論文

Vacuum Assisted Resin Transfer Molding 공정에서의 Microvoids 형성과 이동에 관한 연구

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Experimental Study of the Microvoids Formation and Transport in the Vacuum Assisted Resin Transfer Molding Process

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Abstract

In RTM process, the content of microvoids can be critical due to the fact that the presence of microvoids degrades mechanical properties on the fabricated composite parts. The present paper proposes an experimental method of observation in void formation and transport. VARTM processes are performed under observation with a digital video camera and then the microvoid formation in the flow front and transport are videotaped and observed both in channels and tows. The obtained data are used in the mathematical model in order to determine the model constants. Experimental results and expected results from the mathematical model show a good agreement with each other.

초 록

RTM 공정에 의하여 생성된 제품은 microvoids의 함유량에 의하여 기계적인 물성치에 큰 영향을 받는다. 본 연구에서는 이러한 microvoid의 형성과 이동을 실험적으로 관찰할 수 있는 방법을 제시하였다. Vacuum assisted RTM 공정에서 유동선단에서의 microvoid의 형성과 이동을 DV camera로써 관찰을 한 후, 그것에서 void의 함유량을 구하고, 실험에서 얻어진 결과로 microvoid model에 필요한 factor들을 얻어낼 수 있었다. 이렇게 하여 얻어진 결과를 다시 실험적인 결과와 비교함으로써 서로 일치하는 결과를 얻어낼 수 있었다. 이번 연구에서 얻어진 결과를 수학적인 모델에 대입함으로써 VARTM 공정 중 microvoid의 함유량을 예측할 수 있다.

Key Words : 마이크로보이드(microvoid), 진공어시스티드 알티엠(vacuum assisted resin transfer molding, VARTM), 모세관넘버(capillary number), 보이드 이동(void transport)

Nomenclature

Ca : Capillary number

U_c : Resin velocity in channel

U_t : Resin velocity within tows

d_c : Average channel width

d_t : Distance between fibers

l_t : Tow width

$F_{K,C}(\phi)$: Shape factor(porosity, channel)

$F_{K,T}(\phi)$: Shape factor(porosity, tow)

$F_{c,T}(\phi)$: Shape factor(capillary pressure)

$\Pi_C(\phi)$: Probability factor(void formation, channel)

$\Pi_T(\phi)$: Probability factor(void formation, tow)

$K(\phi)$: Macroscopic permeability of the fiber preform

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1. Introduction

Resin transfer molding(RTM) is a cost-efficient method of 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 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.

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 microvoids that are in turn responsible for the degradation of mechanical properties of the product. 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. These microvoids may cause severe degradation of quality and strength.

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 is found to play 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 microanalysis method was used for the above issues in VARTM process. Microscopic flow model was used 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. An experimental method of observation in void formation and transport is proposed. VARTM processes are performed under observation of a digital video camera and then the microvoid formation in the flow front is videotaped and observed both in channels and tows. The obtained data are used in the mathematical model in order to determine the model constants.

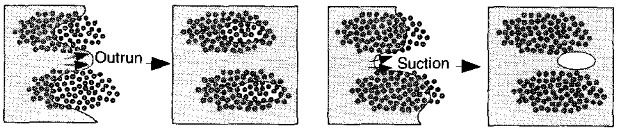
The developed analysis technique can be used for locating the optimal processing conditions and design parameters in manufacturing of composites by VARTM.

2. Microscopic Flow Model

2.1 Resin Flow Within and Between Tows

Typical preforms used in VARTM consist of fiber tows of random or regular textures with highly non-uniform micro architectures. Between tows are channels, through which the resin can flow rather easily, and hence the effective permeability is high. The local permeability within a tow, on the other hand, is low because of the presence of fibers. However, the capillary pressure within the tow is much larger than between the tows. The effects of local variation of permeability and the capillary pressure compete with each other, and the resulting local resin velocity depends on both factors.

