Analysis of non-isothermal mold filling process in Resin Transfer Molding (RTM) and Structural Reaction Injection Molding (SRIM)

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Abstract In this paper, we present a modeling and numerical simulation of a mold filling process in resin transfer molding/structural reaction injection molding utilizing the homogenization method. Conventionally, most of the mold filling analyses have been based on a macroscopic flow model utilizing Darcy's law. While Darcy's law is successful in describing the averaged flow field within the mold cavity packed with a porous fiber preform, it requires experiments to obtain the permeability tensor and is limited to the case of porous fiber preform – it can not be used to model the resin flow through a double porous fiber preform. In the current approach, the actual flow field is considered, to which the homogenization method is applied to obtain the averaged flow model. The advantages of the current approach are: parameters such as the permeability and effective heat conductivity of the impregnated fiber preform can be calculated; the actual flow field as well as the averaged flow field can be obtained; and the resin flow through a double porous fiber preform can be modelled. In the presentation, we first derive the averaged flow model for the resin flow through a porous fiber preform and compare it with that of other methods. Next, we extend the result to the case of double porous fiber preform. An averaged flow model for the resin flow through a double porous fiber preform is derived, and a simulation program is developed which is capable of predicting the flow pattern and temperature distribution in the mold filling process. Finally, an example of a three-dimensional part is provided.

1 Introduction

Resin Transfer Molding (RTM) and Structural Reaction Injection Molding (SRIM) molding are relatively new processes for manufacturing continuous fiber reinforced materials. They are among the several processes that have been developed for mass production of these materials. In RTM/SRIM, the mold is packed with dry fiber preforms which act as reinforcements. These preforms are impregnated progressively by the resin injected through injection ports of the mold. After the mold is completely filled, the resin solidifies in the curing phase and the product is taken out of the mold.

The analysis of a mold filling process is a very important step in the product development stages of RTM/SRIM products. It can provide useful information to a mold designer such as pressure distributions and flow front profiles within the mold cavity which can be used to predict operating parameters, possible location of defects, hard to fill regions, and proper locations of air tabs and injection ports. Conventionally, these data were obtained based on experience and repeated experiments which are time consuming and inefficient. In order to optimize the manufacturing process and reduce the cost, computer simulation of the mold filling process is necessary. So far, many computer programs have been developed which can simulate the mold filling process. However, most of these programs require as an input the permeability tensor which must be obtained by experiments.

In this paper, we develop a computational model to calculate the permeability effective heat conductivity of the impregnated fiber preform and use it to simulate a non-isothermal three dimensional mold flow problem. The ability to calculate the permeability and the effective heat conductivity can be very valuable to the mold designer, since it enables him to try all possible different fiber arrangements – or different microstructures – as well as different air tab and injection port arrangements to avoid defects. The mold designer may then conduct few experiments with some of the best fiber arrangements found in the calculation for more accurate analysis.

Here, we also consider the mold flow through double porous fiber preforms. In many mold filling processes, the fiber preforms used are woven structures made of fiber bundles which consist of much thinner fibers. For such fiber preforms, there are two different level of pore structures: the pore structure between the fiber bundles, and the pore structure inside the fiber bundles. In the mold filling, the pores between the fiber bundles are filled first and then the pores within the fiber bundles are filled up. This will create along the flow front an intermediate region where the fiber bundles are partially impregnated. Depending on the width of the region and fiber orientations, the air inside the fiber bundle can be trapped and cause defects in the product. In the current analysis, this partially impregnated region can be estimated, which, with some experimental data, can be used to predict the partial impregnation inside the fiber bundles.

Many researchers have investigated the mold filling process in the context of RTM and SRIM. Gonzalez, Castro, and Macosco (1985) studied the process using a disk-shaped mold. They de-coupled the chemical reactions and heat transfer from the...
mold flow and solved a 1-D mold filling problem using both analytical and numerical methods. Coulter and Gücü (1988) studied the effects of anisotropic reinforcements on the mold flow. They considered an isothermal flow and developed a 2-D finite difference code to simulate the mold flow utilizing boundary fitted curvilinear coordinate systems. Young, Han, Fong, and Lee (1991) investigated the effects of permeability variations in a similar 2-D setting. They simulated the mold flow utilizing the Fluid Analysis Network (FAN) method. Bruscheck and Avani (1993) considered a non-isothermal flow and solved a 2-D momentum equation with a 3-D energy equation. They simulated the flow using the finite element/control volume method.

