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FACTORS AFFECTING THE AIR VOIDS IN VACUUM ASSISTED IMPREGNATION OF FIBERS USING FLOW-FACILITATING MEDIUM

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SUMMARY: In vacuum-assisted resin transfer molding, part of the air under the vacuum bag remain in the preform, either as visible dry spots or as smaller voids distributed over the article under fabrication. The flow-facilitating medium on top of the preform is also responsible for the capture of air due to the stratification of flow between the different media. The major factors affecting the air void in a vacuum-assisted liquid-molded product are the vacuum pressure, degassing quality of the resin supplied, the fiber texture, the permeability ratio between the fiber and the flow-facilitating medium, the mold shape, the topological design of the harness of inlets/outlets, etc. Although some still remain uncharted, these are the key factors affecting the size and population of the air voids in the product. A parametric investigation was conducted numerically in order to identify the effects of each factor and/or the combinations of the factors. The mathematical model developed in this study considering the above aspects of air voids during fabrication can be used to locate the optimal processing conditions and trade-offs in the design and manufacturing of vacuum-assisted liquid-molded composite products.

KEYWORDS: Vacuum Assisted Resin Transfer Molding, Dry Spots, Microvoids, Capillarity

INTRODUCTION

Resin transfer molding (RTM) is a cost-efficient method for manufacturing composite parts of complicated shapes. Since it is difficult to build a closed mold for large structures, however, one major problem in applying RTM process to large structures is the tooling. Vacuum assisted resin transfer molding (VARTM) as an alternative engages an open mold to house the part under fabrication that is sealed along the edge of a flexible vacuum bag. Resin is introduced into the preform from the inlet gates at the ambient pressure. Since the maximum inlet pressure is limited to 1atm, the impregnation process is noticeably slow. A sacrificial medium is used on top of the fiber preform in order to facilitate the resin flow. A harness of distributed inlets and vents, such as Resin Distribution Lines (RDL) and Vacuum Distribution Lines (VDL), are usually preferred to matrices of point inlets or point vents.

The vacuum pressure is a decisive factor that determines the amount of air entrapped in the pores of fiber preform. The residual air results in the defects such as dry spots or micro-voids that are in turn responsible for the degradation of mechanical properties of the product [1-8]. The spatial variation of resin pressure inside the vacuum bag during resin infiltration may result in a non-uniform fiber volume fraction [9]. Although the average velocity field of the resin may appear smooth, the local velocity can vary considerably from point to point at the micro scale. The reason is that the fiber preform has a non-uniform microstructure, and hence its local permeability and the local capillary pressure may differ by several orders of magnitude between inside and outside fiber tows. This non-uniform velocity field leads to the formation of air voids on the micro scale [10-12].

The void content in a given fiber preform is known to largely depend on the capillary number, which is defined as the ratio of viscous force to capillary force [13-18]. In addition to the initial air in the pores of fiber preform, microvoids come from various sources including the mixed-in air in resin through the inlet, the volatile substances contained in resin, etc. The initial void contained in the resin supplied from the inlet is identifiable since they are rapidly blown up near the flow front to form a narrow band of foamy region along the flow front. Some portion of the distributed voids - especially those in the channel between fiber tows - are mobile and hence will flow along with the resin, even faster than resin occasionally.

On the macroscopic scale, the air voids interact with the global distribution of pressure in resin and hence the resin flow pattern as well. The flow-facilitating medium on top of the preform is also responsible for the capture of air due to the stratification of flow between the different media.

The major factors affecting the air void in a VARTM product are the vacuum pressure, degassing quality of the resin supplied, the fiber texture, the permeability ratio between the fiber and the flow-facilitating medium, the mold shape, the topological design of the harness of inlets/outlets, etc. Although some still remain uncharted, these are the key factors affecting the size and population of the air voids in the product. Among the above listed, the vacuum pressure plays a dominant role on the size of the residual dry spot. It is also observed that for moderate vacuum pressures, a dry spot is likely to undergo a few distinguishable cycles of packing and bleeding in succession.

In this study, a unified macro- and microanalysis method was established to account for the above issues in VARTM process. Mathematical models were introduced to describe the macroscopic resin flow considering the compression of residual air in the preform. Microscopic flow model was also developed to account for the void formation due to the variation of resin velocity at the flow front. Since the microvoids can flow along with the surrounding resin during mold filling, the model also accounts for the mobility of the microvoids. According to these mathematical models, a numerical simulation code was written to perform a combined macro- and micro flow analysis. The analysis technique and the numerical simulation code developed in this study can be used for locating the optimal processing conditions and design parameters in manufacturing of composites by VARTM.

