수지이송성형시 다층 예비성형체 내부에서의 수지유동 및 투과계수에 관한 연구

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A Study on Resin Flow through a Multi-layered Preform in Resin Transfer Molding

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KEY WORDS : RESIN TRANSFER MOLDING, MULTI-LAYERED PREFORM, EFFECTIVE AVERAGE PERMEABILITY, TRANSVERSE FLOW

ABSTRACT

When the preform is composed of more than two layers with different in-plane permeability in resin transfer molding, effective average permeability should be determined for the flow analysis in the mold. The most frequently used averaging scheme is the weighted average scheme, but it does not account for the transverse flow between adjacent layers. A new averaging scheme is proposed predicting the effective permeability of the multi-layered preform, which accounts for the transverse flow effect. The new scheme is verified by measuring the effective permeability of the multi-layered preforms and the difference in each flow front position.

1. INTRODUCTION

In resin transfer molding, mold filling is governed by the flow of resin through the preform which is considered as an anisotropic porous media. The resin flow is usually described by Darcy's law and the permeability tensor must be obtained for filling analysis.

A preform basically consists of a number of the layers of fiber mats. These layers may be composed of different materials and each layer has different in-plane permeability. In particular, a preform has multiple layers composed of different kinds of fibers and the difference of in-plane permeability between different layers may be large. Therefore it is necessary to evaluate the effective average permeability.

One of the simplest average schemes is the weighted average scheme [1].

$$\overline{K}_{ij} = \frac{1}{H}\sum_{l=1}^{n} h^l K_{ij}^l \qquad (1)$$

where $\overline{K}_{ij}$ is the averaged in-plane permeability tensor, K_{ij}^l is the in-plane permeability tensor for each layer, H is total preform thickness, h^l is individual layer thickness, and n is the total number of layers. Several researchers have shown that for relatively thin preforms with moderately varying permeabilities, this scheme provides an estimate of the effective permeability within 10% to 15% error of the experimental value [2].

But this scheme does not account for transverse flow in thickness direction. The weighted average scheme implies that flow across the preform layers is instantaneous owing to the assumption of a plug flow profile through the thickness during the mold filling process. For multi-layered preform, the transverse flow effect cannot be neglected. Especially, when the preform is relatively thick and the difference of the in-plane permeabilities between adjacent layers is large, the transverse flow effect is more significant. When the in-plane permeabilities are not the same, a non-uniform flow front develops through the thickness of the preform due to transverse flow, which has been verified experimentally. In practice, the transverse flow across preform layers takes place in a region near the flow front and is a strong function of both the in-plane permeabilities of the adjacent layers and their transverse permeability [3].

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In order to account for transverse permeability effect, numerical simulation of three dimensional flow is necessary. In a three dimensional problem, the additional material property required is the transverse permeability for each element of the preform. This property is difficult to measure because of the limited length scale available and limited availability of the compression characteristics of preforms. Hence, averaging the properties in the thickness direction has been the general practice as the error made in the measurement of transverse permeability may be of the same order as the error made in the estimation of effective average permeability. Moreover, to describe flow in RTM process, three dimensional flow simulation is highly inefficient and time consuming as the computational time increases by one order of magnitude with each additional degree of freedom. It may also be unnecessary because the transverse flow in the third direction in most cases may be limited only near the flow front region. An effective average permeability accounts for the transverse flow near the flow front region will enable us to eliminate one dimension, yet to capture the effect of a non-uniform stacking sequence, while maintaining computational efficiency [4]. Thus there is a need to develop general schemes to calculate the effective permeability, accounting for the transverse flow between layers, for a preform with multiple layers.

In this study, a new averaging scheme is suggested to predict the effective permeability of the multi-layered preform, which accounts for the transverse flow effect by including transverse permeability directly. The effective permeability is measured experimentally for the multi-layered preforms which are composed of glass fiber random mat, carbon fiber woven fabric, and aramid fiber woven fabric. By comparing with the experimental result, the new averaging scheme is verified to be more accurate than the weighted averaging scheme that do not consider the transverse flow.

The advancement of the flow front for the multi-layered preform is observed by using a digital camcorder. The difference in the flow front is also calculated in the course of calculating the effective average permeability and is compared with the result obtained from the image of the digital camcorder.

2. THEORY

Based on two dimensional geometry, a new scheme predicting the effective average permeability is developed. Darcy's law is used in describing the flow through fiber preform.

$$\bar{u} = -\frac{K}{\mu}\nabla P \qquad (2)$$

where $\bar{u}$ is Darcy's velocity, μ is Newtonian viscosity of the fluid, ∇P is pressure gradient and K is permeability tensor of the porous medium.

The new scheme accounts for the effects of the difference in flow fronts and transverse flow between adjacent layers. When the flow in the mold is unsaturated, the effective average permeability is predicted by using pre-predicted mold filling time and transverse permeability. The resulting equation that calculates the effective average permeability is as follows.

$$K = \frac{\mu L^2 \varepsilon}{P_0}\left(\frac{-B+\sqrt{B^2+4A^2+4AL}}{2A}\right)^{-2} \qquad (3)$$

where ε is porosity of preform, P_0 is inlet pressure, L is the length of mold, and A, B are the constants determined by in-plane and transverse permeability, the geometry of preform , and the processing condition.

