수지 이송 성형에서 투과율 계수의 수치적 계산

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Numerical Calculation of Permeability in Resin Transfer Molding

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ABSTRACT

Complete prediction of second order permeability tensor for three dimensional preform such as plain woven fabric and braided preform is critical to understand the resin transfer molding process of composites. The permeability can be obtained by various methods such as analytic, numerical, and experimental methods. For several decades, the permeability has studied numerically to avoid practical difficulty of many experiments. However, the predicted permeabilities are a bit wrong compared with experimentally measured data. In this study, numerical calculation of permeability was conducted for two kinds of preforms i.e., plain woven fabric and circular braided preform. In order to consider intra-tow flow in the unit cell of preform, the proposed flow coupled model was used for plain woven fabric and the Brinkman equation was solved in the case of the braided preform.

1. Introduction

Determination of permeability in RTM is of much importance because flow through the preform is generally governed by volume averaged velocity based on Darcy's law. There are several ways in the determination of permeability, that is, analytic, numerical, and experimental methods. In this study, the permeability is predicted numerically based on unit cell approach of the plain woven fabric and circular braided preform and the values were compared with experimental results which were obtained by unidirectional and radial flow experiments.

2. Plain woven fabric

The in-plain and transverse permeaibilties for woven fabric were predicted numerically by the coupled flow model, which combines inter- intra-tow flow. The following equation was derived based on the model.

$$K_{tot} = K_m + \frac{1}{2} V_{b,macro} K_f + \frac{1}{2V_{b,macro}} K_w$$

where K_{tot}, K_m, K_f, K_w are total, matrix, fill, and warp permeabilities, respectively. K_m and K_f were obtained from micro-unit cell analysis. The three dimensional flow analysis was carried out by using CVFEM. Unit cell of plain woven fabric is depicted as shown Fig. 1. It was assumed that the cross-section of yarn is elliptical and the path of the yarn is sinusoidal. Each layer of multi-layered preform was thought to be in contact with one another. As the woven fabric is

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compacted, the minor axis of the elliptical cross-section is reduced.

3. Circular braided preform

The braided preform is produced by using a 3-D circular braiding machine which has the compressed air mode and 11 machine pattern. 3-D circular braiding process is composed of two motions, beating and step motions. The beating motion makes the structure of yarn more solid-like by compacting the yarns in axis direction and the step motion comprises four steps to obtain the same arrangement of carriers. Based on the carrier motion, a geometric modeling is conducted. The braiding machine is composed of 12 carriers in radial direction and 48 carriers in circumferential direction, i.e., 1248 preform patterns are available. But 748 carriers are used in this study. The braided preform has a geometrical structure repeated per pitch length along cylindrical mandrel axis and the repeated structure again consists of the same 24 unit cells in the circumferential direction. As 7 carriers exist in the radial direction on the machine bed, each unit cell comprises 7 sub-unit cells, that is, 5 inner unit cells and 2 surface unit cells. Figure 2 shows the unit cell which is composed of the sub-unit cells. In order to calculate permeabilities by using the numerical method, a curved unit cell is flattened.

4. Numerical analysis

In the case of the plain woven fabric, the Stokes equation is solved and for the braided perform both the Stokes and Brinkman equations were employed respectively in the intra- and inter-tow regions as governing equations. The equations can be cast in the following general forms.

$$\nabla \cdot J = S$$

$$\nabla \cdot g = 0$$

where J is the diffusion flux, S is the source term, and g is the mass flux vector. By applying appropriate conservation principles to a control volume, integral forms of equation can be obtained as follows.

$$\int_{\partial V} J \cdot n ds = \int_{\partial V} S dV = 0$$

$$\int g \cdot n ds = 0$$

If velocity components and pressure were stored at the same grid points and interpolated by similar functions like linear functions, the resulting discretization equations could experience physically unrealistic checkerboard type pressure fields. To overcome this problem, we formulated interpolation function accounting for the influence of the pressure gradient on the velocity distribution within each element.

5. Experiments

Unidirectional and radial flow experiments were performed for plain woven fabric and braided perform, respectively. The results were compared with the predicted permeability. The permeability was determined by measuring the pressure gradient in the mold, where fluid was assumed to be Newtonian behavior.

6. Discussions

6.1. Plain woven fabric

The micro and the unit cells which represent the intra- and inter-tow regions respectively, were used to predict the permeability of plain woven fabric. Unlike past studies, this study was based on a three dimensional unit cell in which curved elliptical yarn was taken into account. The coupled flow model through which the microscopic and macroscopic flows are combined was proposed to predict the three dimensional second order permeability tensor. It was shown that the in-plane flow is more important than the out-of-plane flow as shown in Fig. 4.

