Active Flow Control in a VARTM Process Using Localized Induction Heating

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SUMMARY: Variabilities in preform permeability can lead to the formation of dry spots and nonuniform flow progression during mold filling in the vacuum assisted resin transfer molding (VARTM) process. Real-time flow control can improve fill uniformity and eliminate potential fill related defects. Flow control schemes commonly manipulate the inlet pressures or flow rates and have been shown in the literature to be limited in their ability to steer the flow in regions far from the inlet ports [1]. A viable solution to this problem is localized heating of the resin during the mold filling process, which can reduce the local viscosity of the flowing resin to compensate for spatial preform permeability variation. In this paper localized heating is achieved using an induction heater with carbon fiber susceptors embedded in the preform layup. This type of control must be applied to the VARTM process in such a way as to heat in the lagging regions while avoiding overheating and thus prematurely curing the resin. To this end, this paper presents a real time control strategy that is demonstrated in a lab scale experimental setup, and is shown to be successful in improving the uniformity of the flow during mold filling of heterogeneous preform layups.

KEYWORDS: Vacuum Assisted Resin Transfer Molding (VARTM), Induction Heating, Active Control, Permeability Variations.

INTRODUCTION

Vacuum assisted resin transfer molding (VARTM) is an attractive and affordable method of producing composite products. In this process, a fibrous reinforcement material, termed preform, is laid into a single hard sided mold and sealed with a vacuum bag. Vacuum is drawn on the system through the exit vents and catalyzed resin is drawn from the inlet ports through the porous preform material. Part defects often arise in this filling stage when the flow follows the path of least resistance entrapping a void in a region of local low permeability or when the last location within the mold to be filled is not adjacent to an exit vent. Thus achieving uniform fill and complete fiber saturation is an essential part of producing quality products. Despite an optimum process design, process and material parameter uncertainties as well as real time and run-to-run variabilities can cause deviations from design targets [2]. Therefore, reliable fabrication must employ real-time process control to realize complete fill despite practical unpredictabilities.

Conventional control schemes seek to vary inlet pressures or flow rates in RTM process, equivalently vacuum levels in the VARTM process, with the goal of steering the flow through a desired fill pattern. It has been shown that this type of control has diminishing capabilities as the flow front moves away form the controlled boundary [1]. Spatially localized control schemes are one way of increasing controllability in heterogeneous preform layups. Here, heat will be used to locally reduce resin viscosity and compensate for flow restriction in low permeability areas. The feasibility of this concept was investigated in a previous study [3, 4], where a numerical model was used to study the effects of induction heating on the flow enhancement. In addition, a simulated optimal control scheme was developed utilizing a numerical process model of non-isothermal mold filling for VARTM [5, 6]. The goal of the present study is to implement the previously developed control scheme on a standard VARTM process and perform experiments to evaluate the effectiveness of the control on a variety of preform layups.

APPROACH

Experimental Setup

A standard VARTM molding process consisting of a square mold with line inlet and outlet located at either end, venturi pump, resin trap and resin source container, was augmented with components for induction heating control, including an Ameritherm NOVA 1.0 induction heater with a pancake style coil, a motion control system, and a computer image capture system. These components were tied together by the software based control implemented in LabVIEW. More detailed descriptions of this experimental setup can be found elsewhere [4].

During an experiment, preform layers are placed within the mold along with a carbon fiber susceptors layer. Resin is drawn into the mold with a vacuum and flow fronts were fed back from a CCD camera to the controler. Based on the information on the lagging areas of the flow front at each time instant, the induction coil was moved and powered such that the flow is steered to a desired pattern. These experiments were conducted using a glycerin and water mixture as the working fluid that closely matches the viscosity of an actual resin-catalyst system. The temperature dependence of the viscosity of glycerin, however, was found to be not as strong as that of the resin mixture. This substitution of working fluids therefore gives conservative estimates of the effects of local heating during the VARTM process.

Active Control

The active control of induction heating in the VARTM process has two main requirements: voltage and motion control. Induction coil voltage must be varied to provide significant aid for flow permeation in low permeability areas while ensuring that material temperatures are limited to within a prescribed value so as to minimize the effects of the cure reaction if an actual resin system were used. The induction coil must also be moved to insure that heating is applied to appropriate regions of the molded part.

A fundamental challenge of the chosen heating control method is that material temperatures must be limited so as not to gel the resin during the filling stage of the process.

