Unified saturation and micro-macro voids method in Liquid Composite Molding

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ABSTRACT: The topic of this paper concerns void defects. We introduce a model to describe the macroscopic resin flow considering the compression of residual air in the preform. A microscopic flow model is also developed to account for the microvoid formation due to the variation of resin velocity at the flow front. According to these mathematical models, a numerical simulation code was developed to perform a combined macro and micro flow analysis with the saturation of the medium. The results of these simulations are compared with experimental results obtained by the laboratory device. We present the real-time measurement of the void content evolutions during the injection, using an original sensor. Our technique is based on the electrical conductivity of the injected liquid. After the material and method presentation, some results obtained during injection are shown. The developed analysis technique and the numerical simulation code can be used for obtaining the optimal processing conditions and design parameters in manufacturing of composites by Liquid Composite Molding (LCM) processes.

Key words: Void defect, Air compression, Microvoid, Real-time measurement, LCM

1 INTRODUCTION

Liquid Composite Molding (LCM) processes, such as Resin Transfer Molding (RTM) and Vacumm Assisted Resin Transfer Molding (VARTM) are gaining their popularities for the manufacturing of large and complex parts in the aeronautic and aerospace industries, by virtue of their cost-effectiveness. In the case of LCM processes, however, the air can be entrapped in the part during the process, and this residual air results in the defects such as dry spots or microvoids that are, in turn, responsible for the degeneration of mechanical properties of the final product [1-8]. In general, most fabrics consist of fiber tows that are woven or stitched, and hence the microstructure of fabrics is non-uniform. Although the field of resin average velocity may be appear smooth, the local velocity can vary significantly, from point to point, at the micro scale. Due to the non-uniform microstructure, the local permeability and the local capillary pressure may differ by several orders of magnitude between inside and outside the tows. This leads to the non-uniform velocity field and, subsequently, the formation of air voids at the micro scale.

Given the fiber preform, the microvoid content has been known to largely depend on the capillary number, which is a dimensionless number to be defined as a ratio of viscous force to capillary force [9].

$$Ca^* = \frac{\mu v}{\gamma \cos\theta} \qquad (1)$$

If the global resin velocity is smaller than the capillary suction inside the fiber tows, microvoids are formed in the large channel between the fiber tows. On the contrary, microvoids are entrapped inside the fiber tows when the global resin velocity is greater than the capillary suction between the fiber bundles.

Once the microvoids are formed, they may be transported along the pressure gradient. In general, the void content is measure from the final part where the time evolutionary features of microvoid physics cannot be observed. To deal with this problem, we

developed a special sensor that measures the electrical conductivity of liquid which can be correlated with the void content.
In this study, we present mathematical models for the analysis of formation of macro and micro voids during the filling process. Then, these models are validated through the real-time experimental observation using the special sensors.

2 MACROSCOPIC FLOW MODEL

2.1 Resin flow model

We can derive the governing equation for resin flow combining Darcy's law into the mass conservation equation for incompressible fluid. Kempner et al. proposed a unified governing equation for thermoset composite manufacturing [10].

$$\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu}\frac{\partial P}{\partial x_j}\right) = -\frac{1}{V_f}\frac{\partial V_f}{\partial t} - \frac{1}{{V_f}^2}\frac{\partial V_f}{\partial x_i}v_i^f \qquad (2)$$

where V_f is the fiber volume fraction and v_i^f is the volume-averaged velocity of fibers.
Depending on the process characteristics, the above equation can be further simplified. In RTM (Resin Transfer Molding) process, the fiber volume fraction does not change since the fiber reinforcement is located between two rigid toolings during the mold filling process, and the fiber velocity is negligible.
Consequently, the governing equation becomes a Laplacian equation.

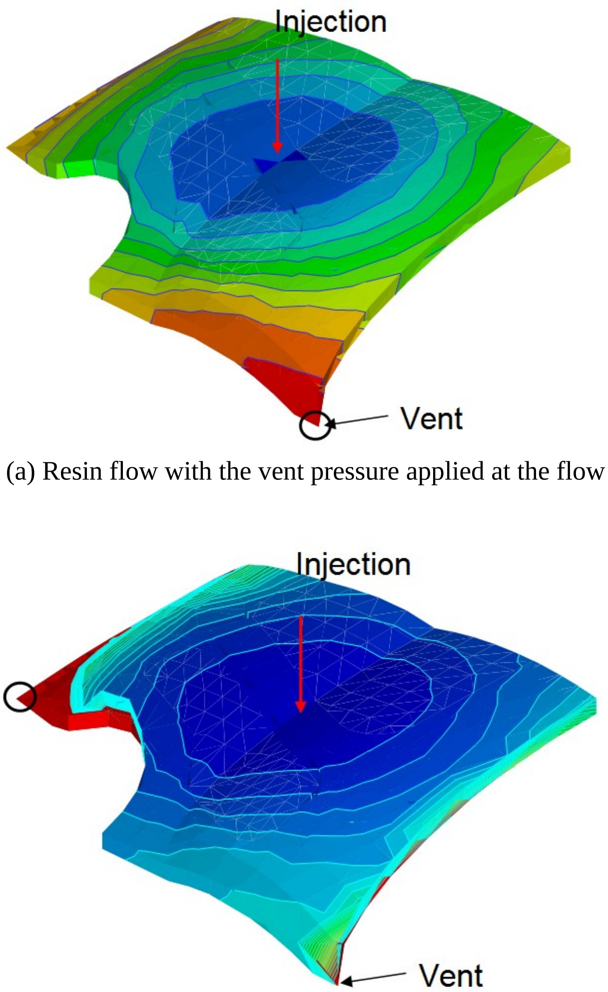
$$\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu}\frac{\partial P}{\partial x_j}\right) = 0 \qquad (3)$$