6.2. Circular braided preform

The permeability for each principal direction was obtained numerically with respect to the entire porosity as shown in Fig. 5 (a). The permeability increases with the increase in the entire porosity and the permeability for y direction has the highest value. The results are explained if geometrical architecture is examined. Because the average yarn orientation angle from the mandrel axis is 26, the flow in y direction will be dominant. The contribution on permeability tensor of the intra-tow flow (e.g., intra-tow permeability) can be neglected if the entire porosity is above about 0.6. In this case, it is sufficiently accurate that the tow is regarded as impermeable solid and is numerically much efficient. When the porosity is low, the permeabilities for thickness direction of the preform are different in two cases considering the tow as porous medium and solid. Therefore, the flow through the tow along the direction of thickness is important at low porosity and must be taken into account. The predicted permeability was compared with the experimental results as shown in Fig. 5 (b). When the thickness of the mold cavity is reduced much to achieve high fiber volume fraction, it is difficult to generate an FE mesh owing to high compaction and geometrical complexity, and large deformation of the transparent top plate of the mold is observed. Therefore, both the numerical prediction and experimental measurements are performed for the porosity higher than 50 %. There are some discrepancies between numerical and experimental results in the case of x direction. The differences may be attributed to the nesting and shifting effects of the layers between sub-unit cells, distortion of the unit cell during flattening the cylindrical preform, and coarseness of the FE mesh.

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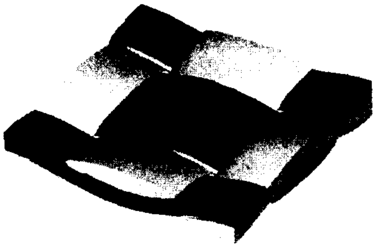


Fig. 1. Architecture of unit cell for plain woven fabric

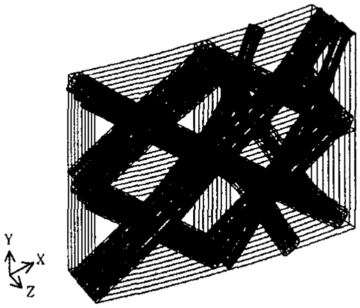


Fig. 2. Curved unit cell for 3-D circular braided preform

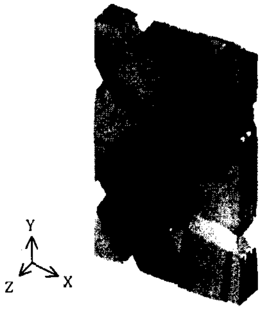


Fig. 3. Geometrical structure of flattened unit including sub-unit cell

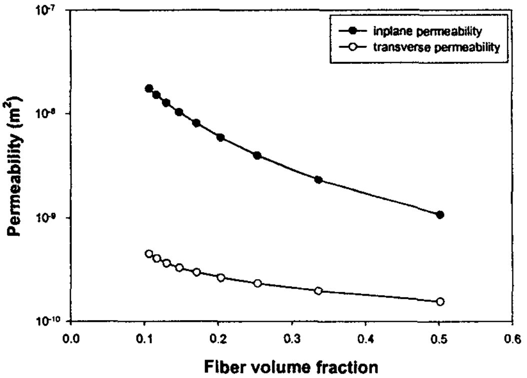
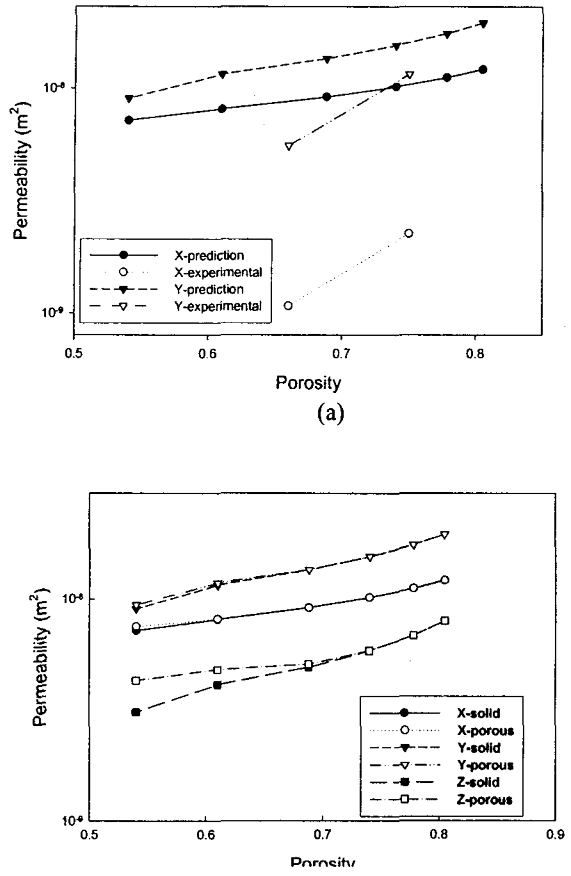


Fig. 4. Predicted permeability with respect to fiber volume fraction.



(a)

(b)

Fig. 5. (a) Comparison of permeabilities predicted for each direction as a function of porosity, (b) Comparison of permeabilities predicted for each direction as a function of porosity