In the case of a high resin velocity, voids will form within fiber tows because the flow in the channel is faster than in the tow due to the high permeability of the channel, Figure 1a. For a low resin velocity, however, the capillary flow will dominate within tows and hence voids will form in the channels between tows, Fig. 1(b).



(a) High resin velocity (b) Low resin velocity

Fig. 1 Void formation within and between fiber tows.

The resin velocity in the channel, u_C, can be approximated as

$$u_C = -F_{K,C}(\phi)\frac{d_C^2}{\mu}\frac{dP}{dn} \tag{1}$$

where $F_{K,C}(\phi)$ is a shape factor dependent on the porosity ϕ, d_C is the average channel width, and is the resin viscosity. Subscript C stands for 'channel' and subscript K

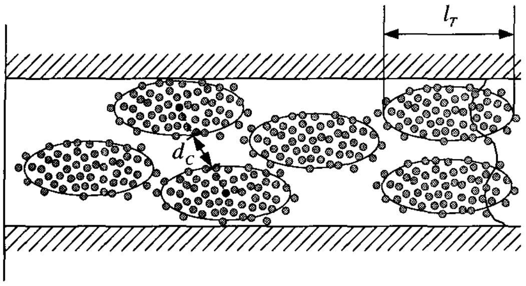


Fig. 2 Flow front of resin in the channel between fiber tows.

denotes the local permeability. μ is the normal gradient of pressure at the flow front. It has been assumed that the capillary pressure *dP/dn* is negligible in the channel because the channel width is much larger than the inter-fiber spacing within the tow.

The time $\Delta t_{l_T,C}$ required for the flow front within the channel to traverse the tow width l_T (see Fig. 2) can be approximated by

$$\Delta t_{l_T,C} \approx -\frac{l_T}{F_{K,C}(\phi)\frac{d_C^2}{\mu}\frac{dP}{dn}} \tag{2}$$

Note that the global pressure gradient, since it is an approximation within short range, is assumed to remain constant, when the flow front moves the small distance l_T.

For the flow within a tow, the capillary pressure is considerably higher because of the small gap size d_T between fibers. Using a shape factor $F_{K,C}(\phi)$, one can express the capillary pressure as

$$P_{c,T} = \frac{F_{c,T}(\phi)\gamma\cos\theta}{d_T} \tag{3}$$

Here γ is the surface tension of the resin and θ is the contact angle. In the equation (3), $P_{c,T}$ is assumed as a constant since $\gamma\cos\theta$ represents resin property, d_T represents average property within tow, and $F_{c,T}(\phi)$ is a shape factor representing capillary pressure dependent on the porosity ϕ. Here, the contact angle θ has an effect on the resin velocity - as the contact angle increases, capillary pressure decreases, resulting the velocity decrease. Subscript *T* stands for 'tow' and subscript *c* (in lower case) denotes 'capillarity'. Thus the resin velocity u_T within the tow is given by

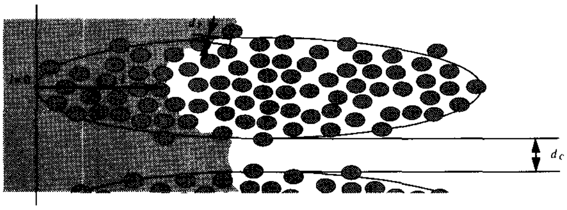


Fig. 3 Flow front of resin within a tow.

$$u_T = \frac{dl}{dt} = -F_{K,T}(\phi)\frac{d_T^2}{\mu}\left(\frac{dP}{dn} - \frac{P_{c,T}}{l}\right) \tag{4}$$

where l is the distance from the wet edge of the tow cross-section to the flow front, and $F_{K,T}(\phi)$ is a shape factor for the tow permeability. Since the direction of macro flow by resin pressure gradient is opposite to the capillary suction, $P_{c,T}/l$ is subtracted from the normal gradient of pressure at the flow front.

