Design and Performance of a New VARTM Resin Injection Line

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SUMMARY: Improving control of the resin flow and resulting flow front within a mold during VARTM will be an important development that significantly improves molded part quality. Additionally, current practices like extending injection times to minimize dry spot formation result in excessive resin waste as well as increased cycle times. To improve process controllability during VARTM, a new and innovative resin injection line was designed and tested. The injection line, which consists of individual segments each independently operated, allows for the control of resin flow to different locations within the mold. Several generations of prototypes have been used to demonstrate that a simple vacuum-based actuation technique for each line segment provides the most cost effective configuration that meets the performance requirements. Current research is focusing on optimal design geometry that improves dynamic response and minimizes hysteresis-like behavior.

KEYWORDS: VARTM, injection, smart line, flow control, segments.

INTRODUCTION

Liquid composite molding processes such as VARTM (Vacuum Assisted Resin Transfer Molding) offer numerous advantages over other processes because of the low tooling costs and it’s applicability to large structures. VARTM basically consists of the following steps: 1) Placement of a stack of dry fiber reinforcements known as a preform over a tooling surface which is enveloped and sealed with a flexible plastic bag and tacky tape; 2) Applying a vacuum and drawing resin into this assembly through the injection line under vacuum and filling the entire space between the preform fibers in the mold; and 3) Curing of the resin in the mold. To achieve a defect free part with out dry spots and voids, it is essential to saturate the entire space between the preform fibers. The inherent variations in the key process parameters such as the preform permeability (k), fluid viscosity (μ), fiber volume fraction (V_f) and the compaction pressure along with the preform preparation and preform placement fundamentally influence the permeation of the resin through the preform. The formation of dry spots and voids that results in the manufacture of defect parts has created a genuine need for better flow control approaches in VARTM.

REVIEW OF CONTROL TECHNIQUES FOR VARTM

Improved control of resin flow has been attempted in the past with several approaches. Feedback control [3] of the VARTM process was developed to adjust vacuum levels at several vent locations within the mold. The system was based on computer-controlled pressure regulators and venturi pumps; vacuum sensors were used to measure in-situ vacuum levels at different locations in the system. This system, which was able to control accurately and quickly the vacuum levels in the vents, showed potential for flow front control. Flow rate control [2] during VARTM processing was developed in which the system applied a computer-controlled vacuum differential between the injection and vent gate with feedback from a precision scale. The controller was implemented in Lab VIEW to support the data acquisition and actuation and was applied to various molding applications to improve both processability and part quality. In another study, an Intelligent Process Control (IPC) system [1] was developed to fully automate the VARTM process, to allow material, process and part traceability and to ultimately reduce scrap and end-user costs through sensor-based real-time quality control. Based on this work, a sequential resin injection system was proposed, developed and implemented which helped in reducing the resin fill time. Recently, enhancement of flow in VARTM using localized induction heating was attempted in which an induction heating was used as a method of locally reducing the resin viscosity to counteract the effects of localized low permeability regions within the preform [4].

Each of the control techniques mentioned above for VARTM utilize distribution lines for resin injection and vacuum supply, and provide very limited controllability of the resin flow within the mold. As a result, dry spots and void formation continue to limit the complexity of the mold designs as well as production efficiency. An alternative control method that shows promise for improved resin control in VARTM by manipulating the flow from different segments or regions of the mold is examined in [7]. The underlying basis for this new resin injection technique is presented in this paper.

OBJECTIVE

The objective of this research is to propose a design and examine the performance of a new, segmented VARTM resin injection line. This paper discusses the design strategy for the line segments, the actuation method employed to control these segments, and the effectiveness of the line as a means to control resin flow from an injection line.

SEGMENTED INJECTION LINE DESIGN

Conceptual Design

The "Segmented Injection Line" consists of multiple segments that can be individually actuated thereby controlling the resin flow to different parts of the mold. Initially several different actuation methods including piezoelectric-based devices, magnetism, hydraulic and electromagnetic restrictive materials were accessed to determine the best method of actuation. A simple vacuum-based actuation technique for each line segment proved to be the most cost effective technique that meets the performance requirements. The design of the vacuum-based injection line is presented herein.

