Theoretical and Experimental Evaluation of a Segmented Injection Line for Improved Resin Flow Control in VARTM

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SUMMARY: During the infusion of resin into a closed mold that contains a preform in the VARTM process, resin flow is often affected by the inherent variations in permeability resulting from the part design as well as the variability associated with the mold lay-up. Current injection methods used for VARTM provide very limited control of the resin flow within the mold; this can result in part defects including dry (unfilled) regions and voids. Improved control of resin flow appears possible with several approaches including the development a multi-segment resin injection line that provides real time modifications to the flow front. The objective of this paper is to study the performance of a segmented, controllable (smart) resin injection line that can be used for real time control of the resin flow to different parts of the mold thus reducing part defects. Simulations of different smart injection line configurations for various mold geometries using several FEA models are studied, and the effectiveness of the smart line injection is analyzed under different scenarios including variable mold permeabilities as well as more complex geometric features in the mold. Simulation results indicate there is a significant decrease in the void area with some part designs using the segmented injection line. Optimal flow control is achieved by changing the lengths of the injection line segments and using suitable control strategy; both of which are mold and part dependent. The effectiveness of this methodology is verified with experiments that use feedback from resin sensors and actively control the resin flow in the mold.

KEYWORDS: VARTM, injection, simulation, flow control, dry spots, voids.

INTRODUCTION

VARTM (Vacuum Assisted Resin Transfer Molding) is a liquid composites manufacturing process that offers numerous advantages over other processes because of the low tooling costs and the manufacturing benefits for large structures. In VARTM, a stack of dry fiber reinforcements known as a preform is placed over a tooling surface and is enveloped and sealed with a flexible plastic bag and tacky tape. Drawing vacuum through a vent line compacts the preform and conforms it to the tool surface and the resin is drawn into this assembly through the injection line by connecting the resin reservoir to the tooling. The pressure difference of one atmosphere between the resin reservoir and the vacuum vent port drives the resin into the assembly to impregnate the empty spaces between the fibers.

After the resin reaches the vent port, a reasonable amount of time is allowed for the resin to bleed out of the vent before terminating the injection from the resin reservoir. This not only saturates the spaces between the fiber tows, but also insures the fiber tows also become fully wetted with resin. The vacuum may be maintained for an additional time after injection is completed to allow resin to equilibrate and to maintain the compaction pressure and deformation.

The preform permeability (k), fluid viscosity (μ), fiber volume fraction (V_f) and the compaction pressure are the parameters that fundamentally influence the permeation of the resin through the preform. The preform permeability, a function of the preform microstructure, often exhibits large variabilities there by creating local areas of either high or low permeabilities. Due to these variations, the actual resin flow pattern often deviates from the desired flow pattern thereby creating areas into which the resin doesn't permeate; these regions of unfilled preform are termed dry spots and voids. The formation of dry spots and voids result in the manufacture of defect parts which is a major disadvantage of the VARTM process. Hence, there is a genuine need for better flow control approaches in VARTM to compensate for permeability variations, and therefore reduce or eliminate the dry spots and voids.

Current methods used for VARTM that utilize distribution lines for resin injection and point or line sources of vacuum provide very limited controllability of the resin flow within the mold. As a result, dry spots and voids continue to limit the complexity of the mold designs as well as production efficiency. Previous research attempted to control flow using feedback of resin position [5], flow rate control [2], intelligent process control [1], localized induction heating [4] and differential vacuum [6]. Despite the availability of advanced, adaptive control methodologies, very little practical value can be derived from these techniques for VARTM until improved methods for actuation of the flow within a mold are developed. Alternative control methods that show promise for better flow control in VARTM include controlling the resin flow from different segments or regions of an injection line, and changing the local permeability of either the distribution media or the preform. This paper focuses on the improved control of the resin flow in VARTM using a segmented injection line.

OBJECTIVE

The primary objective of this paper is to investigate the potential improvements in control of resin flow using a segmented injection line. In this effort, our goal was to study the effect of the segmented injection line, which we call as a "Smart Line" of injection, in providing real time control of resin flow. Specific performance metrics, including resin flow front controllability and void formation are used in this paper to compare this approach to conventional VARTM injection methods.

