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THERMAL AND FLOW ANALYSES OF A RESIN TRANSFER MOLDED COMPOSITE CYLINDER

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Abstract: This paper presents the results of mold filling and cures analyses of a Resin Transfer Molding (RTM) process. Three dimensional mold filling and cure analyses have been performed to model resin transfer molding of a hollow composite cylinder. Fiberglass and carbon fiber mats with EPON826 epoxy resin composites are considered. Numerical models are developed in commercial finite element software to simulate resin flow into a mold of cylindrical shape. The cylindrical part has inner and outer diameters of 9 and 10 centimeters, respectively while its length is 100 centimeters. Resin flow through fiber mats is modeled as flow through porous media with Darcy's law. The effects of reinforcement type on mold filling times are investigated. In modeling the composite cure cycle, three-dimensional energy and species equations are solved in the mold domain using a finite difference method. Thermal and cure histories of the composite part are determined in the cure cycle. Based on the results of this investigation the injection cycle of the process is the most time consuming part in the manufacturing of these composite parts. This information can help in the design of the mold, selection of injection pressure, and the cure cycle parameters prior to part manufacture.

Keywords: Resin Transfer Molding, Mold Filling, Flow Through Porous Media, Thermal and Cure analyses

1. INTRODUCTION

Resin Transfer Molding (RTM) is a process which involves transfer of resin into an enclosed mold containing previously positioned reinforcement preforms. This process can be employed to manufacture large and complicated parts. Typical examples of products that are produced with RTM include fiberglass boats, swimming pools, bathtubs, and parts in automotive and aircraft industries [1,2]. The reinforcement is composed of several layers of woven fiber mats laid inside a two-piece mold. The mold is closed and resin is injected into the mold through one or multiple injection ports and impregnates the fibers of the preform. The injection is continued until the mold is completely filled. The mold filling process is carried out under low pressure, thus reducing the restrictions on the tooling equipment. Once the mold is filled, injection is stopped and the part is cured inside the mold by increasing the mold wall temperature. The integrity of the finished part in RTM process depends on the selection of the preform, surface treatment of fibers, design of the mold, the choice of resin type, filling parameters, and the resin cure conditions.

Mold design is a highly labor intensive and complex operation [1]. Proper mold filling requires proper positioning of the inlets and outlets, close monitoring of mold temperature and injection pressure, and selection of optimum resin flow rate into the mold. If the inlet pressure or resin flow rate is set too high, fiber wash out could occur [2]. Fill time must be long enough to ensure complete fiber impregnation. Also, by proper positioning of the injection ports, one can reduce the possibility of void formation. Mold wall temperature should be set at proper levels to assure complete cure of the part in a reasonable time. If the mold wall temperature is set too low the part might not cure at all or cure time becomes too long. This increases production time and cost. If the mold wall temperature is set too high, resin could char and damage the part. Thus, before any attempt is made in manufacturing, the optimum injection and cure cycle parameters must be determined for each part geometry and resin/fiber combination.

Due to the interaction of different variables and the complexity of the process, mold and process design and optimization is currently performed using the trial and error practice. Experimental methods for optimization of mold and process design can be too time consuming and economically prohibitive. A computer model capable of simulating the process can help manufacturing engineers and mold designers in optimizing various parameters involved before a new mold or part is manufactured.

