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EFFECT OF PREFORM ASPECT RATIO ON THE UNIDIRECTIONAL FLOW FRONT DURING MOLD FILLING

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SUMMARY: In this paper, the conventional mold-filling simulation physics for the liquid composite molding (LCM) processes is investigated during the transient 1D flow in a flat rectangular mold containing an anisotropic fiber preform. The previous research indicates that the aspect ratio of the preform sample used in the experiment has a strong influence on the mold-filling pattern. The simulated flow-fronts are found to be significantly different ('tilted') from to the straight flow fronts associated with the 1D flow and the deviation seems to increase with an increase in the aspect ratio. However, 1D mold filling experiments conducted with an anisotropic biaxial stitched fiber mat do not show any tilt in flow-fronts during the impregnation of the fiber mats. Besides, the experimental inlet pressure-history is found to be nonlinear (drooping) compared to the linear simulated inlet pressure-history. The findings indicate that aspects of the predicted transient flow, especially the flow-front shape, are unrealized in real experiments and hence point to yet another weakness of the conventional single-scale flow model used in the LCM mold filling simulations.

KEYWORDS: Liquid Composite Molding (LCM), Resin Transfer Molding (RTM), mold filling, 1D flow experiment, permeability

INTRODUCTION

Liquid Composite molding (LCM) techniques which include Resin Transfer molding (RTM), Vacuum Assisted Resin Transfer Molding (VARTM), Seemann Composites Resin Infusion Molding Process (SCRIMP) and Structural Reaction Injection Molding (SRIM) have become important methods for manufacturing polymer composites that are very popular in automotive, defense, sporting goods and aerospace industries. The process steps and many practical tips about RTM have been summarized by Hansen [1]. Some of the advantages of the RTM process are low investment costs, closed process with very small emission of solvents, wide range of possible resins and fiber reinforcements, tight tolerances, good surface quality on both sides, complexgeometry components, sandwich laminates with metal inserts, simple curing cycles, moldability of both small and large components, and finally, inexpensive molds. In single-scale porous media such as random mat, it is assumed that the fiber preform behind the flow front is fully saturated with the resin, and therefore, the flow in this region can be modeled using the equation of continuity and Darcy's law corresponding to the single-phase flow in porous media:

$$\nabla . v = 0 \quad , \quad v = -\frac{K}{\mu} \nabla p \qquad (1)$$

Here v is the volume-averaged velocity of resin in fibrous porous media, p is the pore-averaged resin pressure, K is the permeability tensor for the fiber preform, and μ is the resin viscosity. Recently, researchers [2-9] discovered that the physics of resin flow may differ in certain types of fiber mats (such as the uncrimped stitched mats) and therefore, the conventional model may not be suitable for such situations. Lundstrom et al. [10] used the multicavity parallel flow technique to measure the in-plane permeability of the anisotropic fiber mats. They found that the accuracy of the 1D flow based permeability measurement methods could be affected by the ratio of sample's length *L* to its width *W* (henceforth to be referred to as the aspect ratio *L/W* in this paper). Tan and Pillai [11] used a numerical investigation on the effect of aspect ratio, anisotropy and mat rotation on the transient filling pattern in the 1D flow mold involving anisotropic fiber mats. They discovered that the flow fronts are often tilted and two dimensional, and violate the pure 1D flow assumption invoked while analyzing such flows. Our main objective in this paper is to investigate if the two dimensionality or `tilting' of flow fronts, predicted by the LCM mold-filling simulation based on the conventional physics using the saturated flow assumption behind the moving flow-front, can be observed in real 1D flow molds.

THEORY

The control volume/finite element method (CVFEM) has been used by the authors [11] to simulate the isothermal mold-filling process where the Darcy's law combined with the conventional continuity equation with no unsaturated flow effects (i.e., Eqn. 1) yields a Laplace equation for pressure distribution in the assumed saturated region behind the flow front. The simulation implements a novel algorithm to satisfy the requirement of constant pressure at the inlet on the 1D flow mold during the constant injection rate conditions. (A gap at the inlet part of the mold with much larger width compared to the inter-fiber spacing found in the fiber mats ensures that the pressure gradient in the empty mold cavity is much smaller than the pressure gradient inside fiber mat, and hence the pressure imposed on the inlet face of the preform rectangle is held a constant.)

Our experimental setup to study the shape of the developing flow-front in the standard 1D mold under constant injection-rate is shown in the Fig. 1. (Other details of the experiment can be found in [12].) In order to compare the real flow-front with the predictions of the conventional single-scale flow model, we run our numerical simulation for mold-filling based on the conventional physics [11] for the anisotropic preform used in the present experiment. All input parameters in the numerical simulation are obtained from the experiment: the preform aspect ratio *L/W* is 4, the principal permeabilities are $1.97 \times 10^{-9} m^2$ and $1.54 \times 10^{-9} m^2$, respectively; the porosity of the fiber mat is estimated as 0.634.

