RESIN FLOW SIMULATIONS IN LIQUID COMPOSITE MOLDING PROCESSES: RECENT ADVANCES AND FUTURE DIRECTIONS

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SUMMARY

The modeling approach to accommodate the variations in material data, preforming and the infusion process in Liquid Composite Molding process is presented. Simulation examples that design robust injection schemes as well as passive and active flow control and their implementation are presented. Future outlook of simulations in manufacturing of composites is outlined.

Keywords: Mold Filling, Resin Flow, Composites, Modeling and Simulation, Resin Injection

INTRODUCTION

Liquid Composite Molding

The Liquid Composite Molding labels a family of composite molding processes which use liquid, usually a thermoset resin to impregnate a stationary fibrous preform. The most common processes include Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM), though there are numerous other variations.

During the RTM process, the fibrous preform is placed into a rigid mold cavity. The mold is closed and the resin is injected into the cavity. Once the liquid resin reaches the vents, the injection is discontinued and the resin is allowed to cure before the final composite part is de-molded.

The VARTM process is similar, but the mold is one-sided. Preform is placed on the mold surface. In most cases, it is covered with a flow enhancement layer known as a distribution media (this variation is usually known as SCRIMP [1]) and finally this assembly is encapsulated with a plastic bag. Vacuum is drawn to compact the reinforcement and prevent it from moving. Resin injection is driven by the atmospheric pressure as the preform in the mold is under vacuum. Once the preform is saturated with resin, the part is cured and de-molded. There are other variations of LCM such as RTM Light in which one uses a compliant tool on the bagging side to provide better surface finish and a modest control of dimensional tolerance. One promising deviation for high volume applications is Compression Resin Transfer Molding (CRTM) in which the mold is kept partially open to inject the desired amount of resin which spreads over the preform. The injection gate is closed, the mold platen is pressed down on the resin to force it into the preform. The preform is also compressed until the desired volume fraction is achieved.

Resin Flow Modeling

The path and the time the resin takes to impregnate the preform and the dynamic pressure distribution in the mold during the impregnation phase are crucial for the process design. It will depend on the process and material parameters such as required pressure, material permeability and compliance as well as on the part geometry and injection/venting arrangement. It is difficult to estimate the resin flow path and time by heuristic methods in all but the most trivial cases. The science of flow modeling offers significant help and has proven to be very useful [2-7].

The framework for modeling the resin impregnation as flow through porous media and incorporating it in a simulation of the filling stage has been developed for some time and has been validated for the RTM process. The transition of this modeling to processes that involve deformable and dual scale porous fibrous media(VARTM, RTM light, CRTM, etc.) is still not complete, though attempts are reported and useful results were obtained [8-9].

LCM Processing and Material Variability

The process models and the resulting simulations of liquid molding have been validated in laboratory settings and produce the same unique solution every time they are run. However, the practical issue arises in manufacturing on the shop floor where the flow pattern during injection fails to repeat itself under the same processing conditions. Research has shown that the variation is not between the model and reality, but between individual instances of the process itself and due to insufficient material characterization.

The material characterization for LCM flow modeling provides a range of values, rather than a “universal” permeability constant. The source of this variability may be partially due to minor variation in fabric architecture, due to manual cutting and placing of the fabric in the mold and due to layering and "nesting" of the fabrics together to form the multi-layered reinforcement and is usually unpredictable. The issue is compounded when significant local permeability changes can occur around the inserts and along the edges and corners due to poor preform cutting, inaccurate placement and by the preform failure to conform to the mold surface, particularly around sharp corners. All these local variations will modify the resin filling patterns possibly changing the last place reached by resin (the desirable vent location). These effects will cause failure of the filling process if either the resin gels before the injection is complete or if the resin reaches the vent location before the regions between the fiber tows and within the fiber tows are saturated[10-13]. The effect of race-tracking channel on resin flow in a one-piece automotive trailer is shown in Figure 1.

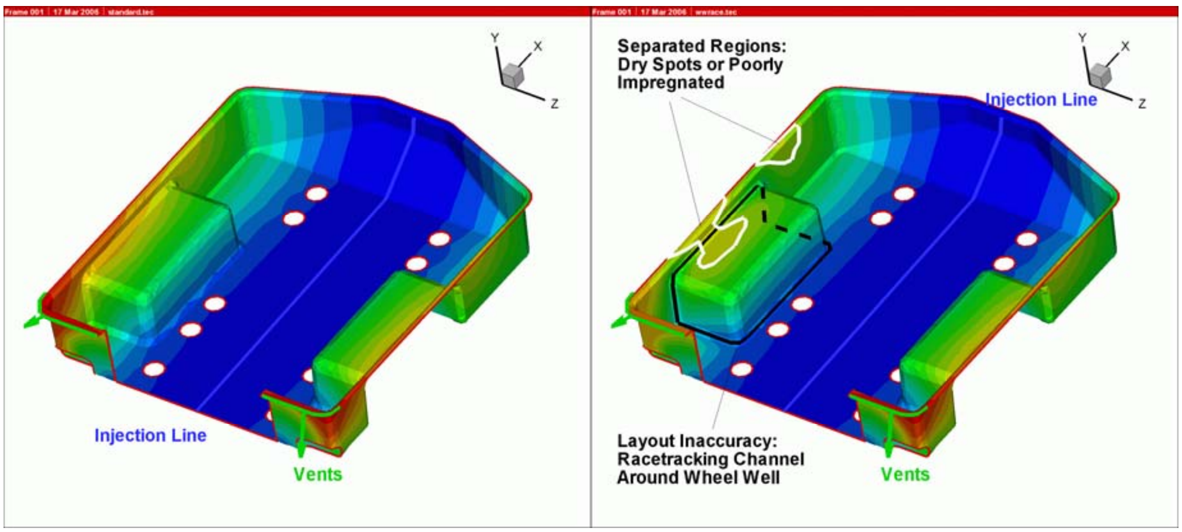

Figure 1. *Racetracking channels around wheel-well influencing the resin flow path in a composite part. The location of possible channels can be estimated. The magnitude of racetracking will vary.*

The model predicts injection only for a particular case as dictated by the data provided in the flow simulation. How can a flow model be used to address the unknowns in the process and propose a process design that accounts for the variations expected on the shop floor, in the mold and in the material to result in a void free part? The modeling approach needs to be modified to focus on multiple scenarios that account for variations of the material and the process process.

