ANALYSIS OF THREE DIMENSIONAL RESIN TRANSFER MOLD FILLING PROCESS

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Resin Transfer Molding(RTM) is a process in which thermoset resin is injected into a mold cavity pre-loaded with porous fibrous preform. For parts with small thickness, the mold filling process can be modeled as two dimension by neglecting the resin flow in the thickness direction. However, thicker parts require extensive resin flow along the thickness and thus the three dimensional effect in the resin flow must be considered. In this study, numerical simulations of three dimensional mold filling process during resin transfer molding were performed. The location of resin front, pressure, temperature and the degree of cure were calculated as functions of time. Experiments were also performed. To measure the resin front location as a function of time in the preform, optical fiber was used as a sensing element. The agreements between the experimental data and the numerical results were found to be satisfactory. The computer code developed in this study was applied to SCRIMP that is a kind of vacuum assisted RTM with flexible tooling.

Key words : RTM, CV/FEM, Mold Filling, Optical Fiber

INTRODUCTION

The resin transfer molding(RTM) is a method in which thermosetting resin is injected into preheated mold, impregnating fiber preform, and then cures(Fig.1).

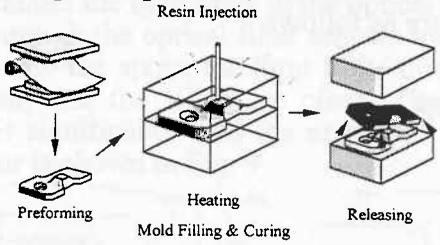


Fig. 1 Resin transfer molding process

In RTM process, the injection pressure, the temperature of the mold, the permeability of the fiber mat and the resin viscosity are the major processing variables. All of the process variables are interrelated each other and have effects on the mechanical properties of products. Therefore it is essential to predict the effect of process variables in order to optimize the conditions.

In this study, an attempt was made to develop a computer code, which can simulate RTM mold filling process three-dimensionally including the temperature and curing effects.

In order to validate the developed computer code, flow front location inside the thick preform as a function of time should be monitored during the filling process. The resin front locations were monitored using fiber optic sensors. Experimental data were compared with numerical results. In addition, the three dimensional permeability should be measured to simulate the three dimensional RTM process because the permeability is a material property of the fiber preform. Three dimensional permeability was measured also using optical fiber sensors.

MATHEMATICAL MODELING AND GOVERNING EQUATIONS

In RTM mold filling process, thermoset resin flows through porous fiber mat. Therefore the flow can be assumed to follow the Darcy's law [1]

$$\bar{V} = -\frac{1}{\mu}[K]\nabla P \qquad (1)$$

where $\bar{V}$ is the velocity of the resin flow, μ is the viscosity of the resin, $[K]$ is the permeability tensor, P is the pressure of the resin.

The energy equation of the resin is as follows [2]

$$\phi\rho_r c_{pr}\frac{\partial T_r}{\partial t} + \rho_r c_{pr}\, V\cdot\nabla T_r = \phi\nabla\cdot k_r\nabla T_r + \phi h_v(T_f - T_r) + \phi\dot{G} \qquad (2)$$

where ρ, c_p, k, h_v are the density , the specific heat, the thermal conductivity of the resin and the convection heat transfer coefficient between fiber and resin, respectively. T is the temperature of the resin and ϕ is the porosity of the fiber fabric. The subscripts r and f represent fiber and resin, respectively. $\dot{G}$ is the heat generated by resin curing reaction and is expressed as [3]

$$G = \Delta H(k_1 + k_2\alpha^{m_1})(1-\alpha)^{m_2}$$

The energy equation of the porous media can be written as follows[2]

$$(1-\phi)\rho_f c_{pf}\frac{\partial T_f}{\partial t} = (1-\phi)\nabla\cdot k_f\nabla\cdot T_f + \phi h_v(T_r - T_f) \qquad (3)$$

The mass conservation of the chemical species represents the conversion between monomer and polymer [2]

$$\frac{\partial\alpha}{\partial t} + \frac{\dot{V}}{\phi}\cdot\nabla\alpha = \nabla\cdot D\nabla\alpha + \dot{m} \qquad (4)$$

where α is the degree of cure, D is the mass diffusion coefficient, $\dot{m}$ is the mass generation of the resin polymer.