2. LITERATURE SURVEY

Large amount of research has been carried out on modeling RTM processes using finite element methods in recent years. Golestanian et. al. have modeled resin flow in rectangular and irregular mold geometries [3,4]. First, they have determined fiber mat permeabilities for woven fiberglass and carbon mats experimentally. Next, a numerical simulation was performed and the results were verified with experimental measurements. Their results showed the importance of edge effects on resin flow behavior in small cavities. In a separate research, they also performed thermal and cure analyses of rectangular composite parts. Finally, using these results, they determined curedependent mechanical properties of both composite systems [5]. Trochu, Gauvin, and Gao [6] developed a finite element model capable of predicting pressure distributions and resin front positions within the mold. They considered mold configurations with one or two injection ports. They also studied molds with inserts and the case of anisotropic preforms. They presented experimental verifications of their models. Chan and Hwang [7] employed a two-dimensional finite element method to model resin transfer molding process of thin composite parts. They investigated the effects of inlet resin temperature and resin injection pressure on the mold filling time. No experimental verification is presented for their models. Gauvin and Trochu [8] simulated two dimensional flows through molds to obtain resin front and pressure distributions. They presented comparisons between experimental and numerical results for three cases. Parnas and Phelan [9] considered one-dimensional flow through the mold to study the effects of preform heterogeneities in RTM. In their work, consideration was given to the macroscopic flow of resin through the preform and the impregnation of the fiber bundles. Boundary inhomogeneities were investigated by solving the problem of parallel flow through porous media bounded by an open channel next to the mold wall. The results of their work illustrated the importance of edge effects and deviation of experimental results from those obtained from Darcy's law. Perry et al. [10] also performed flow analysis of an RTM process. They conducted permeability measurements on woven graphite fibers. A two-dimensional mold filling was modeled by these researchers. In another study, Um and Lee [11] simulated the mold filling stage of resin transfer molding using boundary element method. They also presented experimental verification of their results. They considered resin flow in two and three dimensions. Isothermal mold filling of two- and three-dimensional cases were modeled by Young et al. [12]. They presented experimental verification of their model. Broschke and Advani [13] considered mold filling stage for an anisotropic preform. They used finite element method to model three-dimensional shell geometry. Their analysis concentrated on variation of fiber mat permeability. They also presented experimental verification of their models. Lam et. al. used finite element method to simulate mold filling in rectangular and semi-cylindrical compo-site parts [14]. They considered one dimensional resin flow and did not model composite cure. Lim and Lee [15] simulated mold filling of thick rectangular composite parts. They also performed thermal and cure analysis of the composite part. They determined three-dimensional permeability tensor for glass fiber mats. These investigators compared their flow analysis results with experimental measurements and found up to 32% error in resin front positions. This error was observed in some locations, but was much lower in most places inside the mold cavity. These researchers also performed flow analysis in centrifugal pump cover geometry. They did not perform any thermal and cure analyses. Han et. al. performed permeability measurements of anisotropic fiber preforms with high fiber contents [16]. These investigators performed pressure measurements at four locations in the flow field to determine the permeabilities for several types of fiber preform. Choi et. al. [17] used a finite element software package to determine permeability at a microscopic level. They then developed a flow model to predict resin flow in real fiber preforms. Their model predicts the interrelation-ship between preform properties such as permeability, fiber packing, fiber radius, and fiber volume fraction. Sawley et al. used smoothed particle hydrodynamics in finite element models to predict flow through porous media [18]. They modeled the porous media as a network of particles between which fluid flows. They performed experimental measurements and compared the results with their numerical results. They demonstrated that Darcy's law predicts flow accurately when the drift velocity is low. Kay investigated the possibility of manufacturing the front part of a helicopter by an RTM process [19]. He showed that this part which consists of many different pieces could be manufactured as one single piece, thus reducing labor and manufacturing costs. He used an electron beam curing resin for this part. He did not, however, present any results on ther-mal and cure analyses.

All of the above investigators modeled resin flow inside the mold as flow through porous media and employed Darcy's law in their analyses. Most of these researchers have considered two-dimensional rectangular molds. None have modeled resin flow in three-dimensional cylindrical molds. No one has performed thermal and cure analyses of cylindrical composite parts manufactured with an RTM process. The current research is intended to cover areas not addressed by other researches. Three dimensional mold filling and cure analyses have been performed to model resin transfer molding of a hollow composite cylinder. Details of these models and the results of these analyses are presented in the following sections.

3. THEORY AND IMPLEMENTATION

In order to simulate resin transfer molding of a hollow composite cylinder two main tasks have been performed: 1- Three dimensional mold filling and 2- Cure and thermal analysis. The first task was carried out by a commercial finite element software while for the second task a finite difference program was developed and used by the authors. These two tasks will be explained in the following sections.

3.1 Resin flow analysis

Numerical models are developed in ANSYS finite element software to simulate the mold filling stage of an RTM process. In this study the flow of a polymer resin in woven preform mats is considered. The axis of the mold is considered to be horizontal throughout the injection cycle. Flow of the resin in the woven fiber mats was modeled as flow through porous media and Darcy's law was used in the analyses.

