다층 예비성형체에 대한 삼차원 충진해석

양매 • 송영석 • 윤재륜[*]

Three-Dimensional Mold Filling Simulation for Multi-layered Preform in Resin Transfer Molding

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ABSTRACT

Resin transfer molding (RTM) is one of the most popular processes for producing fiber reinforced polymer composites. In the manufacture of complex thick composite structures, analysis on flow front advancement on the resin impregnating the multi-layered fiber preform is helpful for the optimization of the process. In this study, three-dimensional mold filling simulation of RTM is carried out by using CVFEM (Control Volume Finite Element Method). On the assumption of isothermal flow of Newtonian fluid, Darcy's law and continuity equation are used as governing equations. Different permeability tensors employed in each layer are obtained by experiments. Numerically predicted flow front is compared with experimental one in order to validate the numerical results. Flow simulations are conducted in the two mold geometries, rectangular plate and hollow cylinder. Permeability tensor of each layer preform in Cartesian coordinate system is transformed to cylinder coordinates system so that the flow within the multi-layered preforms of the hollow cylinder can be calculated exactly. Our emphasis is on the three dimensional flow analysis for circular three-dimensional braided preform, which shows outstanding mechanical properties such as high impact strength and toughness compared with other conventional two-dimensional laminar-structured preforms.

1. Introduction

During the past few decades, Resin Transfer Molding (RTM), as a kind of Liquid Composite Molding (LCM), has gained more popularities in production of high-volume parts due to its low cost, short cycle time and high quality. The process includes putting fiber preforms designed and cut previously into a mold, closing the mold, injecting resin through gates under proper pressure and when the resin cures, removing the final part out of the mold. This study focuses on mold filling stage, which is regarded as one of the most complicated and critical stages through the whole process, since it has the most important impact on the process performance and final part quality. Studying flow patterns during mold filling is very important to the optimization of the process and the design of the mold. But for multi-layered preforms with different permeabilities or thick part structures, it is not easy to investigate the flow pattern inside the preform even with a transparent mold. Therefore three-dimensional numerical simulations are necessary, which are convenient enough to carry out and have much better accuracy.

In the mold filling stage, there are several variables to control, e.g. injection pressure, permeability of preforms, resin viscosity, and mold temperature. Usually, we use Darcy's law to describe the flow into a porous media, which constructs the relationship among main variables in this process and is perfect enough to describe the mold filling process.

Darcy's Law:

$$\mathbf{u} = -\frac{\mathbf{K}}{\eta} \nabla P$$

Where $\mathbf{u}$ is the velocity vector of fluid, $\mathbf{K}$ is the second order permeability tensor of fiber preform, η is the resin viscosity and ∇P is the pressure gradient.

In the same time, continuity equation is used to calculate the flow field.

$$\nabla \cdot \mathbf{u} = 0$$

In this study, the simulation is carried out under constant pressure which is the same situation as in our experiments, so that the numerical results can be compared with the experimental ones. Then the boundary condition can be given as follows.

At the mold walls: $\frac{\partial P}{\partial n} = 0$

At the injection gates: $P = P_0$

At the flow front: $P = 0$

2. Numerical Method

Mold filling analysis is a transient problem. As a numerical method in the calculation of continuously changing flow domain, Control Volume Finite Element Method is used in this study. The mold cavity is meshed using tetrahedral elements, because they are convenient for meshing of the complicated geometries. Interpolation function for pressure is

$$P = ax + by + cz + d$$

where x, y and z are the coordinates in Cartesian coordinates system, a, b, c, and d are the coefficients determined by element position.

The scheme of the numerical codes is shown as fig. 1.

There are two methods to calculate the time step in the analysis. Before computing the time step, flow front nodes with the control volume are found. One method is to compute the Δt over the whole flow front control volumes (FFCV) as below,

$$\Delta t_i = \frac{V_i}{Q_i}$$

where i is the FFCV index, V_i is the volume of the ith. FFCV, Q_i is the flow rate in the ith FFCV. Then the control volume with minimum Δt is filled in first and the minimum value of Δt is chose as next time step.

The other method is to calculate the fill factor, f, in every time step and calculate Δt by

$$f_i^m = f_i^{m-1} + \frac{Q_i^m t^m}{V_i}$$

$$\Delta t_i^m = \frac{(1 - f_i^{m-1}) V_i}{Q_i^m}$$

where m is the time step index.

Because when the first filled control volume is filled up, the other FFCVs are filled at the same time. When the next time step starts, the partially filled FFCVs won't be empty but continue to be filled up from the last time step.

In the calculation of the fill time for a rectangular mold, the result in the case of second method is 27.5s, the real fill time in the experiment is 28.5s, which shows much better agreement than the first method. So we use the second method in this study.