3. EXPERIMENTS

1. Single layered preform

The in-plane permeabilities of three different fiber preforms, glass fiber random mats, carbon fiber woven fabrics, and aramid fiber woven fabrics, were measured. Volume fraction of each preform was specified experimentally. Each experiment was performed under the constant inlet pressure. Pressure applied by compressed nitrogen was in the range from 0.25 MPa to 0.26MPa. Pressure gradient was calculated from the values of two different pressure transducers. Volumetric flow rate was calculated by measuring both volume of fluid and time. From these data, the in-plane permeability of single layered fiber preform can be calculated by Darcy' law. The advancement of flow front was also observed by using a digital camcorder.

2. Multi-layered preform

2.1. Effective permeability of multi-layered preform

Multi-layered preforms were made by combining two preforms out of the three kinds of fiber preforms. They were glass/carbon, glass/aramid, aramid/carbon. Experiments were performed at constant inlet pressure. Applied pressure in each experiment by compressed nitrogen was in the range of 0.19 MPa to 0.28 MPa.

2.2. Difference of flow front positions

Because the permeability of each layer in multi-layered preform was different, the flow front position of each layer was different. The difference of flow front position was observed through the side of the mold by a digital camcorder. Variation of the flow front difference was observed with respect to time.

4. RESULTS AND DISCUSSION

1. *Single layered preform*

Volume of fluid was measured with the exact elapsed time. Pressure values were measured at two different pressure transducers located in the mold. Permeability of each fiber preform was calculated by applying the Darcy's law.

Mold filling patterns for a glass fiber preform was shown in Fig. 1. Edge effects were observed, which are caused by the poor fitting of the preform in the cavity. Vents might be necessary at proper locations in the mold to prevent the formation of dry spots.

2. Multi-layered preform

The effective permeabilities of multi-layered preforms were measured. The weighted average permeability and effective average permeability were compared with the measured permeability in Fig. 2 and Fig. 3. It is shown that the effective average permeability is closer to experimental results than the weighted average permeability. This is due to the fact that the effective average permeability considers transverse flow between two adjacent layers. The calculated time averaged transverse permeabilities were 1.26×10^{-11} (glass/carbon), 2.13×10^{-11} (glass/aramid), $1.69\times10^{-11}m^2$(aramid/ carbon). These values are lower than the in-plane permeabilities by about two orders of magnitude. Especially, when the difference of in-plane permeabilities between two layers is large, the transverse flow plays a more important role in determining an effective permeability. Therefore, the weighted averaging scheme ignoring the transverse flow effect produces a large error when the difference of in-plane permeabilities between two layers is large.

Using this effective averaging scheme, the advancement of flow front in glass/carbon preform was shown in Fig. 4. The calculated flow front length of carbon layer in glass/carbon preform was compared with the experimental results within 16.55 ~ 23.45 cm from the gate as shown in Fig. 5. And images processed by *Image Pro 4.1* were also shown in Fig. 6. As shown in these results, the flow pattern observed in the experiment was less stable than the predicted flow pattern.

5. CONCLUSION

Permeabilities of three kinds of single layered preform were measured in the saturated flow and permeabilities of three kinds of multi-layered preform were also measured by the same method. A new effective average permeability considering transverse flow between two different layers was proposed and compared with the weighted average permeability and the experimentally measured result. The effective average permeability is much closer to the experimentally measured permeability than the weighted average permeability that does not consider the transverse flow.

Advancement of the flow front in multi-layered preform was investigated theoretically and visualized by a digital camcorder. A commercial image analysis software was used to determinine the exact position of flow front. The calculated advancement of flow front showed a good flow pattern. However, the experimental flow front pattern shows a little unstable tendency with respect to the calculated result. It is expected that the effective average permeability can be used for modeling the resin flow through the multi-layered preform in resin transfer molding.

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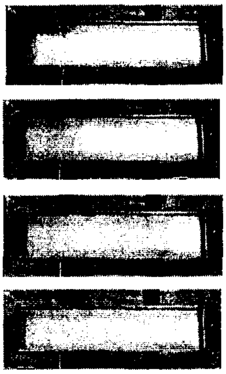

Fig.1. Advancement of the resin flow front in glass fiber preform.

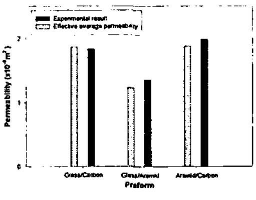

Fig. 2. Predicted values of the effective average permeability in comparison with the experimental result.

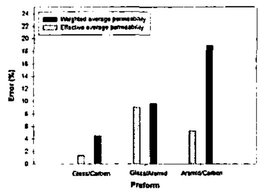

Fig. 3. Errors of the two averaged permeabilities obtained from the experimental results.

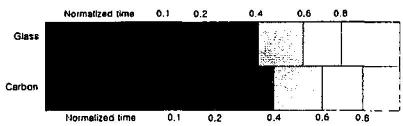

Fig. 4. Advancement of the flow front in glass/carbon fiber preform.

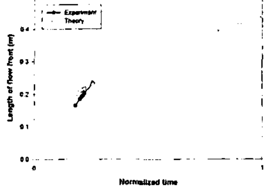

Fig.5. Comparison of the calculated flow front length with the experimental result in glass/carbon preform.

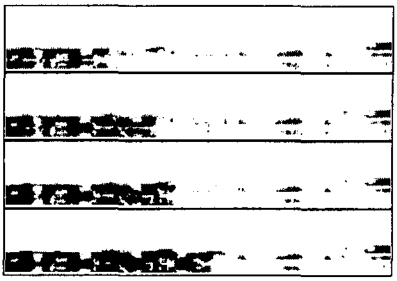

Fig. 6. Advancement of the resin flow front in glass/carbon fiber preform (images processed by *Image Pro 4.1*).