MATERIALS AND METHODS

The development of a smart segmented injection line was achieved by creating controllable segments of the line which can be turned on or off to control the flow of resin. Details of the design of a multi-segment, "Smart Line" are presented in Ref [10].
The smart line configuration is based on simulations used to understand the relationship between the segment length and the resulting controllable region within the mold. The independent design parameters in this approach as shown in Figure 1 are the number of segments within the injection line (1, 2, 3, . . .), length of the individual segments (L1, L2, L3, . . .), control action distance (CD), length of the mold (L), width of the mold (W), local and bulk permeabilities of the preform. The corresponding dependent parameters would be the flow front pattern, void area and fill time. The individual segments of the injection line can be turned on or off depending on the situation. Control action distance (CD) would be the distance from the injection line at which a segment is opened or closed.

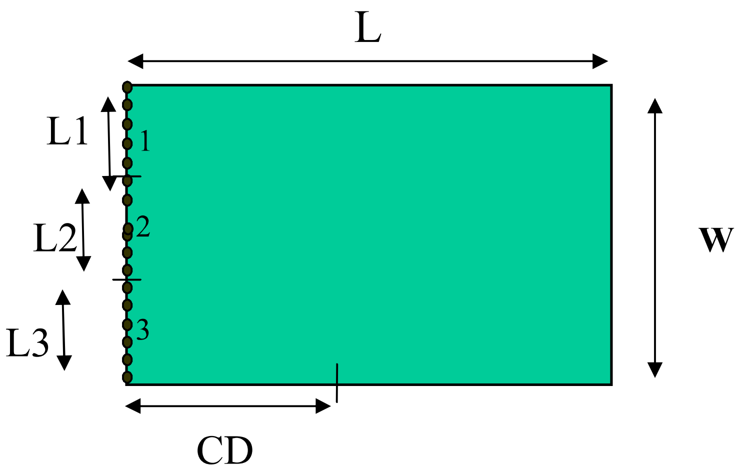

Figure 1: A simple rectangular preform that includes a segmented injection line.

To study the effects of the segmented injection line in steering the resin to all parts of the mold and to achieve the desired flow front pattern, we considered various preform patterns including molds with: different permeability regions, inserts, and race tracking channels. Once a heterogeneous preform pattern was selected, the flow pattern of the resin through this mold using the conventional VARTM method and a single injection line was first studied. An open loop (uncontrolled) flow pattern was observed as the resin progressed more quickly through the regions of higher permeabilities leaving the regions of low permeabilities dry. This resulted in the formation of the dry spots and voids. Next, for the same preform pattern, the various resin flow patterns were computed using LIMS (Liquid injection simulation software developed at the Center for Composites Materials, University of Delaware) [7, 8, 9]. The segmented injection line configuration was examined with different numbers of segments and varying lengths of the individual segments as well as different control action distances. From this, the relationship between the various line segment configurations and the controllable mold regions was determined.

By the analysis of all this data obtained using LIMS, the best suited control strategy for the selected preform pattern that prevented void formation was determined in terms of the number of segments of the injection line required (1, 2, 3 or more), lengths of the various segments (L1, L2, L3 and so on…) and the control action to be taken at different control action distances (CD). Experiments were conducted using the control strategy data obtained from this analysis, and the results are presented in the next section.

RESULTS AND DISCUSSIONS

Experiments were performed to validate the simulation results for various preform patterns. Conventional VARTM set up using a single line injection and modified set up using a segmented injection line were used for experiments, and is illustrated in Fig 2. The ability of segmented injection line to steer the resin in a desired pattern through a heterogeneous preform pattern is analyzed in this section. The preform pattern of 80 cm x 60 cm size with a high permeability region of size 30 cm x 20 cm was selected for analysis [Fig3]. The resin flow patterns for the selected preform pattern using the conventional VARTM set up with