The time $\Delta t_{l_T,T}$ required for the flow front within a tow to traverse the tow width is then obtained by integrating Eq. 4 and using the conditions of $\Delta t = 0$ at $l = 0$ and $\Delta t = \Delta t_{l_T,T}$ at $l = l_T$.

$$\Delta t_{l_T,T} = -\frac{l_T}{F_{K,T}(\phi)\frac{d_T^2}{\mu}\frac{dP}{dn}}\left\{1 + \frac{P_{c,T}/l_T}{dP/dn}\ln\left(1 - \frac{dP/dn}{P_{c,T}/l_T}\right)\right\} \tag{5}$$

Dividing Eq. 5 by Eq. 2, the time ratio $\Delta t_{l_T,T}/\Delta t_{l_T,C}$ is given by

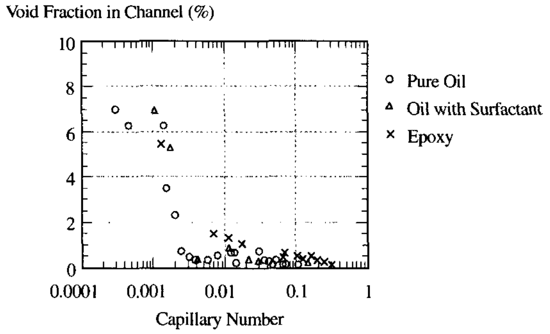
$$\frac{\Delta t_{l_T,T}}{\Delta t_{l_T,C}} = \frac{F_{K,C}(\phi)d_C^2}{F_{K,T}(\phi)d_T^2}\left[1 + \frac{P_{c,T}/l_T}{dP/dn}\ln\left(1 - \frac{dP/dn}{P_{c,T}/l_T}\right)\right] \tag{6}$$

The ratio of the viscous force to the capillary force is defined as the capillary number:

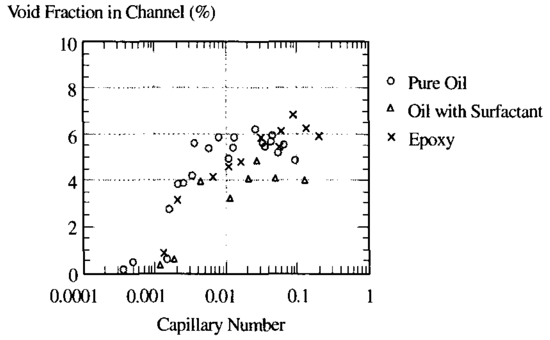
$$Ca = \frac{\mu v}{\gamma} \tag{7}$$

where v is the global (macroscopic) resin velocity. A modified capillary number to account for the effect of contact angle θ between fiber and resin is defined as:

$$Ca^* = \frac{\mu v}{\gamma\cos\theta} \tag{8}$$



(a) Void fraction in channels, Chen et al.(1995)



(b) Void fraction in tows, Chen et al.(1995)

Fig. 4 Void content as a function of Ca.

The global resin velocity is related to the global pressure gradient through the Darcy's law:

$$v = -\frac{K(\phi)}{\mu}\frac{dP}{dn} \tag{9}$$

where $K(\phi)$ is the macroscopic permeability of the fiber preform as a function of porosity.

Then the time ratio as a function of the capillary number is:

$$\frac{\Delta t_{l_T,T}}{\Delta t_{l_T,C}} = \frac{F_{K,C}(\phi)d_C^2}{F_{K,T}(\phi)d_T^2}\left\{1-\frac{K(\phi)}{Ca^*}\frac{F_{c,T}(\phi)}{d_T l_T}\ln\left(1+\frac{Ca^*}{K(\phi)}\frac{d_T l_T}{F_{c,T}(\phi)}\right)\right\} \tag{10}$$

Here $F_{K,C}(\phi)$, $F_{K,T}(\phi)$, $F_{c,T}(\phi)$, $K(\phi)$, d_T and l_T are properties of the fiber preform only, independent of the injected fluid. Therefore, it is concluded from Eq. 10 that the time ratio remains constant for different fluids and processing conditions as long as the capillary number is kept the same. The time ratio describes the competition between the intra-tow and inter-tow flow fronts.