While many methods have been proposed and developed to simulate the mold filling process in these investigations, most of the analyses are based on the same macroscopic flow model - Darcy’s law. Darcy’s law states that the averaged resin velocity, $\mathbf{V}$ is proportional to the pressure gradient:

$$\mathbf{V} = -\frac{1}{\mu} \mathbf{k} \nabla P$$

(1)

where $\mathbf{k}$ is the permeability tensor, $P$ is the resin pressure, and $\mu$ is the viscosity. While Darcy’s law is successful in describing the overall (or averaged) behavior of the mold flow, it does not give any information on the actual flow field in the pore structures of reinforcing fiber mats. All the interactions between the resin and fiber mat are summarized and represented by a single permeability tensor $\mathbf{k}$, which must be obtained by experiments.

Here, we take the microscopic approach to model the non-isothermal mold flow. In the microscopic approach, the flow through the fiber preform is analyzed based on the boundary conditions which account for all the fibers in the flow field. It may seem beyond the limitations of the computational capability to calculate the actual flow field within the fiber mat while considering the reinforcing fibers as boundary conditions. However, there is a method to calculate the averaged flow field while taking care of the actual flow field. Using the homogenization method, one can simulate the mold filling process in terms of averaged flow field and calculate the actual flow field between the reinforcing fibers whenever necessary.

The homogenization theory appeared in the 1970’s and has been the subject of considerable research in different areas of applied mechanics. The theory deals with partial differential equations of physics in heterogeneous materials with periodic structures when the characteristic length of the period is small. The fundamentals of the theory can be found in the works of Lions (1981) and some generalizations can be found in the works of Lene (1984). Application of the method to the flow and transport through porous media was first done by Keller (1980) and Tartar (1980) who showed the derivation of Darcy’s law as a macroscopic equation from Stoke’s equations as a micro-model. After the pioneering work of Keller and Tartar many applications followed (Arbogast 1989, Hornung 1991).

In the homogenization method, it is assumed that the flow domain is locally formed by spatial repetition of a “microscopic cell” which is very small compared to the overall dimension of the flow domain. With this assumption, the governing equations for the actual flow field are converted to a set of microscopic equations and macroscopic equations. The microscopic equations govern the characteristic flow field within the microstructure, and the macroscopic equations govern the averaged flow field of the mold filling. From the solutions of the microscopic equations, the permeability and averaged heat conductivity of the flow domain are calculated which, in turn, are used to solve the averaged flow field in the macroscopic equations. After the simulation, the solutions of the microscopic equations can be post-processed to give the actual flow field within the microstructure. Advantages of the homogenization method are: parameters such as permeability of the flow domain and effective conductivity of the impregnated fiber preform can be calculated; the actual flow field within the pore structure can be obtained as well as the averaged flow field; and the method is based on a rigorous mathematical theory.

In the following sections, we utilize the homogenization method to obtain the governing equations of a non-isothermal mold flow through double porous fiber preforms. First, we give a brief derivation of the homogenized governing equations for the mold flow through porous fiber mat and compare them with those of other methods in terms of permeability and averaged heat conductivity. Next, we derive the governing equations for the mold flow through a double porous fiber mat. Then, a computer program is developed which is capable of predicting the flow pattern and the temperature distribution within the mold cavity. The program is based on the finite element/control volume method and the Crank Nicholson method and is capable of simulating the mold filling of three dimensional parts. Finally, an example is provided for a simplified composite crossmember of a passenger van. In the example, the flow pattern, temperature distribution, and the actual flow field within the mold cavity is obtained and plotted.

2 Resin flow through porous fiber preform

2.1 Mathematical model

In RTM/SRIM, the mold is pre-packed with fiber preforms. Throughout the mold filling process, the fiber preform is assumed to be rigid – it is not deformed or shifted by the resin flow. The flow of resin through the porous fiber mat is usually very slow and can be modeled as Stokes’ flow which is an inertia-less viscous flow. The inertia effect is negligible because the Reynolds’ number of the resin flow is small, and the effect of the surface tension is negligible compared to the dominant viscous force. With these assumptions, the momentum balance equation and the continuity equation of the resin flow can be written as:

$$-\nabla P + \mu \nabla \cdot (\nabla \mathbf{v}) + \mathbf{f} = 0$$

(2)

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

(3)

where $\mathbf{v}$ is the actual velocity, $P$ the pressure, $\mu$ the viscosity, and $\mathbf{f}$ the specific weight of the resin. The boundary conditions are: pressure is zero at the free flow front, and the normal component of velocity is zero at the mold walls. Either injection pressure or flow rates are prescribed at the injection ports depending on the port types.