The conventional VARTM methods typically use an omega tube [Fig. 1] for the injection line. The resin reservoir is attached to one end of the tube, and the vacuum applied to the mold draws resin through the tube, out the bottom and into the preform. With this configuration, resin flows out from the entire length of the tube, and cannot be regulated unless the supply of resin to the tube is terminated. To improve the controllability of the resin flow from an injection line, independent segments within the line were created. This new configuration is illustrated in Fig 2. A circular tube with several perforations along its length that act as ports for the flow of resin into the mold is placed on top of the preform. Once the

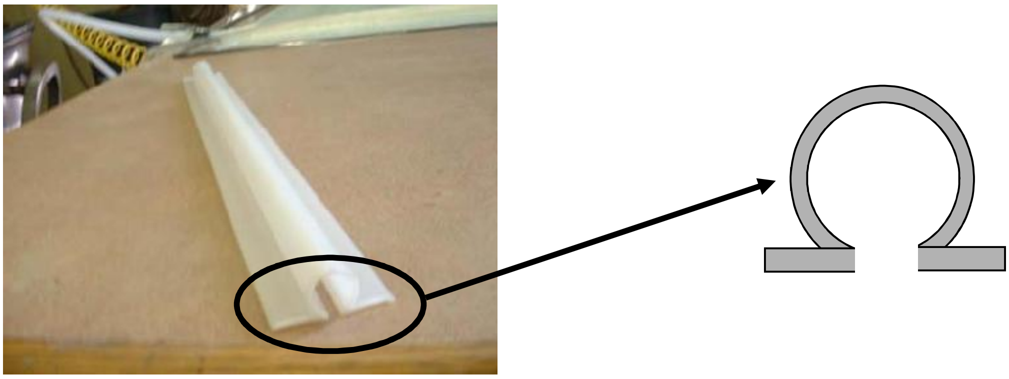


Figure 1: Conventional Omega Tube currently used for both the resin injection line and the vacuum line.

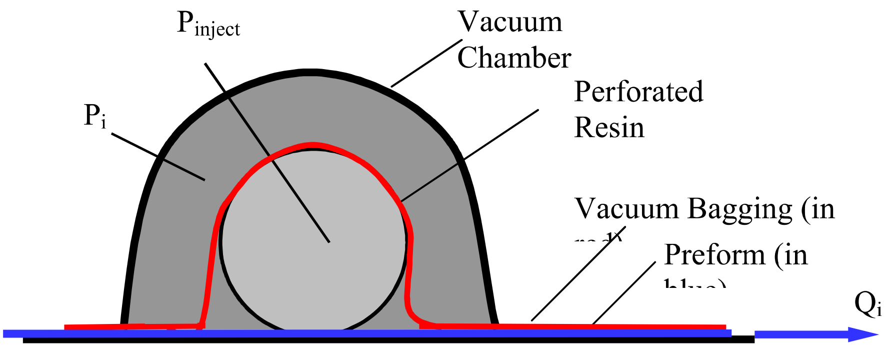


Figure 2: Typical cross-section of the segmented injection line.

tube is in place, the vacuum bag is placed over the entire mold, including the perforated tub. This circular tube is part of the conventional VARTM set up replacing the omega tube. However, unlike conventional VARTM techniques, an additional vacuum chamber is placed on the vacuum bag over the perforated tube. As a result, when a vacuum is applied to the mold, the vacuum bag is drawn against the perforated tube, and resin cannot flow from the holes. However, when a signal pressure, P_i is applied, the bag can be lifted off the perforated tube, thus allowing resin to flow from the tube into the preform. Using this approach, independent injection line segments can be created along the perforate tube with independent vacuum chambers [Fig 3a].