In VARTM (Vacuum Assisted Resin Transfer Molding) process, the fiber volume fraction change can not be ignored. Due to the flexibility of vacuum bag, the preform thickness changes as the resin pressure changes. As a result, the mold gap changes and fiber volume fraction also changes with time. However, the principal fiber movement is in transverse direction, in the case of thin structures. Hence, the planar fiber velocity can be ignored. Furthermore, the fiber volume fraction can be regarded to be uniform in the thickness direction, even though it changes with time. Consequently, the governing equation for VARTM process needs an additional term to consider the temporal change of fiber volume fraction.

$$\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu}\frac{\partial P}{\partial x_j}\right) = -\frac{1}{V_f}\frac{\partial V_f}{\partial t} \qquad (4)$$

2.2 Air compressibility and dry spot formation

To avoid dry spots, air vents are placed at the last fill points. In conventional mold filling processes, the air vent pressure is assigned at the flow front as a boundary condition. As the multiple flow fronts merge and the air is entrapped, however, the air may be compressed and the air pressure may increase. This phenomenon gives rise to a discrepancy in prediction of pressure distribution. The air bubbles interact with the global distribution of pressure in resin and hence the resin flow pattern as well.



(a) Resin flow with the vent pressure applied at the flow front

(b) Resin and air flow with the vent pressure applied at the air vent

Fig. 1 Mold filling simulations of automotive front panel

We can derive the equation relating the air flow to the changes in fiber volume fraction and pressure [11].

$$-\frac{1}{V_f}\frac{\partial V_f}{\partial t}+\frac{1-V_f}{P_a}\frac{\partial P_a}{\partial t}=\frac{K_{ij}}{\mu_a}\frac{\partial^2 P_a}{\partial x_i \partial x_j} \qquad (5)$$

where μ_a is the air viscosity. The second term on the left side is the result of the air being compressible.

The results of numerical simulation of mold filling of automobile front panel are illustrated in figure 1. The last fill point is indicated by a black solid circle. If the only resin flow is considered, the actual last fill point coincides with the air vent position. If the air flow as well as the resin flow is considered, however, the last fill point differs from the air vent position. In this case, as the air is entrapped at this region and is eventually compressed in the mold. Consequently, the mold may not be filled with the resin before the resin starts to gel, and there may remain dry spots in the final part.

3 MICROSCOPIC FLOW MODEL

3.1 Formation of microvoids at the flow front

The resin flows through a complicated network of micro pathways between fibers. This microscopic architecture can be represented by several shape factors. A mathematical model to predict the formation of air voids should be able to obtain the resin velocities within and between the fiber tows and to determine the air void contents. Using these velocities, the required for the resin front to advance a given distance (the cross-sectional distance of the fiber tows in the flow direction) can be estimated within and between fiber tows. The ratio of these two times is calculated as [11, 12]

$$\frac{\Delta t_{l_T,T}}{\Delta t_{l_T,C}}=\frac{F_{K,C}(\phi)d_C^{\ 2}}{F_{K,T}(\phi)d_T^{\ 2}}\times \left\{1-\frac{K(\theta)}{Ca^*}\frac{F_{C,T}}{d_T l_T}\log\left(1+\frac{Ca^*}{K(\theta)}\frac{d_T l_T}{F_{C,T}}\right)\right\} \qquad (6)$$

where $F_{K,C}(\phi)$, $F_{K,T}(\phi)$,and $F_{C,T}(\phi)$ are the shape factors. d_C is the average distance between the fiber filaments and d_C is the average distance between the fiber tows. $l_T(\theta)$ is the width of the tow cross section in different angles. $\Delta t_{l_T,T}$ and $\Delta t_{l_C,T}$ are the times required for the resin to travel the distance of $l_T(\theta)$ within and between the tows. In order to account for the anisotropic effect, the permeability K is given as the function of the orientation θ between the flow front and the fiber tows.