$$\dot{m} = (k_1 + k_2\alpha^{m_1})(1-\alpha)^{m_2}$$

The boundary conditions are as follows

At the injection gate:

$$P|_{inlet} = P_0 \text{ or } u|_{inlet} = -\frac{[K]}{\mu}\nabla P = u_0,$$
$$T|_{inlet} = T_0 \qquad (5)$$
$$\alpha|_{inlet} = \alpha_0$$

At the mold wall :

$$\left.\frac{\partial P}{\partial n}\right|_{wall} = 0, \qquad (6)$$
$$T|_{mold} = T_m,$$

On the flow front region :

$$P|_{front} = 0,$$
$$k\left.\frac{\partial T}{\partial n}\right|_{front} = (1-\phi)\rho_f c_{pf} u_n (T_{f0} - t) \qquad (7)$$

The governing equations described above can be discretized by using the CV/FEM technique [4].

Calculation Procedure

RTM mold filling process is a moving boundary problem, and therefore the computation domain is changing continuously with time. The control volume method saves much trouble when combined with the volume of fluid (VOF) [5-8], where a fixed grid is placed at a molded part and scalar parameter *f* is introduced for each cell to represent the ratio of the occupied volume to the total volume. As the flow front advances, all of the control volumes can be classified into three categories (see Fig.2)

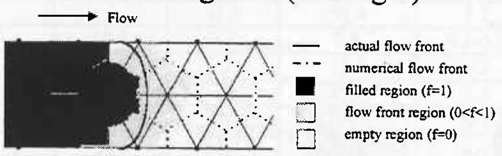


Fig.2 Illustration of the flow front advancing technique

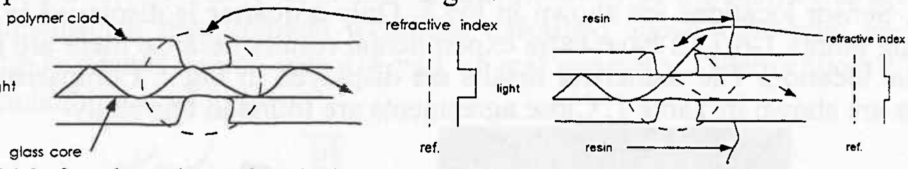
The numerical simulation procedure is as follows. First, the viscosity calculated based upon the temperature and the degree of cure at the previous time step is used to solve the momentum equation. Then the volumetric mass flux through each control surface can be obtained. The flow front advances until there is any new control volume completely filled using this volumetric mass flux.

EXPERIMENT

In order to find out the resin front location in the mold filling process, optical fiber was used to monitor the flow of the resin through fiber preform.

Principle of the Fiber Optic Sensor

In this study, polymer-clad-silica-core optical fiber was used. First, a small section of cladding was removed from the optical fiber by burning away or chemical etching. The size of the bare spot is as small as 1mm. Three or four bare spots are made consecutively on a single fiber in the locations that should be monitored. Optical fiber thus prepared was positioned inside the fiber preform. After that, infrared light signal was transmitted through the optical fiber from one end and the intensity of the light signal is to be checked on the other end. Before the resin reaches the bare spots in the optical fiber sensor, relatively large light signal can be reached through the optical fiber sensors by the total refraction(see Fig. 3). However as the resin reaches the spots, the light leaks through the bare spots because the refractive indices of resin and the silica are close. Therefore, the intensity of the transmitted light signal drops significantly and the arrival of resin front can be detected. Typical output from the sensor is shown in Fig. 4.



(a) before the resin reaches the bare spot (b) after the resin reaches the bare spots

Fig. 3 Fundamentals of the optical fiber sensor during filling process

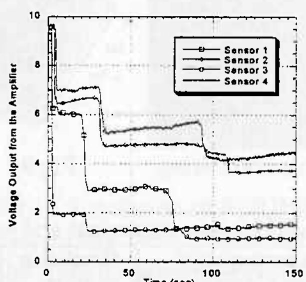


Fig.4 Typical voltage output from the fiber optic sensor

Three Dimensional Permeability Measurement

The measurement of the three dimensional permeability is essential to the three dimensional RTM mold filling analysis. Three dimensional permeability was measured using optical fiber sensors as previously explained. First, the optical fiber sensors are embedded in the fiber preform at designated locations. As the resin reaches the sensing point, the signal from the photo detector is to be changed and the time to the sensing point was recorded.