The schematic illustration of the second method is show in Fig.2.

For solving the flow field in hollow cylinder cavity, permeabilities measured in Cartesian coordinate system is transformed into cylinder coordinate system using the following equations.

$$K_r = K_{tr}$$

$$K_\theta = K_{radial}$$

$$K_z = K_{radial}$$

$$[\mathbf{K}] = \begin{bmatrix} K_r \cos^2\theta + K_\theta \sin^2\theta & \sin\theta\cos\theta(-K_r + K_\theta) & 0 \\ \sin\theta\cos\theta(-K_r + K_\theta) & K_\theta \cos^2\theta + K_r \sin^2\theta & 0 \\ 0 & 0 & K_z \end{bmatrix}$$

where K_{tr}, K_{radial} are the transverse and in-plane permeabilities of preform measured by experiment

3. Experiment

To measure the in-plane and transverse permeabilities of fiber preforms and to validate the simulation results, several experiments are carried out in the rectangular mold and cylindrical mold.

The rectangular mold composed of a lower base plate, an upper transparent plate and a rectangular rim to fix up the upper plate on the base one. By controlling the distance of the two plates we can control the height of the mold to determine the porosity of fiber preforms. Employing constant pressure, resin can be injected into the cavity through gate on the central of the base plate and then flow out through each vent at four corners of the base plate. The geometry of the plate is 500×500 mm^2 and the fiber preforms are cut in 450×450 mm^2. A video camera is suspended over the transparent plate to record the flow patterns during mold filling. Through the pressure data with respect to time recorded by Dasylab software developed by National Instrument Corporation, in-plane permeabilities can be measured.

Inner diameter of the barrel mold is 12cm. There are two plates to control the height of mold cavity, i.e., the porosity of fiber preforms. The plates contain many round holes which reduce the resistance during the mold filling. Without observation of the flow front in the barrel, transverse permeability is measured by the flow rate and the pressure data.

Gravity effects are ignored in these measurements, because they are not so significant to affect the measurements.

The resin employed in this study is silicon oil. The viscosity is 9.7×10^{-2}Pa·s.

4. Validation

To validate the simulation, we chose glass woven fabric of one layer. The porosity is set to be 0.47 by controlling the height of the rectangular mold. Comparison of the flow front position changing with respected to time with the experimental data, we can confirm whether or not simulation is accurate enough to predict the flow patterns.

From Fig. 3 we can see that the simulation result is accordant with experimental data. Because we measured the permeabilities at the same conditions, we can use this code to predict the flow patterns.

5. Case Study

Emphasis of our study is on the analysis of mold filling in cylinder geometry. Fig. 4 shows the glass fiber braided preform and Fig. 5 shows the flow front advancement during mold filling. The axial permeability is $5.547\times10^{-9}\mathrm{m}^2$, the radial permeability is $5.6\times10^{-11}\mathrm{m}^2$ and the tangential permeability is $1.073\times10^{-9}\mathrm{m}^2$. The three permeabilities are measured by experiments when the porosity is 0.66. The injection pressure is 35000Pa.

Fig. 6 shows flow front advances of multilayered preforms in cylindrical mold. The middle layer is glass woven fabric, for which in-plane permeability is $20.3\times10^{-9}\mathrm{m}^2$, and transverse permeability is $0.69\times10^{-11}\mathrm{m}^2$,inner and out layer is aramid fabric, for which in-plane permeability is 9.01×10^{-9} m^2, transverse permeability is $0.33\times10^{-11}\mathrm{m}^2$. These permeabilities are measured by rectangular mold. The thickness of each layer is the same. Injection pressure is 100000Pa. As expected, The fluid flows faster in middle layer than upper and bottom layers, but the difference is not so significant.

6. Conclusion

A three-dimensional mold filling simulation code is developed by using reliable time step calculation method. From comparison with experimental data, this code is accurate enough to predict the flow patterns especially in multi-layered preforms in the cylinder mold which is difficult to study.

From the prediction of flow patterns by simulation, we can see that the flow front difference through the whole process is ignorable and gate location should be near the preforms with low permeabilities to avoid dry spots.