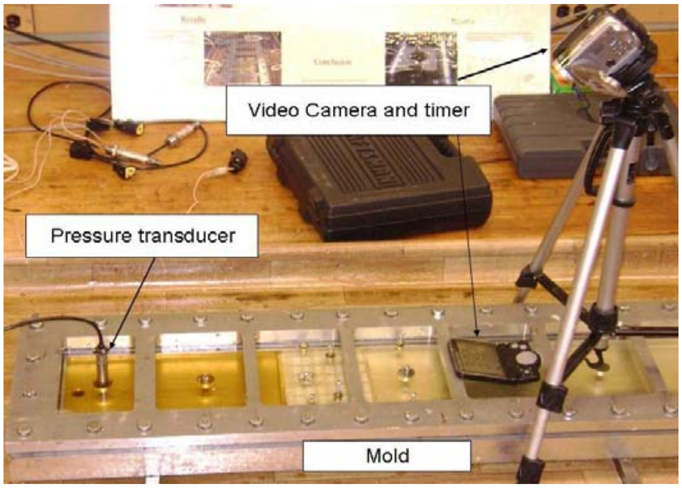
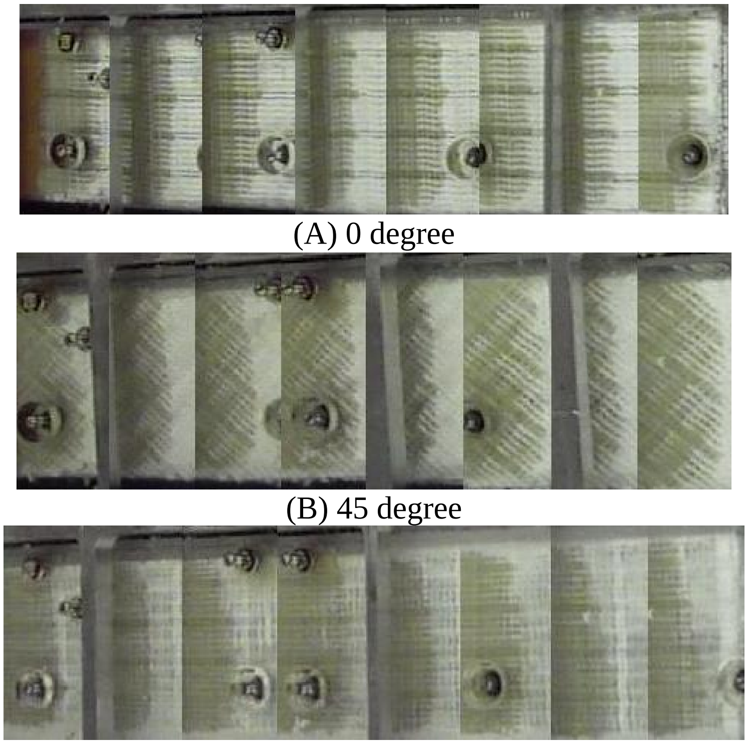


Fig. 1 Part of the setup to conduct the constant injection-rate 1D flow experiment.

RESULTS AND DISCUSSION

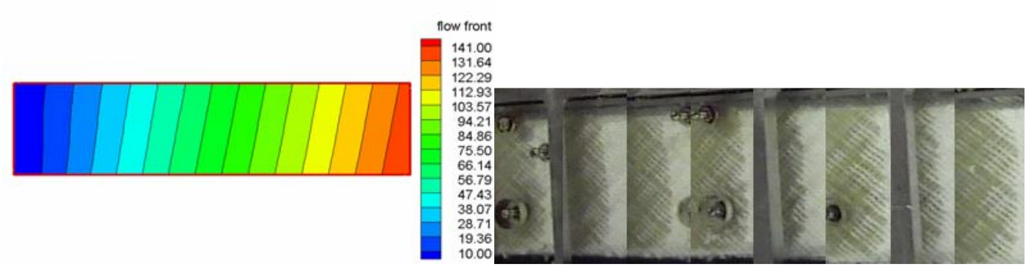
The development of flow front in the 1D flow mold (with *L/W* = 4 for the preform) is presented here in Fig. 2 for three different orientations. The figure shows a composite of several successive flow-front snap-shots with every slide taken at 20 seconds interval. The results show that discounting for the edge-effect as well as local non homogeneity, the shown flow fronts can be taken to be almost straight for the three orientations.



(A) 0 degree
(B) 45 degree
(C) 90 degree

Fig. 2 Developing flow front in the 1D mold at different fiber-mat orientations vis-à-vis the principal permeability directions.