The model agrees with the experimental results by Chen et al., which show the void content to be a function of the capillary number only, Fig. 4(a) and 4(b).

2.2 Number of Voids

The maximum number of voids per unit volume is determined by the microstructure of the fiber preform. Regarding the group of voids in a channel or a tow as a single void of larger equivalent size, the maximum number of voids per unit volume could be the same as the number of tows N_T or the number of channels N_C at most. Furthermore, it is assumed that the void density N_v is related to the time ratio as follows:

$$N_{v,C} = \Pi_C(\phi)\left(\frac{\Delta t_{l_T,C}}{\Delta t_{l_T,T}} - 1\right)N_C \,,\; \frac{\Delta t_{l_T,T}}{\Delta t_{l_T,C}} < 1 \tag{11}$$

$$N_{v,T} = \Pi_C(\phi)\left(\frac{\Delta t_{l_T,T}}{\Delta t_{l_T,C}} - 1\right)N_T \,,\; \frac{\Delta t_{l_T,T}}{\Delta t_{l_T,C}} > 1 \tag{12}$$

Here, as before, subscripts C and T denote channel and tow, respectively. $\Pi_C(\phi)$ and $\Pi_T(\phi)$ are probability factors of void formation to be determined experimentally.

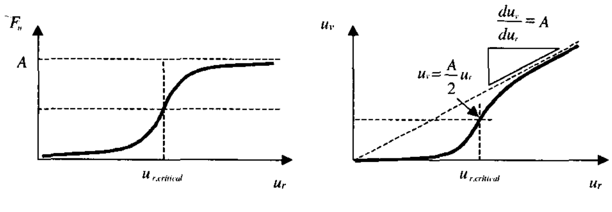
2.3 Transport of Microvoids

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

$$\vec{u}_v = F_u \cdot \vec{u}_r \tag{13}$$

where $\vec{u}_v$ is the microvoid velocity

$$F_u = \begin{cases} A\left(1-\frac{1}{2}e^{k(u_{crit}-u_r)}\right), & u_r \ge u_{r,critical} \\ \frac{A}{2}e^{k(u_{crit}-u_r)}, & u_r < u_{r,critical} \end{cases}$$



Exponential relation

Fig. 5 Relation between the microvoid velocity and the resin velocity.

where F_u is a shape factor for the resin velocity. Model factors u_{crit}, A, and k are to be determined by experiments.

$$\text{B.C.}\quad \begin{array}{ll} \varphi = \varphi_0 \ \text{at the inlet} & \\ \varphi = \varphi_{\text{F.F.}}\left(u_r,\ P_a\right) & \text{at the flow front} \end{array} \qquad (14)$$

The critical resin velocity, $\vec{u}_{r.critical}$ will decide what portion of the void content will migrate with the resin or stay in the pits between fiber tows.

3. Experiments and Results

Experiments were performed in order to obtain the model constants, void fraction during the process, and to obtain the factors for the void transport model. Diesel engine oil (10W-30, LG-Caltex) was used for the fluid and the density of fiber was 580 g/m^2. The mold cavity was 360mm long and 30 mm wide, and 0.5 mm thick.

The resin had a viscosity of 0.101 Pa·s and surface tension of 0.029 N/m at an ambient temperature of 15°C. A vacuum pump was used to create the pressure difference between the inlet and the outlet. Two different vacuum pressures were applied. 88000 Pa of pressure was set for the tow void experiment and 7332 Pa was for the channel void. Single layer of fiber was used, in order to obtain a better observation on the flow front. Fiber volume fraction was 46%.

Unlike the ordinary methods of observing voids, examining the ground cured-specimen with microscope, flow front was videotaped and then observed. This way, direct observation of void formation was achieved. Moreover, one can see the void forming while it is in progress, rather than after all the processes are done. For the void fraction measurements, the shape of voids is assumed as ellipsoid. In each video frame, completed processes are videotaped and captured still-frames are observed to measure the remaining void sizes. The thickness of voids is assumed to be the same thickness to that of the fiber layer. Void fraction was measured in tows (Fig. 6) and channels (Fig. 7), and numbers of voids were counted in both channel and tow.