For the flow of a fluid through a porous medium the equations of continuity and motion are replaced by [3, 21];

Modified equation of continuity:

$$\varepsilon\frac{\partial\rho}{\partial t}+\nabla\bullet(\rho v)=0 \tag{1}$$

Darcy's law:

$$v=-\frac{K}{\mu}(\nabla P-\rho g) \tag{2}$$

In equation (1) ε is porosity of the fiber bed, ρ is fluid density, t is time, and v is fluid velocity. In equation (2) $\underline{K}$ is the permeability tensor, μ is the fluid viscosity, and ∇P is pressure gradient.

In case of an RTM process the resin is considered to be incompressible, then the continuity equation reduces to:

$$\nabla\bullet v=0 \tag{3}$$

In addition, the gravitational forces in the momentum equation are negligible, then equation 2 reduces to:

$$v=-\frac{K}{\mu}\nabla P \tag{4}$$

Then, from equation 3, for the flow of an incompressible fluid through a porous medium with negligible gravitational forces Darcy's law reduces to [21];

$$\nabla \cdot \left(-\frac{\underline{K}}{\mu} \nabla P \right) = 0 \tag{5}$$

Boundary conditions for equation 5 are:

- $P = P_o$ at the injection port, Where P_o is the injection pressure.
- $P = 0$ at the resin front, and
- Along the impermeable mold boundary the derivative of the pressure in the outward normal direction is zero.

Proper modeling of resin flow inside the mold requires the knowledge of the fiber mat permeability and resin properties. This mat property was determined experimentally by the first author for both types of fiber mats (glass and carbon) considered in this research. The details of this analysis are presented in reference [3]. The resulting permeability values are listed in Table 1. Resin and fiber mat physical properties were also taken from reference [3] and are listed in Table 2.

In the present investigation mold filling simulations of the cylindrical mold geometry are carried out for both glass and carbon. Epoxy resin is used as the fluid. The mold geometry and injection port position are shown in Figure 1. Resin is injected from one end of the mold at a constant injection pressure of 500 kPa. in each case. ANSYS finite element software is used in the analysis. Due to symmetry a quarter of the mold has been modeled in ANSYS. The time-dependent resin flow is analyzed as a quasi steady-state problem. This approximation is valid if a proper time stepping is selected [3]. The analysis procedure involves taking a small region at the injection port at the beginning of the injection cycle as the first saturated region. This region is modeled in ANSYS and the boundary conditions are applied. By solving the model, the pressure distribution is determined in this small region. Then the resin front velocity is determined using Equation 1. A proper time step is selected and the resin is advanced into the mold according to the resin front velocity and the selected time step. Finally the new resin saturated region is modeled. These steps are repeated until the mold is completely filled.

The time step selection is based on the Courant number restriction. This means that the resin is advanced one element length at each time step. At the early stages of the modeling smaller mesh and consequently smaller time steps are used. This is because pressure gradients and thus resin velocity is high at the beginning of the injection cycle. Time steps as small as 0.01 seconds are used at the early stages of the mold filling. As the resin front reached the end of the mold time steps as large as 500 seconds could be used. A sample of the meshed geometry in ANSYS software is shown in Figure 2. This figure shows a model at the last stage of the mold filling when the resin has advanced all the way into the mold. Note that smaller elements are used at the resin front position (near the end of the cylinder).

This provides higher precision in the determination of resin front velocity and direction. The resin front profiles at various stages of mold filling process are presented in Figures 3 and 4 for both composites.

Results of flow analysis on carbon/epoxy composite are presented in Figure 3. The numbers given near each profile are time in seconds. Note that resin advances very quickly into the mold at the early stages of the injection cycle. As the resin front advances further into the mold, pressure gradient drops and resin velocity decreases. In fact it takes about 2900 seconds for the resin to fill the last 10 centimeters of the mold. It takes 17770 seconds for this composite to fill completely.