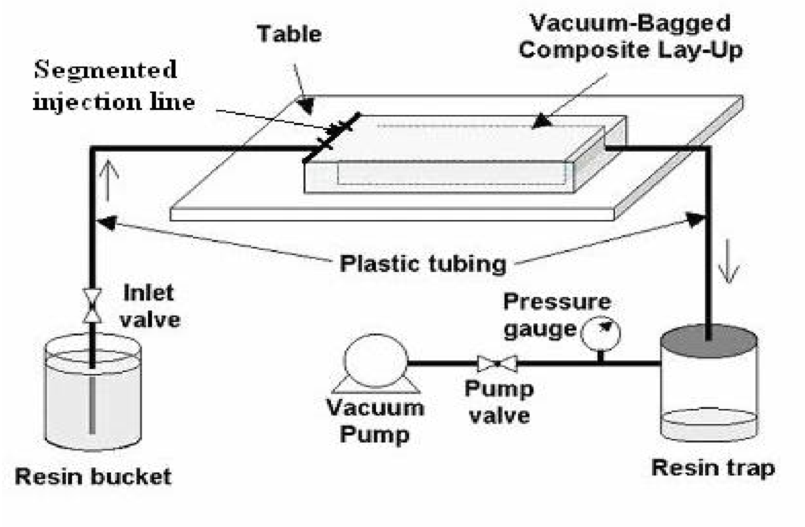

Figure 2: Experimental VARTM setup.

a single injection line were studied by running simulations with LIMS software, and then validated experimentally. Table 1 contains the details of the mold as well as the segmented line configuration used in both the simulations and experiments. As illustrated in Figures 4 and 5, it was observed that for conventional the VARTM method using a single injection line, the resin raced through the high permeability region thereby leaving the flow lagging in the other part of the mold which had lower permeability. This resulted in the formation of the dry spot on the top corner of the mold as seen in the Fig 5. The simulated and experimental results obtained for the conventional VARTM set up using single line injection are plotted at various filling stages in the mold and presented in the Fig 4, 5. Comparison of this data confirms that the simulated and experimental results were very similar.

A subsequent experiment was conducted using the modified set up with a prototype segmented injection line.

The number of segments and the control strategy required to steer the resin uniformly through the mold was determined by running a number of simulations for various injection line configurations using LIMS; the corresponding best configuration for the injection line is presented in Table 1. At the start of the injection both the segments of the injection line were kept open. Once the flow reached the higher permeability region, the second segment of the injection line was closed and the resin was allowed to impregnate only through the first injection line segment. This control action was taken at a distance of 20 cm from the point of injection along the length of the mold.

This decreased the resin flow velocity through the high permeable region and the desired resin flow pattern steering the resin uniformly to all parts of the preform pattern was achieved. This eliminated the dry spot that had formed in the conventional VARTM tests. The simulated and experimental results obtained for the modified VARTM set up using the segmented injection line are plotted at various filling stages in the mold and are presented in the Fig 6 and 7. The simulation and experimental results were found to be virtually identical. The effectiveness of the segmented injection line is validated by achieving the controlled resin flow pattern through the heterogeneous preform pattern selected. Additionally, the effectiveness of this methodology was studied by extending experimental and simulation analysis to preform patterns with induced race tracking, inserts and other homogeneous and heterogeneous patterns. Results again confirmed that improved preform filling could be achieved with the segmented injection line when compared to conventional VARTM injections methods.

Table 1: Control action strategy and segmented line configuration with reference to Fig 1