MACROSCOPIC FLOW MODEL

Mass-Momentum Balance

In the vacuum-assisted infiltration of resin in process, resin is infused under vacuum into the fiber preform that is semi-constrained. The article under fabrication is bounded by the solid surface of the mold on the skin side, while it is consolidated at the ambient pressure against a flexible membrane on the reverse side. The following model describes the combined mass and momentum balance between the resin and the deformable fibers [19, 20]

$$-\frac{1}{V_f}\frac{\partial V_f}{\partial t}-\frac{1}{V_f}\frac{\partial V_f}{\partial x_i}v_i^f=\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu_r}\frac{\partial p}{\partial x_j}\right) \tag{1}$$

where V_f is the fiber volume fraction, v_i^f is the velocity of fibers, p is the resin pressure, μ_r is the resin viscosity, and K_{ij} is the permeability tensor of the anisotropic fiber preform. When high permeability layers are used over the fiber preform, an effective permeability tensor is used for K_{ij}. Subscripts i and j are the direction indices.

Since the resin flow is slow and the preform deformation is negligible in the planar directions, the in-plane fiber velocities can be neglected. A VBRTM part is usually thin compared to its planar dimensions, and the resin pressure and fiber volume fraction are assumed to be uniform through the thickness, that is;

$$\begin{gathered} v_x^f \approx 0 \\ v_y^f \approx 0 \\ \frac{\partial V_f}{\partial z} \approx 0 \end{gathered} \tag{2}$$

The assumptions in Eq. (2) simplify Eq. (1) as follows.

$$-\frac{1}{V_f}\frac{\partial V_f}{\partial t}=\frac{\partial}{\partial x_i}\left(\frac{K_{ij}}{\mu_r}\frac{\partial p}{\partial x_j}\right) \tag{3}$$

where indices i and j now denote x and y directions only, not the thickness direction z.

Since the vacuum bag is flexible, ambient pressure is balanced by the fiber deformation stress and the pressure of resin or residual air. The thickness and hence the fiber volume fraction of the preform are not uniform in the plane because of the variation of pressure. The Carman-Kozeny equation is used to describe the permeability at an arbitrary fiber volume fraction [21]:

$$K_{ij}=\frac{d_f^2}{16k_{ij}}\frac{\left(1-V_f\right)^3}{V_f^2} \tag{4}$$

where d_f is the fiber diameter and k_{ij} are constants.

The relation between the fiber compaction pressure σ and the fiber volume fraction is proposed as

$$\sigma = A\left[\exp\left(\lambda \frac{V_f}{V_{f,0}}\right) - \exp(\lambda)\right] \tag{5}$$

where $V_{f,0}$ is the fiber volume fraction at zero compaction pressure, and A and λ are model constants. Eq. 5 is a modified version of the simple exponential model to satisfy the zero-fiber-compaction-stress condition at the inlet gate where $V_f = V_{f,0}$. If the fiber-swell is negligible, the left hand side of Eq. 3 can be set to zero and the compaction model in Eq. 5 becomes irrelevant.

The equation relating the airflow to the changes in fiber volume fraction and pressure can be derived following the same procedure as for Eq. (3). The result is given as follows.

$$-\frac{1}{V_f}\frac{\partial V_f}{\partial t} + \frac{1-V_f}{p_a}\frac{\partial p_a}{\partial t} = \frac{K_{ij}}{\mu_a}\frac{\partial^2 p_a}{\partial x_i \partial x_j} \tag{6}$$

where μ_a is the air viscosity.

The pressure distribution and the subsequent resin flow inside the vacuum bag can now be calculated by using Eq. (3) for the resin-impregnated area and Eq. (6) for the dry area.

The solution to Eqs.(1)~(6) provides the resin front location and the pressure, temperature and degree of cure distributions as functions of time. As the equations are coupled and the geometry is usually complicated, numerical method must be employed. In this study, CVFEM was used for its efficiency in handling the moving flow front.