Resin front positions for the fiberglass/epoxy composite are shown in Figure 4. Fill time for this composite is about 2800 seconds. This is almost one-sixth of the fill time obtained for the carbon/epoxy composite. The reason for higher fill time for carbon/epoxy composite is lower permeability of carbon fibers compared to fiberglass fibers. See Table 1.

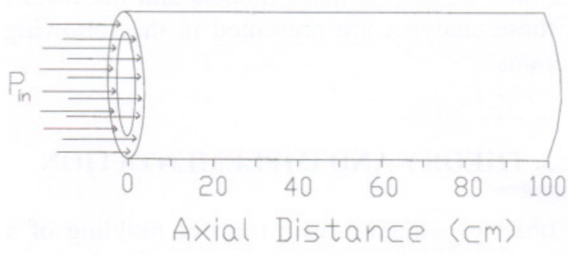

Fig. 1. The cylindrical mold geometry and the end injection port position.

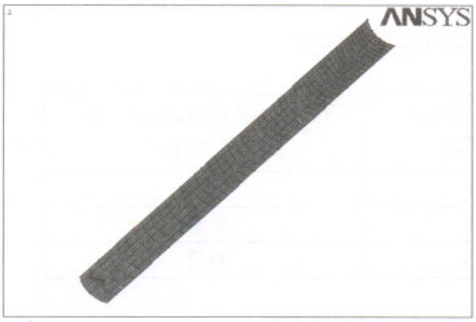

Fig. 2. Meshed geometry of the cylindrical mold. Note that smaller elements are used at the resin front (end of the cylinder).

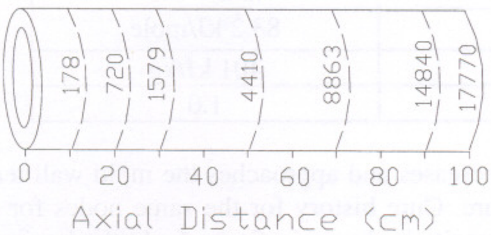

Fig. 3. Resin front positions for carbon/epoxy composite. The given times are in seconds.

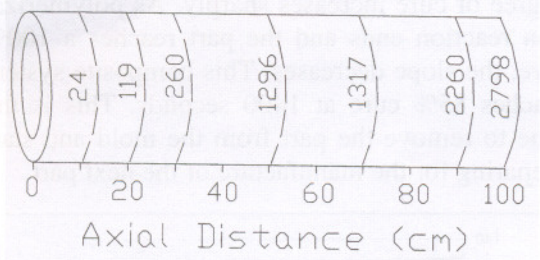

Fig. 4. Resin front positions for fiberglass/epoxy composite. The given times are in seconds.

Table 1. Experimental Permeability results for the fiber mats.

Fiber Mat	Permeability (m^2)
Glass	2.18e-8
Carbon	3.56e-9

3.2 Cure and Thermal analyses

After the injection cycle of the process was analyzed, the cure cycle was modeled. The goal in this stage of the analysis was to determine thermal and cure histories for both composite systems. The energy equation in cylindrical coordinates with no convective heat transfer is given by:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(r k_r \frac{\partial T}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial \theta}(\frac{k_\theta}{r}\frac{\partial T}{\partial \theta}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) + \dot{S} \tag{6}$$

where; ρ is the density, C_p is the specific heat, T is temperature, k_I are thermal conductivities, r, θ, and z are coordinates. $\dot{s}$ is the source term due to resin cure given by;

$$\dot{S} = C_I k_o \exp(\frac{-E}{RT})(1-\psi)^n (\Delta H) \tag{7}$$

In equation 7: C_I is the initial concentration of uncured resin, k_o is the pre exponential constant, E is the activation energy, R is the gas constant, and ΔH is the heat of reaction. Finally, ψ is resin degree of cure given by;

$$\psi = \frac{C_I - C_A}{C_I} \tag{8}$$

where C_A is the local concentration of uncured resin.