Acknowledgement

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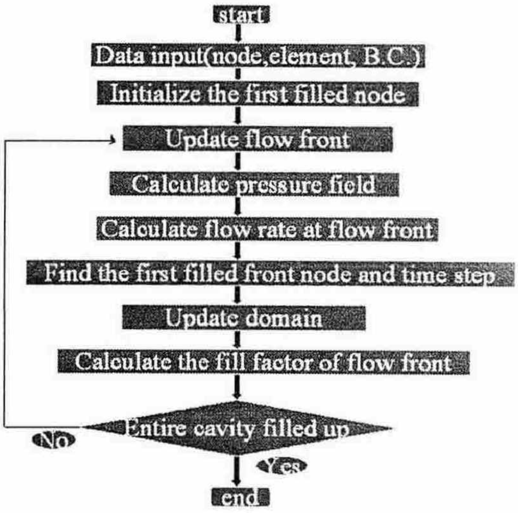

Fig. 1 Flowchart of three-dimensional mold filling simulation

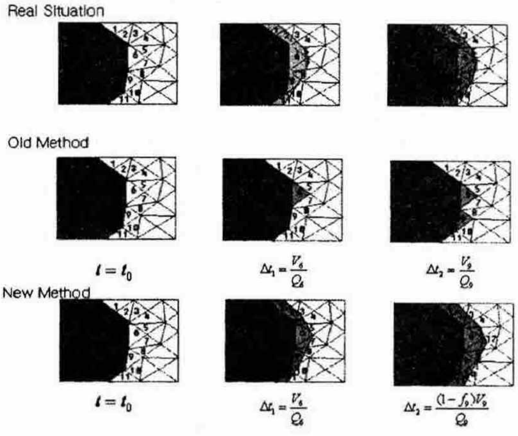

Fig. 2 Comparison of two methods in the calculation of time step.

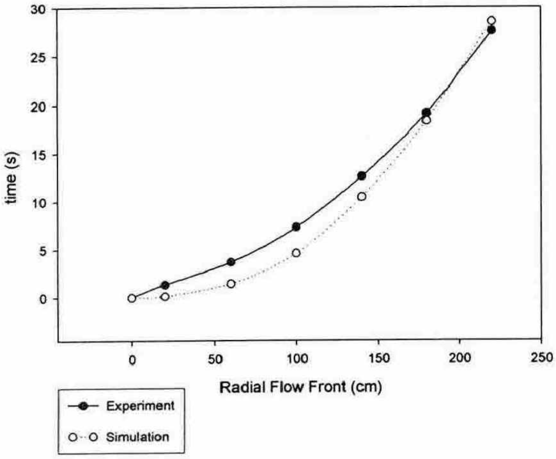

Fig. 3 Comparison of flow front in glass woven fiber

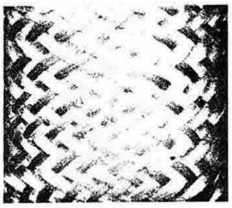

Fig. 4 Glass braided preform

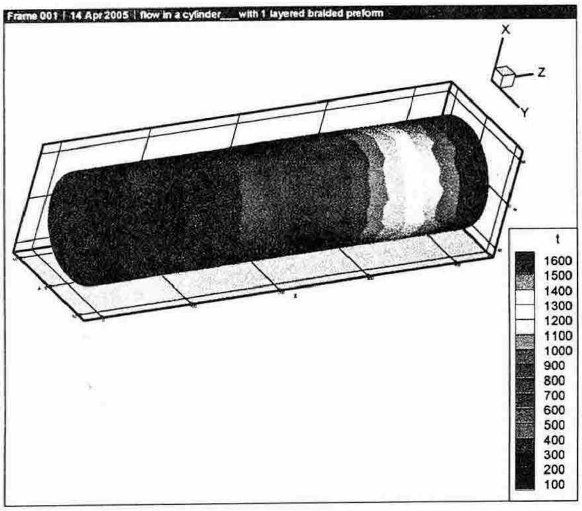

Fig. 5 Flow front advancement in a cylindrical mold with glass fiber braided preform

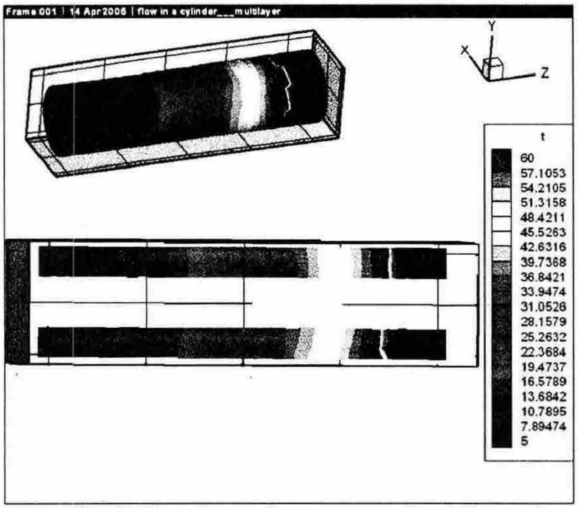

Fig. 6 Flow front advancement of multilayered preforms in cylindrical mold