MICROSCOPIC FLOW MODEL

Formation of Microvoids at the Flow Front

The resin flows through a complicated network of micro-conduits between fibers. This microscopic architecture can be represented by a few shape factors. A mathematical model to predict the formation of air void should be able to calculate the resin velocities within and between the tows and 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 direction) can be estimated within and between tows, and the ratio of these times is calculated as follows [22].

$$\frac{\Delta t_{l_T,T}}{\Delta t_{l_T,C}} = \frac{F_{K,C}(\phi) d_C^2}{F_{K,T}(\phi) d_T^2}\left\{1 - \frac{K(\theta)}{Ca^*}\frac{F_{c,T}(\phi)}{d_T l_T(\theta)}\log\left(1 + \frac{Ca^*}{K(\theta)}\frac{d_T l_T(\theta)}{F_{c,T}(\phi)}\right)\right\} \tag{7}$$

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.

Transport of Microvoids in the Resin-impregnated Region

The micro-void transport equation for channel voids can be written as follows.

$$\frac{\partial \varphi}{\partial t} + \nabla \cdot (\varphi \vec{u}_v) = \dot{S} \tag{8}$$
$$\vec{u}_\mathrm{v} = F_u \cdot \vec{u}_\mathrm{r}$$

$\dot{S}$ = volumetric source of air added to the channel-void fraction from tow-voids squeezed out, evaporation of volatile substances, etc.

where $\overset{\rho}{u}_v$ is the microvoid velocity and φ is the void content in channels

The boundary condition for the above equation is given as follows:

$$\text{B.C.} \quad \begin{aligned} &\varphi = \varphi_0 \ \text{ at the inlet} \\ &\varphi = \varphi_{\mathrm{F.F.}}(u_\mathrm{r},\ P_\mathrm{a}) \qquad \text{at the flow front} \end{aligned} \tag{9}$$

When the microvoids are added to the macrovoids, the global pressure equation is affected by the amount of added air from the microvoids in channels.

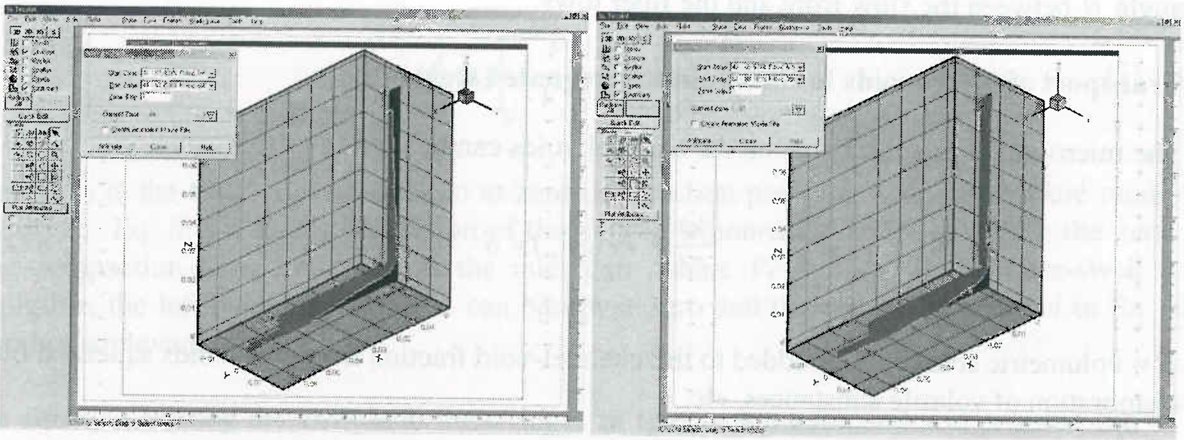
$$\frac{\partial \rho_a}{\partial t} - \nabla \cdot \left(\rho_a \frac{K}{\mu} \nabla P_a \right) = \dot{m}_a \tag{10}$$
$$\dot{m}_a = \int_{CS} \rho_a \varphi \vec{u}_\mathrm{v} \cdot \vec{n} ds \qquad \text{at the boundary of macro-voids}$$

NUMERICAL RESULTS

The following is the simulation result for the resin flow during VARTM process considering the macro- and the microvoids. The inlet void content was 1.5% by vol. at 1.0atm (about 5% at the local inlet), and the vacuum pressure was 0.3atm. The final size of the macrovoid was about 6% of the total volume. The small bubbles dangling on the vertical wall is the air that was bled by the large dry spot. Figure 1a shows the flow front locations at t=650s and t=3,883s. Figure 1b is the map of pressure in resin and Figure 1c is for the volumetric content of voids in resin.