The species equation for this case, when the resin is stationary in the mold, is given by:

$$\frac{\partial \psi}{\partial t} = k_o \exp(\frac{-E}{RT})(1-\psi)^n \tag{9}$$

The energy and species equations are coupled through the source term. Thus these equations should be solved simultaneously in the composite domain. A finite difference method based on Patankar's formulations was used to solve these equations. A total of 1500 nodes were used in the model for both types of composite systems. Initial composite temperature was assumed to be 60 degrees centigrade at the beginning of the cure cycle. The mold wall temperature was kept constant at 130 degrees centigrade throughout the cure cycle. Fiber volume fraction of 0.45 was considered for both composite systems. A 5-second time step is used in the analyses. The required thermal and kinetic properties of the fiber mats and epoxy resin were taken from reference 3 and are listed in Tables 2 and 3.

Table 2. Properties of Fiber Mats and Epoxy Resin

Material	Density (kg/m^3)	Specific Heat (J/kg K)	Thermal Conductivity (W/m K)
Fiberglass	2560	670	1.04
Carbon	1760	870	8.50
Epoxy Resin	1160	1255	0.2

Table 3. Kinetic Parameters for Epoxy Resin (EPON 826)

Parameter	Symbol	Value
Pre-exponential Constant	K_o	7.88E7 sec^{-1}
Activation Energy	E_k	83.2 kJ/mole
Heat of Reaction	ΔH	401 kJ/kg
Order of Reaction	N	1.0

A careful review of the results revealed minor thermal and degree of cure gradients through the part thickness. There were no differences in thermal and cure results of nodes along the cylinder (z-direction). This was expected since all boundary nodes along the cylinder were kept at the constant cure temperature. Nodes at different locations through the composite thickness showed between 2 degrees difference in thermal results. This difference is more pronounced at the early stages of the cure cycle and diminishes as thermal energy is conducted to the inner sections of the part from the wall. Largest difference in degree of cure through the thickness of the part was about 2 percent. Based on these observations, four nodes in thickness direction of the composite part were selected for the presentation of the results. These nodes will be referred to as nodes 1 through 4. Nodes 1 through 4 are located at 0.2, 0.4, 0.6, and 0.8 of cylinder thickness measured from the outer composite diameter respectively. The results for every other data point is plotted in the figures to reduce the number of symbols in each curve. This was done to make the curves more clearly in each plot.

Figure 5 presents thermal history of the reference nodes for the carbon/epoxy composite. Note that the composite is initially at 60 degrees centigrade. Temperature increases due to higher mold wall temperature and resin exotherm as the part cures. In fact resin exotherm is responsible for a peak temperature of 2.2 degrees above the mold wall temperature for this composite. Once the polymerization reaction is nearly complete no more exotherm is present and the composite temperature decreases and approaches the mold wall temperature. Cure history for the same nodes for this composite is shown in figure 6. At the beginning of the cure cycle the degree of cure increases slowly. Once the polymerization reaction starts the degree of cure increases sharply. As polymerization reaction ends and the part reaches a 100% cure, the slope decreases. This composite system reaches 85% cure at 1400 seconds. This is the time to remove the part from the mold and start preparing for the manufacture of the next part.

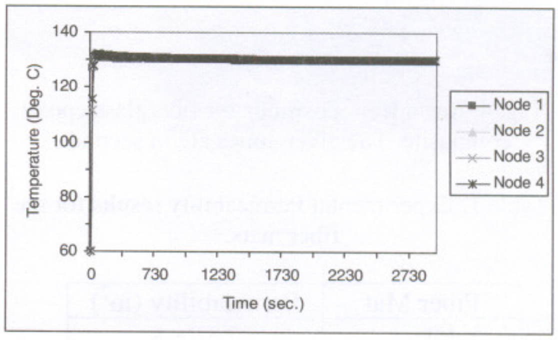

Figure 5. Thermal history for carbon/epoxy composite.

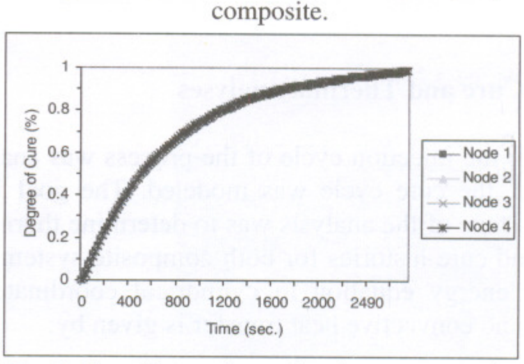

Fig. 6. Cure history for carbon/epoxy composite.

