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RESIN TRANSFER MOLDING 공정에서의 기공 형성에 관한 3차원 모델링

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Three-Dimensional Modeling of Void Formation During Resin Transfer Molding

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Key Words : RTM, micro-void, capillary number, void transportation

Abstract

In resin transfer molding (RTM), resin is forced to flow through the fiber perform of inhomogeneous permeability. This inhomogeneity is responsible for the mismatch of resin velocity within and between the fiber tows. The capillary pressure of the fiber tows exacerbates the spatial variation of the resin velocity. The resulting microscopic perturbations of resin velocity at the flow front allow numerous air voids to form. In this study, a mathematical model was developed to predict the formation and migration of micro-voids during resin transfer molding. A transport equation was employed to account for the migration of voids between fiber tows. Incorporating the proposed model into a resin flow simulator, the volumetric content of micro-voids in the preform could be obtained during the simulation of resin impregnation.

1. INTRODUCTION

In a family of liquid composite molding processes including resin transfer molding, resin is injected into a fiber perform of non-uniform microstructure. The tortuous flow paths between fibers yield a severe mismatch of resin velocity within and between the tows of fiber, resulting in the formation of air voids on the micro scale [1-4]. The presence of micro-voids is known to degrade many properties of the fabricated composite part [5-13].

In the present study, a mathematical model was developed to describe the void formation resulting from a microscopically non-uniform velocity field at the resin flow front. Since the micro-voids are mobile during impregnation of the preform, especially in the pores between fiber tows, the model also accounts for the migration of micro-voids by solving a separate transport equation.

The compression of air in a dry spot may affect the initial pressure of micro-voids. The mass conservation equation for a compressible gas along with the ideal gas assumption was employed to simulate the pressure build-up in the dry spots. With a few model constants to be determined empirically, the proposed model and the simulation code can be used for predicting the void content in the composite products fabricated by liquid molding techniques.

2. TIME-RATIO MODEL

During liquid composite molding, the resin flows through a network of micro-conduits between fibers. This microscopic architecture of fibers can be represented by a few shape factors. A mathematical model to predict the formation of air void should be able to calculate the mismatch of resin velocities within and between the fiber tows to determine the size and the content of air voids. Using these velocities, the time required for the resin front to move a given distance (the cross-sectional distance of the fiber tows in the flow

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direction) can be estimated within and between tows, and the ratio of these times is calculated as follows [14].

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

where $F_{K,C}(\phi)$, $F_{K,T}(\phi)$, $F_{c,C}(\phi)$ and $F_{c,T}(\phi)$ are the shape factors. ϕ is the porosity of the fiber mat. d_C is the average distance between fiber filaments, and d_T is the average distance between tows. $l_T(\theta)$ is the width of tow cross section in different angles. $\Delta t_{l_T,T}$ and $\Delta t_{l_T,C}$ 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 functions of the angle θ between the flow front and the fiber tows.

3. MICRO-VOID TRANSPORT MODEL

Since the channels between the fiber tows are connected, the micro-voids in the channels can flow along with the resin. Assuming the resin-air mixture as a continuum and defining the mass fraction of air in the resin-air mixture, the transport equation for the micro-voids in channels can be written as follows.

$$\frac{\partial \varphi}{\partial t} + \nabla \cdot (\varphi \vec{u}_{\text{void}}) = 0 \quad (2)$$

where φ is the mass fraction of air in the resin-air mixture in the channels between fiber tows.

The velocity of voids is a function of resin velocity. It is observed from experiments that a micro-void is stagnant unless the velocity of the surrounding resin is lower than a critical value. Above the critical value, the velocity of an air void is a function of the resin velocity.

$$\vec{u}_{\text{void}} = \begin{cases} 0 & \text{if } \vec{u}_{\text{resin}} < \vec{u}_{\text{r.critical}} \\ C_1 \vec{u}_{\text{resin}} + C_2 & \text{if } \vec{u}_{\text{resin}} > \vec{u}_{\text{r.critical}} \end{cases} \quad (3)$$

In Eq. 3, the selection of $\vec{u}_{\text{void}}$ above a critical resin velocity $\vec{u}_{\text{r,critical}}$ was rather arbitrary, hence reminding that various forms of $\vec{u}_{\text{void}}$ can be used as long as they can represent the relation between the two velocities.

The boundary conditions are given as follows

$$\begin{aligned} \varphi &= \varphi_0 && \text{at the inlet} \\ \varphi &= \varphi_{F.F.}(\vec{u}_{\text{resin}}, p_{\text{air}}) && \text{at the flow front} \end{aligned} \quad (4)$$

where φ_0 is the initial void content in resin and $\varphi_{F.F}(V_{\text{resin}}, p_{\text{air}})$ is determined by the time ratio in Eq. 1 and given elsewhere [14].