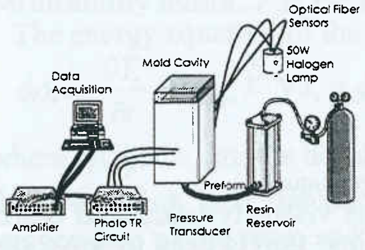


Fig. 5 Three dimensional experimental apparatus

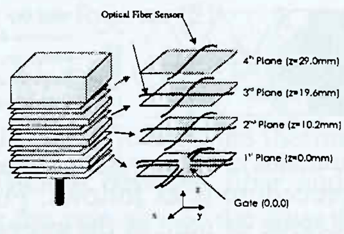


Fig. 6 Embedded optical fiber sensors inside fiber preform

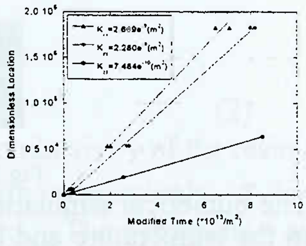


Fig.7 Curve fit of three dimensional permeability .

Once the times to reach specific locations are given, three dimensional permeability can be obtained from curve-fitting to the following equation[11-12].

$$\frac{1}{3}\rho_{fi}^{3} - \frac{1}{2}\rho_{fi}^{2} + \frac{1}{6} = \phi_i \qquad i=x,y,z \qquad (10)$$

where $\rho_{fi} = \frac{r_i}{r_{0i}}$ and $\phi_i = K_i \frac{P_0 t}{\mu \varepsilon r_{0i}^2}$. r_i is the resin front location, r_{0i} is the radius of the inlet gate, P_0 is the inlet pressure, t is the fill time. μ is the resin viscosity and ε is the porosity. In this study, three bare spots per each optical fiber were prepared and embedded it inside the preform. Fig. 6 illustrates how optical fibers were placed. In case of chopped strand mat, In this study, three dimensional permeability of glass fiber chopped strand mat was measured. The inlet pressure was 0.142MPa and the fiber volume fraction was 20.9%. From the voltage output data, the time of resin front arrival at each sensing point can be monitored. Based on Eq. (10), the three dimensional permeability was obtained (see Fig.7). As is expected, K_x is very similar to K_y assuring that in-plane permeability is isotropic.

Comparison between Experimental and Numerical Results

Using the calculated permeability, numerical simulation was performed for the same geometry. Sensor locations are shown in Fig.8. Only a quarter is displayed in this figure. The sensing points 1-6,7,12 have extra experimental results because there are two sensors at the same location. The numerical results are displayed in Fig.9. Comparisons between two results are shown in Table 1. Close agreements are found in this study.

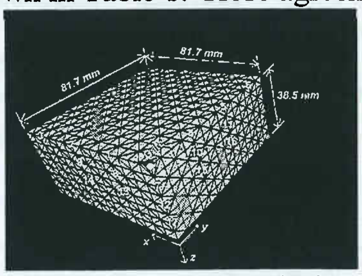


Fig.8 Sensing points numbering

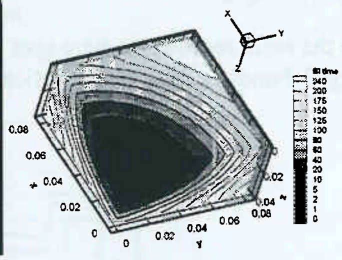


Fig.9 Numerical results

Table 1. Comparison between numerical and experimental results

Number of sensing points	Experiment(sec)		Simulation (sec)	Error (sec)	Error (%)
	sensor 1	sensor 2			
1	2.5	2.5	2.6	0.1	4

2	21.9	23.5	23.3	0.2-1.4	0.9-6.4
3	76.1	83.3	79.8	3.5-3.7	4.2-4.9
4	3.8	4.7	3.3	0.5-1.4	13.2-29.8
5	31.3	32.6	29.3	2.0-3.3	6.4-10.1
6	96.1	93.6	100.6	4.5-7.0	4.7-7.5
7	1.6	1.6	0.7	0.9	56.3
8	6.9		5.9	1	14.5
9	33.5		29.7	3.8	11.3
10		10.3	7	3.3	32
11		45.1	36.4	8.7	19.3
12	10.3	9.7	9.5	0.2-0.8	2.1-7.8
13	18.8		18.6	0.2	1.1
14	45.1		47.7	2.6	5.8
15		20.1	20	0.1	0.5
16		64.8	55.4	9.4	14.5
17	34.4		35.1	0.7	2

Application to SCRIMP

One of the practical applications of three dimensional RTM process was for special case called SCRIMP (Seemann Composite Resin Infusion Molding Process). SCRIMP is the process combining RTM, VARI (Vacuum Assisted Resin Injection) and vacuum bagging. SCRIMP uses high permeable layer (medium) mounted on fabric layers so that resin can be introduced easily in the planar direction and then flows through the thickness. Its major application is large-scale parts with low void content. Fig.10 shows the schematic diagram and apparatus of SCRIMP.