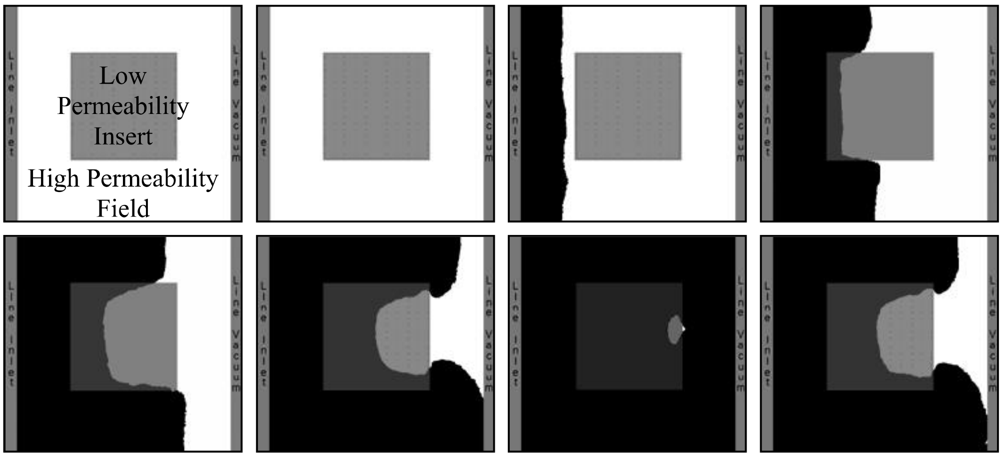
To this end, an upper bound for material temperature is specified as 100°C in this study. It is not practical to feed back material temperatures from within the molded part, where the maximum material temperatures occur, so a feed-forward scheme was developed which solves a simplified energy equation based on a lumped capacitance approach to quickly estimate material temperatures [7]:

$$\rho c \frac{\partial T}{\partial t} = \frac{-c_f h}{d}\left(T - T_\infty\right) + q''' \tag{1}$$

In this equation h is the convection heat transfer coefficient [7], d is the molded part thickness, T is the resin saturated preform temperature, q''' is the volumetric heat generation, and T_∞ is the ambient temperature. The term, c_f, is a correction factor used to compensate for the simplifying assumptions of uniform temperature through the thickness, negligible conduction in every direction, and negligible advection. A value of $c_f = 0.45$ was found to most closely fit the analytical solution to the experimentally validated numerical model presented in [4, 6]. Estimated temperatures from the model (Eq. 1) are used to choose induction coil voltages that maximize the temperature without surpassing the upper bound and thus minimize the fill times. When combined with appropriate coil motion the objective is to achieve uniform flow progression throughout the fill. Control of the motion of the coil in the y-direction (along the overall flow direction) is such that the induction coil always follows the flow front, lagging just enough to not heat any unfilled areas. The desired motion of the coil in the x-direction (width-wise direction) is to supply heating to areas lagging behind the mean flow front, thus the coil is located in the x-direction such that it is aligned with the largest flow lag. The only desired heating areas across the width of the mold are those determined as stated above. Following this logic, the induction coil is turned off during its transit in the x-direction to the target.

RESULTS AND DISCUSSION

Experiments were performed on a rectangular mold of overall dimensions 30 *cm* × 30 *cm* using a preform layup with Owens-Corning M8610 continuous strand mat comprising the majority of the mold with a 15 *cm* × 15 *cm* centrally located, low permeability, woven mat insert. The results are discussed by considering one specific preform layup in this Section. The first frame in Fig. 1 depicts the preform layup, where the relatively high permeability continuous strand material is shown in white and the low permeability woven material is seen in grey.