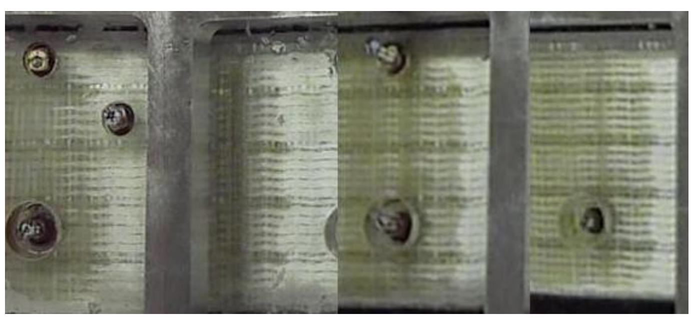
Fig. 3 compares the flow front observed experimentally during the filling of the 1D mold with the one predicted by the simulation. The simulated flow fronts progressively grow tilted with time while the observed flow-front for the bi-axial fiber mat reveals no such change. It can be easily concluded that the progressive tilting of flow front predicted by the simulation is not realized in practice.



(a) (b)

Fig. 3 A typical flow front development during the filling of the 1D mold:
(a) simulation result using the single-scale flow physics showing a clear tilt;
(b) the observed experimental flow fronts with no discernable tilt.

The flow fronts at different aspect ratios are presented in Fig. 4. Results show that discounting for the edge effect as well local non homogeneity in the preform, increasing the aspect ratio has no noticeable effect on the straightness of the flow front. This contradicts simulation results [11] where increased tilting of the flow front is predicted for an increasing *L/W* ratio.



(a) **(b)** **(c)** **(d)**

Fig. 4 The experimentally observed flow-front for the different aspect ratios:
(a) *L/W* = 1; (b) *L/W* = 2; (c) *L/W* = 3; (d) *L/W* = 4.

The inlet-pressure history (the plot of inlet-pressure with time) has been used in the past to detect the presence of unsaturated flow in fiber mats, with a droop in the history associated with the sink effect based unsaturated flow that characterizes the dual-scale fiber mats [3, 4, 6, 7, 8]. Since the biaxial fiber mat used in the experiment is a dual-scale porous medium, we also decided to compare the inlet-pressure history predicted by our simulation (based on the conventional single-scale flow assumption) with the actual pressure history observed during the experiments. Fig. 5 shows the difference in the two inlet-pressure histories: it is clear that the experimentally observed history is curved while the history predicted by the simulation is a straight line. This highlights the second weakness of the flow simulation based on the classic single-scale flow physics—its inability to correctly predict the distribution of pressure inside a mold during mold-filling when using the dual-scale woven or stitched fiber mats.

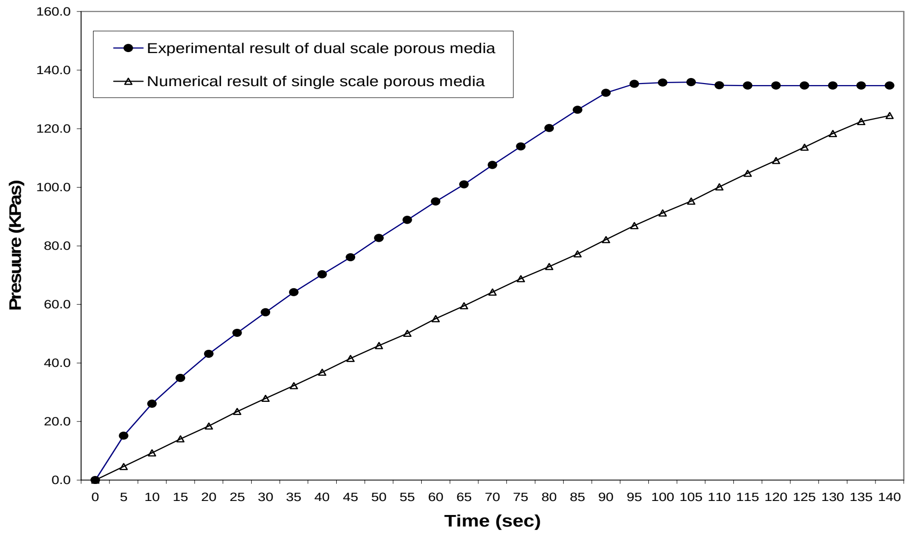


Fig. 5 The inlet-pressure history predicted by the simulation based on the single-scale flow physics with the inlet-pressure history observed for the biaxial fiber mat, a dual-scale porous medium.

CONCLUSION

The tilting of flow-fronts during the filling of a 1D flow mold for the anisotropic fiber mats, as predicted by the flow simulation based on the single scale flow physics, is unrealized in the 1D flow experiments conducted with a biaxial stitched mat having dual scale pore geometry. The dropping inlet pressure history observed in experiments is also not replicated by the simulations. This highlights the utter inability of the conventional single scale flow model used in most LCM flow simulations to accurately predict flow variables during mold filling situations involving woven or stitched mats in LCM.

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