Transport of voids was examined by measuring the velocity of voids in various velocities of resin. In order to measure the void transport velocity, the resin-filling process was videotaped and each transporting void is observed and timed in slow frames. Important factors, such as u_{crit}, A, and k, were determined (Fig. 8). And then the void fraction was measured again considering the effect of void transport (Fig. 9).

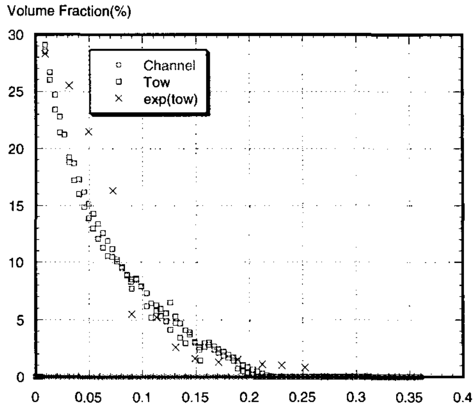


Fig. 6 Void fraction in tow.

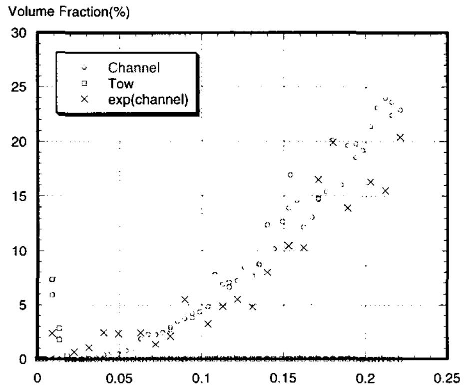


Fig. 7 Void fraction in channel.

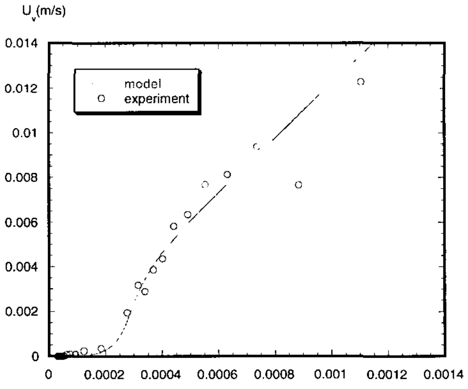


Fig. 8 Void Transport.

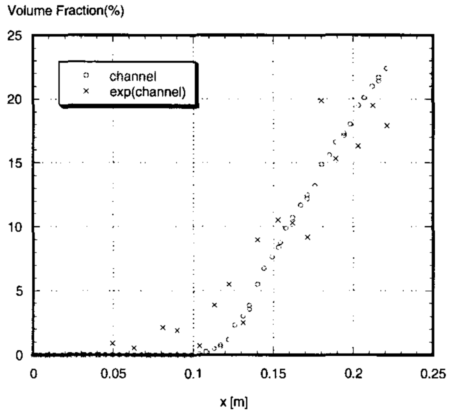


Fig. 9 Void Fraction with Transport.

With the data obtained, the model constants needed in the mathematical model have been found.

Table 1 Model Constants Values

Model constants	value
$F_{K,C}(\phi)$	8.61739e-5
$F_{K,T}(\phi)$	1.054
$F_{C,T}(\phi)$	0.3507
$\Pi_C(\phi)$	5.13
$\Pi_T(\phi)$	4.7
A	12.203
k	18240
u_{crit}	0.00028m/s

4. Conclusion

An experimental method to examine the microvoid formation and transport occuring during VARTM process has been developed. Only by examining the flow front, the experimented results show the same trends as expected. With the mathematical model and the constants obtained from the experiment, the model can predict the content and size of the microvoid in channels as well as tows.

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