Thermal history for reference nodes of fiberglass/epoxy composite is shown in figure 7. This curve has the same trend as the thermal history for carbon/epoxy system. The temperature peak is 2.2 degrees above the mold wall temperature for this composite system as well. Cure history for this composite system is shown in figure 8. The trend is the same as that of carbon/epoxy system. This composite reaches 85% cure at 1400 seconds as well. The reason for equal cure times for both composites is the part small thickness and equal fiber volume fraction of both composite systems.

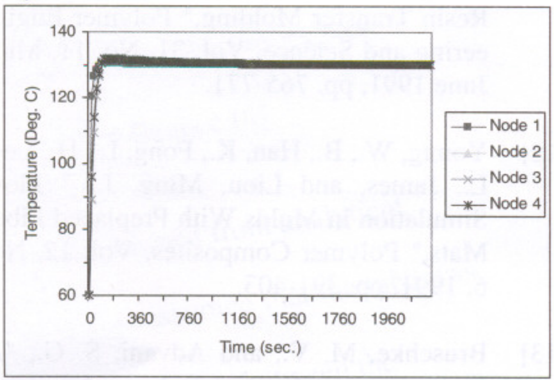

Fig. 7. Thermal history for fiberglass/epoxy composite.

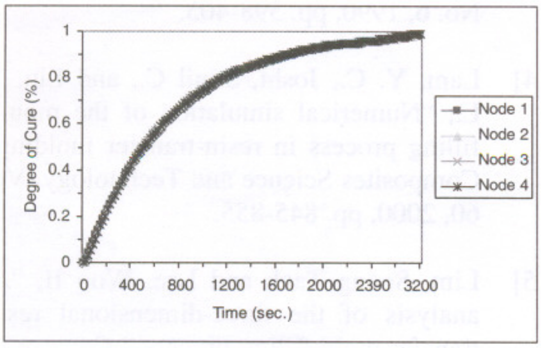

Fig. 8. Cure history for fiberglass/epoxy composite.

3.3 Evaluation of Results

It was necessary to verify the results of this work. This is done by comparing the trends of the current research results to published data. As was mentioned in the literature survey, no one has modeled resin flow and cure in a cylindrical part. Therefore there is no possibility of verifying the results directly. Performing experimental measurements to verify the results is another approach, but this requires rather expensive equipment and that is not available at this time. Therefore it was decided to check the trends of the results with available references. For verifying the results of the flow analysis part previous published work from the first author was selected. In a journal paper from the author's PhD thesis he determined resin flow positions in a rectangular mold [4]. The results of that study also indicated fill times in carbon fibers to be about six times that of glass fibers. This is also what is seen in the results of mold filling analysis in this study. Chachad et al. performed numerical thermal and cure analyses of a pultrusion process [21]. They also performed experimental measurements of temperature and DSC scans to measure the degree of cure for round pultruded parts. The trends of thermal and cure results in their work is very similar to the trends of the results of the current study.

Therefore some degrees of confidence can be put on the results of proposed model for the resin transfer molded composite cylinder .

4. CONCLUSIONS

Resin flow inside the mold was modeled as flow through porous media in ANSYS finite element software. Numerical models were developed which simulate resin flow in fiberglass and carbon fiber mats. Fill times for composites with carbon fibers were much higher than fiberglass composites. The flow analysis results on this composite suggest the need for multiple injection ports for long composite parts. Lower permeability of carbon fibers is the reason for this increased injection time.

In the second part of this study, models were developed to simulate the cure cycle for both composite systems. Resin exotherm resulted in a peak composite temperature of 2.2 degrees higher than the mold wall temperature. Fiberglass/ epoxy composite reached 85% cure in 1400 seconds. Total production time (injection and cure) for this composite system was determined to be 4200 seconds (about 70 minutes). Carbon/epoxy composite reached 85% cure also in 1400 seconds as well. Total production time for this composite is 19170 seconds (about 320 minutes). Production time for carbon/epoxy composite is about 4.5 times that of fiberglass/epoxy composite. Mold filling stage was found to be the most time consuming part of the production in the manufacturing process.

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