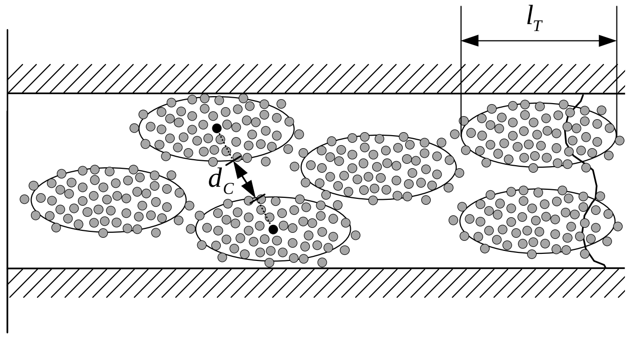


Fig. 2 Flow front of resin between fiber tows

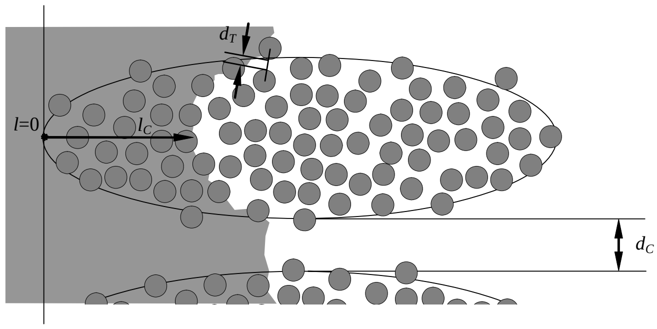


Fig. 3 Flow front of resin within a fiber tow

4 EXPERIMENTAL MEASUREMENTS

4.1 Sensors for void detection

We use the sensors made of two flat brass electrodes to measure the electrical conductivity of liquid. If the electrically-conductive liquid is injected into the mold and passes by the sensor location, the increase of voltage would be observed by the sensor. If the liquid contains non-conducting material, the voltage would drop. The air void can be considered as non-conducting material. Consequently, the voltage can be correlated with the void contents. For the given conductive liquid, the maximum voltage value is obtained. Then, the voltages are measured for given volumes of non-conducting materials in the liquid. In this work, glass beads were used as the non-conducting material for the sensor calibration.

4.2 Experimental results

A linear injection of conductive liquid into a glass fabric was performed. As a conductive liquid, aqueous solution of glycerine was used. The viscosity of the resin was 0.15 Pa·s and the surface tension was 31.7 mN/m. We used a bidirectional glass fabric of which fiber volume fraction is 0.58. Injection pressure was kept constant at 0.175 MPa. The length of rectangular mold was 530 mm. Four sensors are placed at the positions from the resin inlet port; 1*25 mm*, *273 mm*, *383 mm*, *430 mm*.

5 RESULTS AND DISCUSSION

The results of real time measurement of void contents is presented in figure 4. The void content is expressed in terms of degree of saturation. If the degree of saturation is a unity, the composite is free from air void.

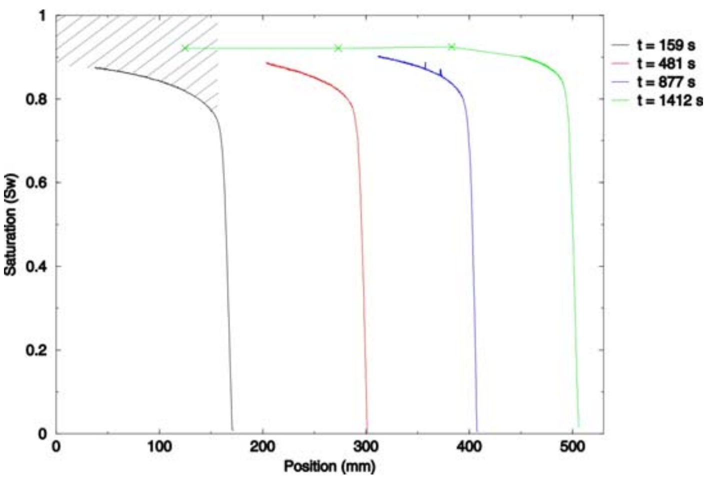


Fig. 4 Degree of saturation as a function of position

We can see that the voids are formed at the flow front and are reduced as the flow passes by. The void can be compressed or collapsed as the resin pressure around the void increases. Otherwise, the void can be transported along the resin flow. For an exact understanding of the physics about the formation and the transport of voids, consequently, the measurement of voids in the final part is not sufficient and the real time measurement of the void contents is essential.

6 CONCLUSIONS

We presented the mathematical models to predict the formation of macro-micro voids during the Liquid Composite Molding process. To validate the model, we also developed the real time sensors that measure the void contents. In the current study, the influence of saturation on the macro flow is not considered. As a future study, this effect (e.g. pressure drooping in the constant flow rate injection) will be taken into account in the mathematical model.

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