4. PRESSURE BUILD-UP IN DRY SPOTS

The air in the dry spots is compressible during resin impregnation. Since the air pressure in a compressed dry spot affects the initial pressure of air in the micro-voids, a proper estimation of the pressure build-up in a dry spot is prerequisite in determining the accurate amount of air entrapped in the micro-voids formed at the boundary of the dry spot.

The mass conservation equation for air is given as follows.

$$\frac{\partial \rho_a}{\partial t} + \frac{\partial}{\partial x_i}(\rho_a u_{ai}) = \dot{m}_a \quad (5)$$

where $\dot{m}_a$ is the volumetric source of air that is added to the dry spot by the migration of micro-voids at the boundary of the dry spot.

$$\dot{m}_a = \int_{CS} \rho_a \varphi \vec{u}_{void} \cdot \vec{n} ds \quad (6)$$

According to Darcy' law, the air velocity can be written as follows.

$$u_{ai} = \frac{u_{ai,D}}{1 - V_f} = -\frac{1}{1 - V_f} \frac{K_{ij}}{\mu_a} \frac{\partial p_a}{\partial x_j} \quad (7)$$

Assuming the air as an ideal gas, the following equation of state can be used.

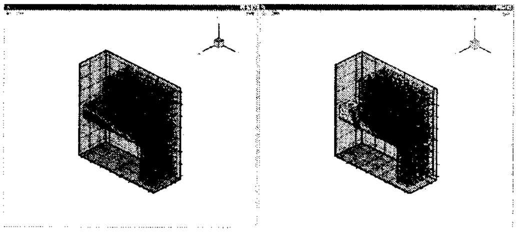
$$p_a = \rho_a RT \quad (8)$$

Combining Eqs. (5)~(8), it follows that

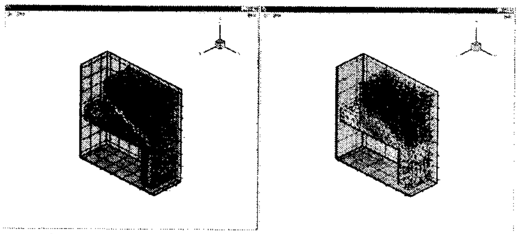
$$\frac{\partial \rho_a}{\partial t} - \frac{\partial}{\partial x_i}\left(\rho_a \frac{K_{ij}}{\mu_a} \frac{\partial p_a}{\partial x_j} \right) = \dot{m}_a \quad (9)$$

5. NUMERICAL RESULTS

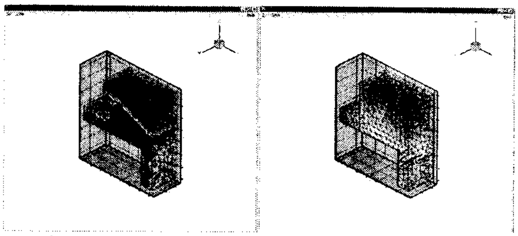
Numerical simulations were conducted to illustrate the capability of the proposed model and the develop simulation code. The numerical example in Figure 1 is for a cutout section of a composite part with a sacrificial layer of flow-facilitating medium on the bottom of the preform. The resin is injected from the left end, and the vacuum port was located a the lower end. As the mold filling proceeds, a dry spot is formed at the dead corner. The compression of air and the subsequent pressure build-up gives rise to a successive packing and bleeding of air in the dry spot. It is observed that a few cycles of the packing-and-bleeding take place before the completion of mold filling.


