velocity and resin interstitial velocity in the preform can be obtained as follows.

\[
\int \dot{h} \, Adt = \int (w \phi) Adt
\]

The term of \( (w \phi) \) is volume-averaged velocity defined in Darcy law.
4. RESULTS AND DISCUSSIONS

In the present study a constant pressure is taken as the injection condition, while either a constant closing speed or a constant clamping force is taken as the compression condition. The planar dimensions of rectangular cavity are 0.30 m × 0.20 m and the height is variable. The final cavity height is 0.006 m. The inlet gate locates at the center of the mold cavity and the radius of inlet gate is 0.01 m. The fiber volume fraction of desired product is 0.3, i.e., the porosity of the fibrous preform is 0.7. The planar permeability and z-directional permeability of random fiber mats (TGFM-300P/E) are 1.03×10^{-10} m^2 and 5.8×10^{-11} m^2 at the porosity of 0.7, respectively. The density and viscosity of the resin system (Araldite LY564 and hardener HY2962) are about 1105 kg/m^3 and 0.5 Pa-s in room temperature.

4.1 Case 1: Constant speed compression

Figures 4 show the flow front of the resin at various time during the mold filling process. As the mold is partially closed, a gap is formed between the fibrous preform and mold. This gap results in a preferential flow. Figure 4a shows the flow front progression in the gap. Before the fluid meets the side-wall, the fluid expands radially in the gap. During the stage the governing equations and boundary conditions can be rewritten in polar coordinate. The relation of radius of flow front versus filling time can be derived easily as below.

\[
\frac{12 \mu \rho_{\text{inj}}}{P_{\text{inj}} h^2} \left( \frac{1}{2} \right)^2 \ln \left( \frac{r}{r_{\text{inj}}} \right) + \frac{1}{4} \left( 1 - \left( \frac{r}{r_{\text{inj}}} \right)^2 \right) \]

(18)

where \( r_{\text{inj}} \) is the radius of the gate. The exact solutions of the Equation (18) are also denoted by dashed lines as shown in Figure 4a. Apparently the predictions of body-fitted FEM model are almost identical to the exact solutions. This offers a way to validate the program code. The switch time from injection to compression is about the filling time of 3.22 seconds. After that, no resin enters the mold cavity. The fluid continues advancing in the gap resulting from the mold closing action. Due to the confinement of the side walls the radial flow transforms into unidirectional flow gradually. The gap is fully filled with resin at the filling time of 12.23 seconds. At this time the gap height is equal to \( \phi h_{\text{fiber}} \) as Equation (7) states.

[Insert Figures 4 about here]

After the gap is fully filled with resin, the resin in the gap begins to penetrate into the fibrous preform due to the mold closing action. Figure 4b shows the resin impregnation front and the mobile mold position at various time during the filling process. For the sake of clear observation, the scale ratio of x-axis to z-axis is 1 to 5 in the plot. Since resin interstitial velocity is higher than mold compression speed, the resin front in the preform moves faster than mobile mold as Equation (12) describes. The final compression stage completes after a total of 34.01 seconds. By comparing figures 4a and 4b, the filling process of resin impregnating the fibrous preform is much slower than that of flow in the gap. The process of resin penetrating into fibrous preform can reduce with the high compression speed at the expense of mold clamping force.

The numerically predicted fluid pressure at the center of the mold and the total mold clamping force are plotted against filling time in Figure 5. During the injection phase a constant pressure of 689Pa (0.1 psi) is applied at the gate. After the required resin volume is injected in 3.22 seconds, a clear discontinuity in the central fluid pressure is present at the onset of compression because of the inlet condition switch.
After that, an approximately linear increase is found until the gap is fully filled with resin. This may be explained by the fact that the filling behavior is near unidirectional during the stage. When the resin in the gap begins to penetrate into the fibrous preform, a discontinuity in the central fluid pressure is present against due to the change of the filling pattern.

The clamping force is similar in variation to the central fluid pressure except injection phase. During injection two distinct increase tendencies are found due to the fact that transformation from the radial flow into the unidirectional flow leads to the different increment of the wetted portion of the mold. The clamping force rises to approximately 644 N at the completion of filling. Notice that the compression time is longer than the injection time even if the clamping force and central fluid pressure at the completion of compression are much greater than those during injection. This shows that the total mold filling time mainly depends on the duration of the compression phase. Precisely speaking, the results are caused by the low permeability of the fibrous preform. That is to say, the process of resin penetrating into fibrous preform is a key factor in RI/CM cyclic period and mold clamping force.