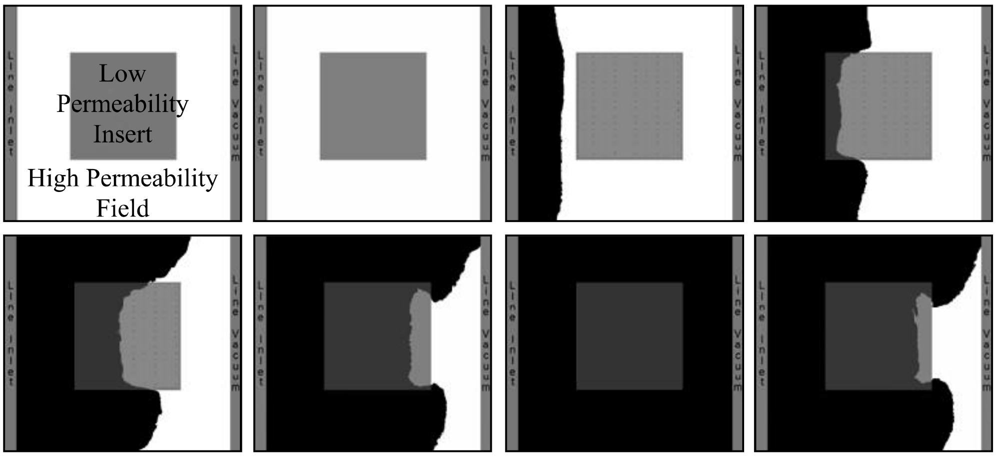
Preform Layup, 0% Fill, 20% Fill, 40% Fill

60% Fill, 80% Fill, Completed Fill Fill Time = 990 s, Ending Fill 76% Fill

Fig. 1: Flow front progression without control (without heating).

Controlled (heated) and uncontrolled (unheated) runs were preformed and flow front information was collected in each experiment at five second intervals in the form of binary image captures. Data collected in the unheated case is presented in Fig. 1. The progress of the mold filling process is illustrated in the six frames following the preform illustration at even intervals of percent fill, defined as the volumetric percentage of the mold that has been filled. The final frame, titled ending fill, will be discussed later. The flow starts from the line inlet and progresses towards the central low permeability (woven mat) patch as indicated by the black areas. A lag develops as the flow enters the low permeability region; this lag continues to grow as the flow passes through the woven mat area. The flow lag is sufficiently large such that the flow pinches off a dry spot at the exit side of the low permeability area. This dry spot will become a defect in the final part and likely result in a part failure.

The heated (controlled) fill profiles for the same preform layup are shown in Fig. 2 following a similar format as in Fig. 1. During this fill, the control dictates coil positions and voltages to steer the flow to a desired uniform flow progression in which the flow fronts are strait lines parallel to the mold width. Here the flow progresses similarly to the unheated case at first; however, upon reaching the low permeability area, the flow is seen to be more uniform than that in the unheated case. For the case studied here, the improved uniformity provided by the control leads to a void-free fill, as observed in Fig. 2.


Preform Layup 0% Fill 20% Fill 40% Fill

60% Fill 80% Fill Completed Fill Fill Time = 540 s Ending Fill 81% Fill

Fig. 2: Flow front progression with control (with heating).

Flow front geometry at the instant the flow reaches the end of the mold is indicated as the ending fill in Figs. 1 and 2. Flow profiles at this instant have important implications on the ability to successfully fill a mold in many liquid molding processes in that voids can be entrapped within the mold if the last location to fill is not adjacent to a vent. Ideally for a square mold configuration with a line inlet and line outlet, the flow would progress uniformly with flow fronts always being parallel to the inlet and outlet. Thus for a perfect fill, the percent fill at the instant the flow reaches the end of the mold would be 100% corresponding to a perfectly uniform profile. The control seeks to match this uniform profile during the entire fill and a good indication of its performance is the improvement of the ending fill shape. For the unheated case (Fig. 1) the ending percent fill noted in the last frame is 76%, and the corresponding profile has unfilled regions along most of the end of the mold as well as a significant portion of the low permeability area. The heated ending profile (Fig. 2) has a percent fill of 81% which is seen as an improvement, and moreover most of the low permeability region is filled at this instant.

Apart from improving the uniformity of the flow, the viscosity reduction achieved via local heating also speeds up the fill. The completed fill times noted in the seventh frames of Figs. 1 and 2 are 990 seconds for the unheated case and 540 seconds for the heated case. The significant improvement in fill time coupled with the improved flow uniformity has a practical impact on production. Additional studies and details on the control may be found in ref. [8], which the interested reader is referred to.

CONCLUSIONS

A flow control for the VARTM process based on localized induction heating was implemented on a lab-scale test bed and used to perform experiments on a heterogeneous preform layup with a centrally located low permeability region.

The control is designed to be independent of preform layup, allowing for compensation of unexpected preform permeability variation throughout the fill by locally heating and thus lowering the resin viscosity. Results show improved flow patterns when using the control, which can avoid entrapment of dry spots within the preform. In addition to improving flow uniformity, the control is able to significantly reduce fill times. Overall the localized induction heating flow control scheme was shown to provide practical improvements to a standard VARTM process.

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