Flow Front Shape Pressure

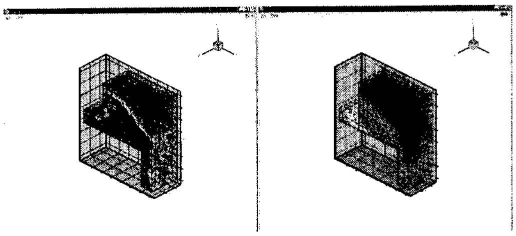
(a) t=9.2sec


Flow Front Shape Pressure

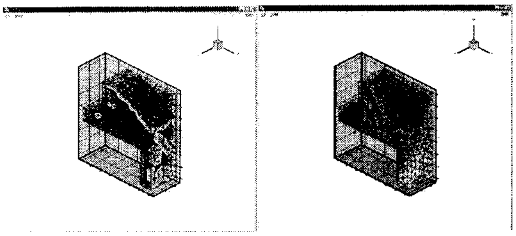
(b) t=21.3sec


Flow Front Shape Pressure

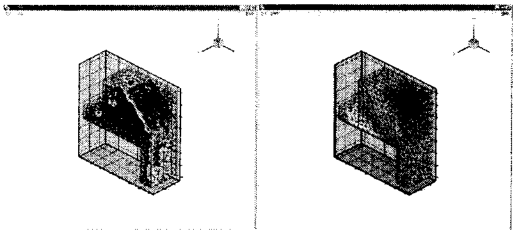
(c) t=29.2sec


Flow Front Shape Pressure

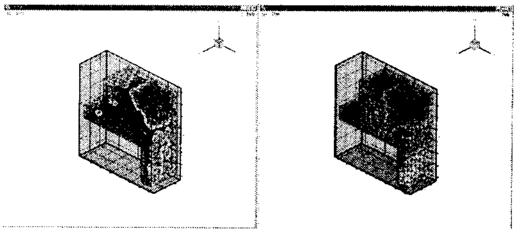
(d) t=36.4sec (first bleeding)


Flow Front Shape Pressure

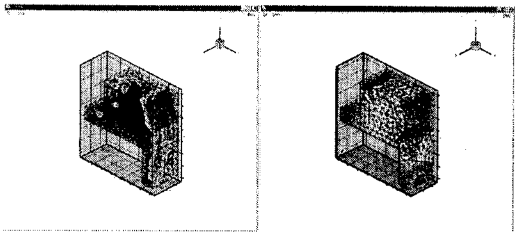
(e) t=43.8sec


Flow Front Shape Pressure

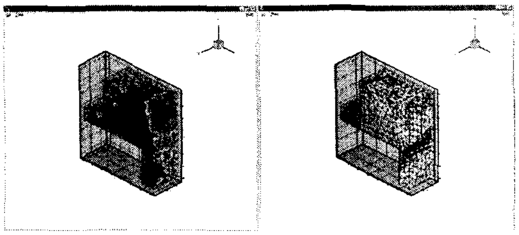
(f) t=49.1sec (second bleeding)


Flow Front Shape Pressure

(g) t=54.5sec


Flow Front Shape Pressure

(h) t=60.9sec (third bleeding)

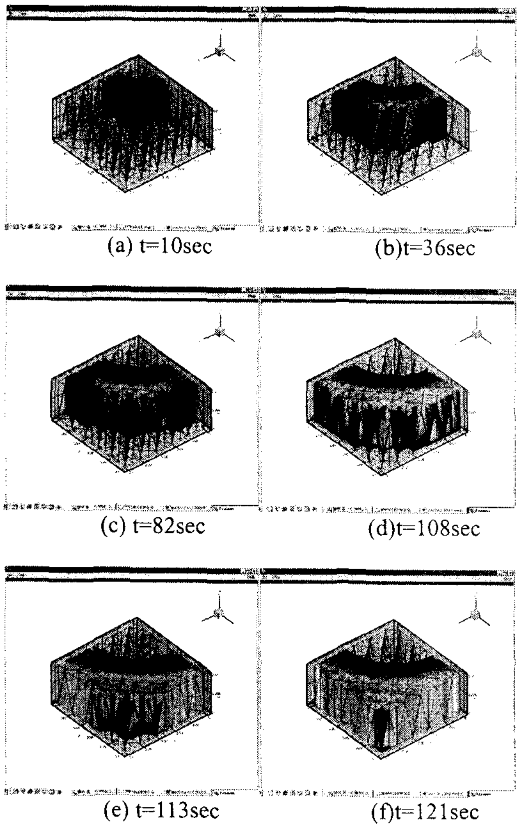


Flow Front Shape Pressure

(g)=67.2sec

Figure 1 Simulation of Resin Flow Considering the Compression of Air in the Dry Spots

In Figure 2 with a second numerical example for a simpler mold shape, the simulated volumetric content of micro-voids is illustrated. Resin is injected at one corner of a square block and evacuated at the diagonal corner to avoid a dry spot. The shaded plot is for the distribution of void content and shows the formation of micro-void at the flow front and their migration along with the resin flow.



(a) t=10sec (b)t=36sec

(c) t=82sec (d)t=108sec

(e) t=113sec (f)t=121sec

Figure 2 Volumetric Content of Air in the Resin-Air Mixture During Impregnation (void content in the channels between fiber tows)

6. CONCLUSION

A mathematical model was developed to analyze the formation and migration of micro-voids in resin transfer molding process. The model recognizes the mismatch of the resin velocity within and between the fiber tows resulting from inhomogeneous microstructure of fiber performs. A transport equation is introduced to solve for the effect of void migration along with the resin flow during impregnation. Also, the build-up of air pressure in the dry spots is taken into account by solving a separate equation for air during the resin flow simulation. The proposed model incorporated in a resin-flow simulator suggests some trends that are intuitively reasonable, and is expected to be useful when used with proper calibration of the model constants by experiments.

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