The resulting constitutive law for the i_{th} injection line segment will be:

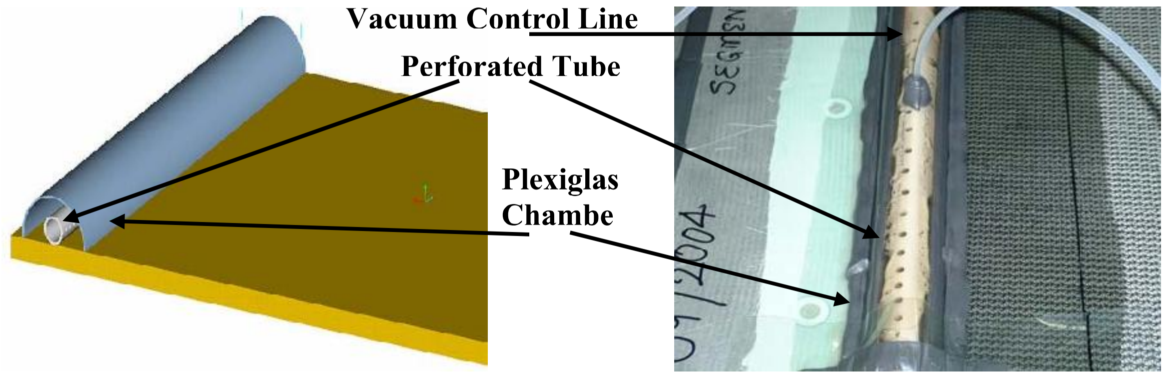
$$\text{if } P_i > P_{inject},\ Q_i = 0 \qquad (1)$$

$$\text{if } P_i < P_{inject},\ Q_i > 0$$

where P_i is the absolute pressure in the vacuum chamber and P_{inject} is the absolute pressure in the perforated resin tube.

Prototype Development

Several different design configurations were examined for the segmented line. For testing purposes, a semi-circular shaped plexi-glass vacuum chamber with both ends sealed was partitioned to create independent segments of injection line. This accommodated visual inspection of the bag and tube during operation. The chamber was placed over the injection line and sealed tightly to the vacuum bag [Fig 3]. Vertical dividers along the chamber segmented the injection line into the desired number of independent segments. A separate small vacuum line (i.e. the actuation signal) was then connected to each section of the vacuum chamber, thus allowing independent opening and closing of each segment.



(a) **(b)**

Figure 3: Solid model (a) and early prototype (b) of one segment of the new injection line.

PROTOTYPE TESTING AND PRELIMINARY RESULTS

Several experiments were conducted to evaluate the performance of the segmented injection line. Initial tests with a single line segment were used to verify the constitutive behavior described in Equation 1. In general, performance was very good as long as the vacuum bag was properly placed over the perforated tube. The intimate contact between the vacuum bag and tube necessary for the bag to seal the perforations required that no wrinkles were present in the bag. Subsequent testing of the single line segment did reveal however, that resin bleeding within the mold would allow the flow front to creep, even after the line segment was turned off. As illustrated in Fig 4, after the segment was closed, the resin flow front continued to propagate into the unwetted mold about 75 mm. As a result, the actual flow front behavior using the segmented line may, in some instances, be confounded by resin bleeding, and the ability to predict and/or control the resin movement within the mold will require a more sophisticated approach than the simple constitutive law proposed in Equation 1.

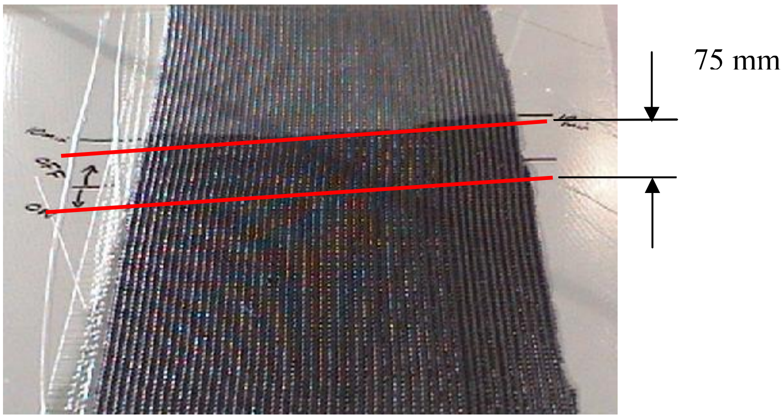


Figure 4: Evidence of resin bleeding 10 minutes after closing the injection line segment.