Parameter	Value	Units
L	80	cm
W	20	cm
L1	20	cm
L2	40	cm
L3	0	cm
CD	20	cm

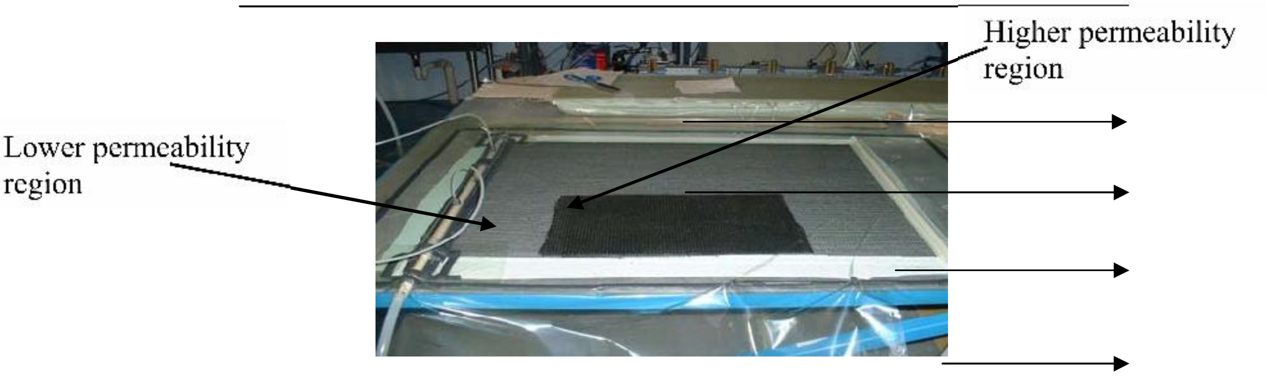

Figure 3: Preform pattern and modified set up using segmented injection line

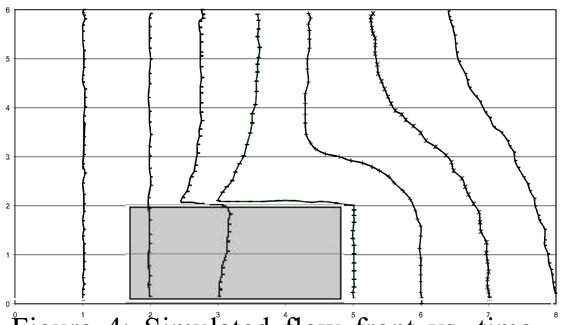

Figure 4: Simulated flow front vs. time for VARTM using single line injection

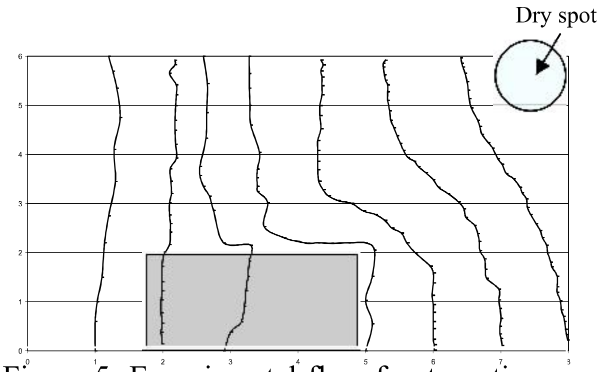

Figure 5: Experimental flow front vs. time for VARTM using single line injection

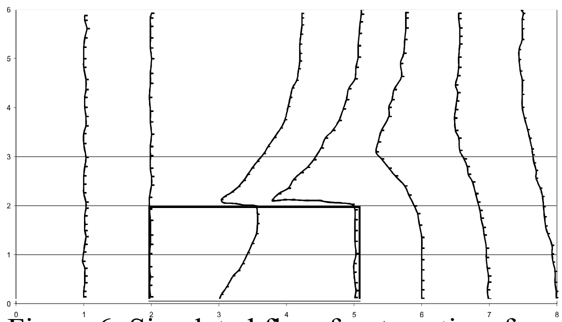

Figure 6: Simulated flow front vs. time for VARTM using segmented injection line

Figure 7: Experimental flow front vs. time for VARTM using segmented injection line

CONCLUSIONS

The capability of controlling the resin flow in VARTM using a novel segmented injection line was demonstrated through both simulations and experiments. This technique has proven to be a very important strategy in achieving better flow control, especially where variations in permeability and complex mold shapes are present. Results indicate there is a significant decrease in the void area with the segmented injection line. Optimal flow control is achieved by changing the lengths of the injection line segments and using suitable control action; both of which are mold dependent.

ACKNOWLEDGEMENTS

This study was supported as part of the Advanced Materials Intelligent Processing Center (AMIPC), Multifunctional Manufacturing Grant from the Office of Naval Research (ONR). The authors would like to gratefully acknowledge this support.

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