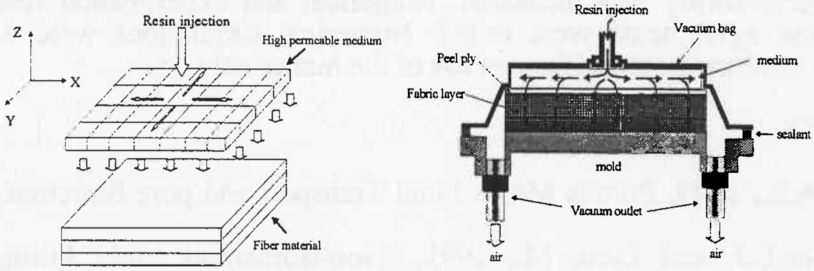
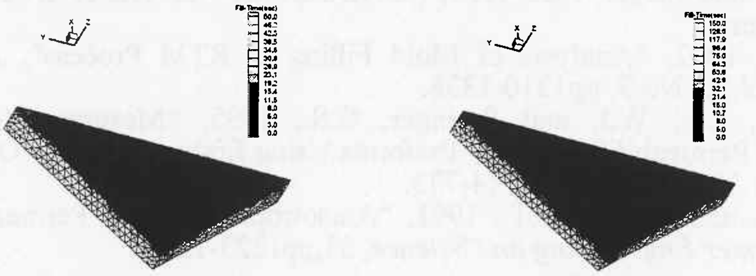


Fig.10 Schematic diagram of SCRIMP

In numerical simulation, there were two layers having different permeabilty. As usual, high permeable layer (medium) has 50~90% porosity and much higher permeability than fabric layers. The permeability of the medium was $2.67\times10^{-7}\,m^2$. The permeability of the fabric (glass - unidirectional stitched mat) was $9.51\times10^{-9}\,m^2$ in the planar direction, $7.40\times10^{-11}\,m^2$ in the thickness direction. The permeability of the fabric was measured by the three dimensional measurement technique described above. The inlet pressure was 1atm and the computed region was 1/4 part of real geometry (30cm×30cm×3cm). The result of simulation was as follows.

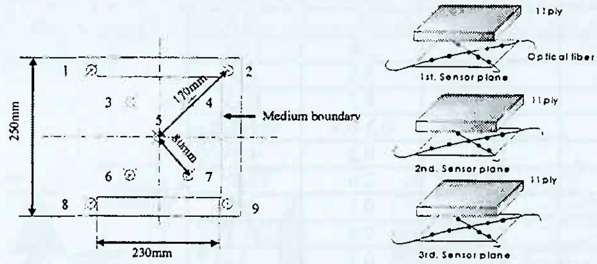


(a) 50sec (b) 150sec

Fig.11 Simulation of SCRIMP

The result shows the features of SCRIMP very well. Resin spreads over very fast through the medium and propagates into the fabric layers simultaneously over all areas. Therefore flow pattern forms nearly parallel flow front and thereby it is possible to achieve fast mold filling.

An experiment was performed to verify this numerical simulation. The mold scale is the same as numerical simulation and the sensor points to detect flow front are as follows.



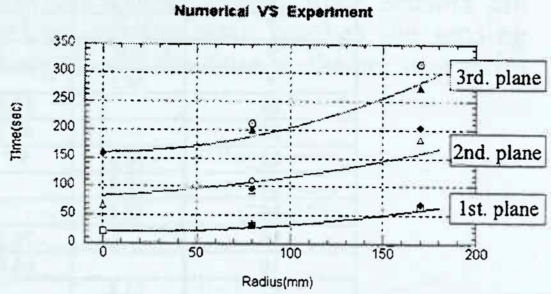


Fig.12 sensor points of planar and axial direction   Fig.13 Comparison between numerical and experiment

In Fig.13, numerical results and experimental data was compared. The results show relatively good agreement between experimental results and numerical simulations.

CONCLUSIONS

Numerical code for the RTM process was developed. Three dimensional analyses of resin flow were performed including non-isothermal effect and conversion distribution. Using optical fiber sensors, the flow front location was monitored and the three dimensional permeability was measured. Numerical and experimental results were also compared. Close agreements were found. Numerical simulations were done for some practical cases to illustrate the effectiveness of the numerical code.

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