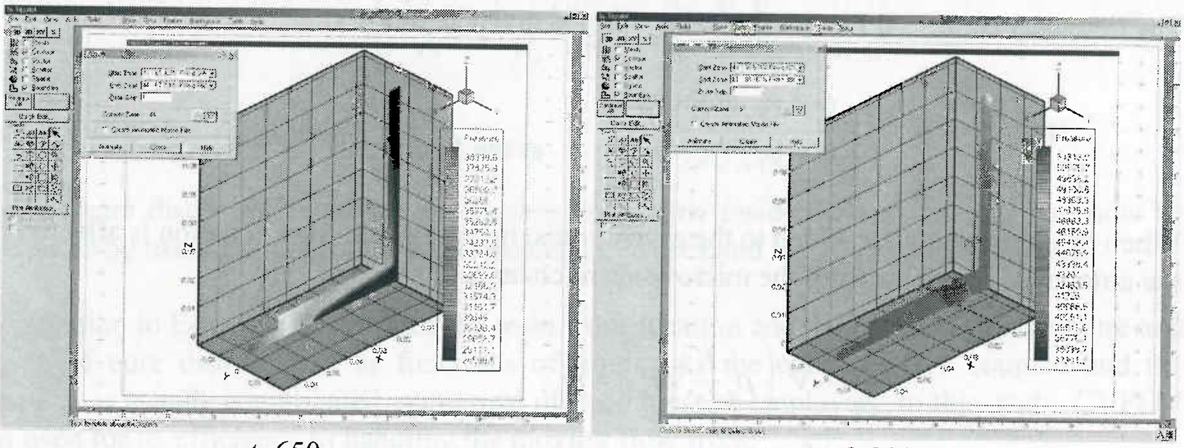
CONCLUSIONS

A unified macro- and microanalysis method was established to analyze the VARTM process. Mathematical models were introduced to describe the macroscopic resin flow considering the compression of residual air in the preform. Microscopic flow model was also developed to account for the formation and migration of microvoids. A numerical simulation code was written to perform a combined macro- and micro flow analysis. The developed analysis technique and the numerical simulation code can be used to obtain the optimal processing conditions and design parameters.



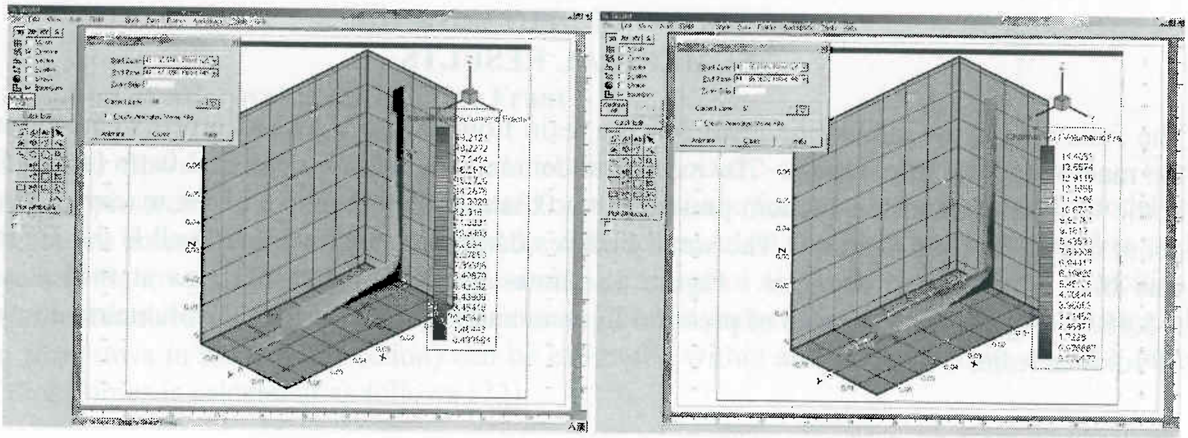
t=650s *t*=3,883s

(a) Flow Front Location



t=650s *t*=3,883s

(b) Pressure



t=650s *t*=3,883s

(c) Content of Microvoids

Figure 1 Simulation of Macro- and Microvoids Considering the Preferential Flow through the Flow Facilitation Medium on Top of the Fiber Preform

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