To investigate the dynamic behavior of the segmented injection line, a 3-segment prototype was fabricated and instrumented with pressure transducers. Pressure within each vacuum chamber segment, along with the resin supply pressure was monitored during various experiments. Of particular interest was the step response of each line segment; a typical test result is shown in Fig 5 for a step-close scenario. In general, the response time to close the segments was relatively high averaging 3 to 4 s. By comparison, the time to open a line segment averaged only 50 ms. This hysteresis-like behavior can be attributed to the fundamental difference between opening and closing a segment. When turned off, the vacuum bag cannot achieve the intimate contact necessary to seal the perforations in the tube until the resin in the vacuum chamber has been displaced into the mold. This phenomenon can be observed in Fig 6. As a result, the response time can be relatively long, especially as the resistance to flow in the mold increases during injection. However, when a line segment is turned on, the vacuum bag can pull away from the perforated injection tube relatively quickly since the resistance to resin flow through the tube and perforations is low. These effects can be substantially reduced by optimizing the vacuum chamber design, thus minimizing the volume of resin that must be displaced, especially during closing.

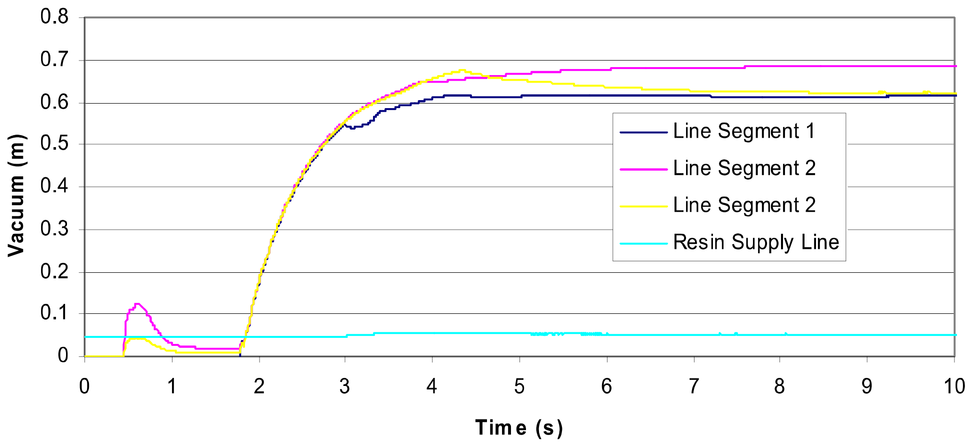


Figure 5. Step response of the segmented resin injection line.

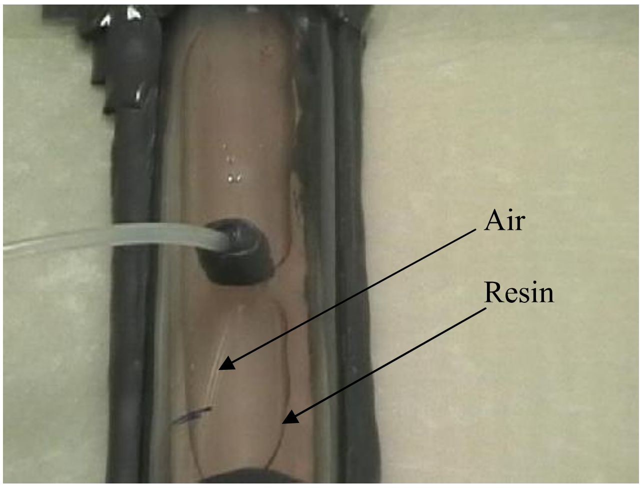


Figure 6. View of one injection line segment during a step response test.

CONCLUSIONS

A multi-segment injection line for VARTM has been design and tested. This new line, which consists of individual segments each independently operated, allows for the control of resin flow to different locations within the mold. Several generations of prototypes have been used to demonstrate that a simple vacuum-based actuation technique for each line segment provides the most cost effective configuration that meets the performance requirements. Experiments using both single and multi-section injection line prototypes prove this configuration is capable of controlling the resin flow from each segment. Dynamic performance tests during opening and closing (step response) operations suggest significant hysteresis-like behavior can occur; this effect can be minimized in future designs with proper vacuum chamber geometry.

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