LCM MODELING

The flow through porous media, such as fiber preforms, is usually described by Darcy's law, that relates pressure gradient with flow velocity. The continuity (mass conservation) equation is used to obtain the governing elliptic partial differential equation for pressure [2]. The boundary conditions to apply are no flow through mold boundaries, prescribed pressure at flow front and prescribed pressure, flow rate or mixed boundary condition at the inlet and prescribed pressure (vacuum) at the moving flow-front. There are several algorithms available [2-7] to solve these equations.

Once the model is available, two issues must be addressed. First, it is necessary to determine whether and how the variability of process parameters may be included in the model. Second, one needs to establish algorithms that can execute the simulation with a range of parameters to determine a robust injection scheme which will produce a composite part without voids despite these variations.

The inclusion of variability in the model is straightforward. The material is described by its permeability **K** and fiber volume fraction v_f. If these properties vary, variable properties may be assigned to the model. The "geometric" variability mentioned above does not imply different part shapes, but just the different preform accuracy along edges and bends. This is equivalent to local changes of permeability and may be handled as such, preferably with one-dimensional race-tracking channels [14].

MODELING THE VARIABLE PROCESS

Every simulation executed describes only one possible combination of material properties. To provide a robust injection scheme, one has to simulate multiple scenarios that represent the expected range of input values. If the process is automated, the computer can execute literally thousands of simulations. With manual execution, the number of cases is more limited, but in many cases it is possible to reduce or even eliminate creation of voids, with a selected number of judicious scenarios.

Robust Injection Schemes

Most of VARTM-manufactured parts are essentially flat panels. To overcome restrictions on injection pressure, the sequential injection lines are introduced on the bagging side and opened when the flow arrives at that location. There are no sharp bends and, as the edges are sealed by the vacuum bag, racetracking-channels are less likely than in rigid molds. Flow is essentially one-dimensional, with the flow at the tool surface lagging behind that in the distribution media. Still, the variation of material parameters may jeopardize the injection, as premature opening of the next sequential line may create a dry spot behind this line (Figure 2, left).

This issue may be addressed by providing a gap in distribution media (Figure 2, right). Under this gap, the flow front near the tool surface which was lagging behind catches up with the flow on the top and becomes one dimensional before the new injection line is opened,. This eliminates the possibility of entrapping a void in the part near the tooling surface. The gap should be as small as possible to avoid a large increase in the filling time but large enough to allow the flow to become one dimensional before the next injection line is opened.

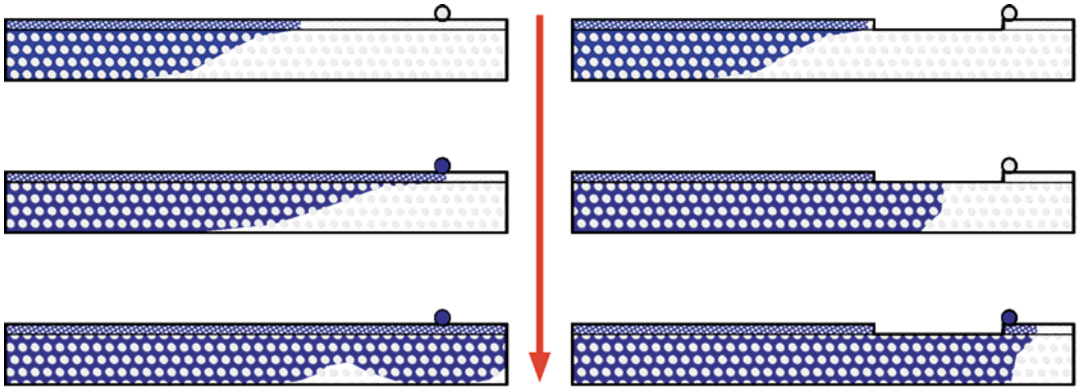

Figure 2. *Schematic of a sequential injection in VARTM: Delay Line before sequential inlet. Early opening (left) will separate a dry spot from the vent. The solution may be a gap in the distribution media (right).*

The success of this injection strategy depend on the values of the distribution media permeability and the in-plane and through-the-thickness permeability of the preform used in the simulation. These may vary greatly from one exeriment to the next. The modeling can overcome this issue by simulating the flow with the highest and lowest value of each of them and selecting a gap or delay size that can produce successful injection for all cases.

Provision of Additional Resin Vents - The "Passive" Control

The traditional answer to varying material parameters and racetracking is creation of extra vents within the mold. The vents are closed during the injection when the resin arrives there, earning the the title of "passive" control [15]. Placement of the vents may be based on intuition, but the modeling capabilities allow one to approach the issue more scientifically and, above all, with better success rate.

The variability in material parameters and racetracking may be included in the model. Discretizing the levels of race tracking strength, finite number of scenarios is generated. Probability levels may be associated with each scenario. Selecting the most likely vent location improves the odds considerably, as demonstrated in Figure 3 [15]. Note that if one adopts more number of vents, the resulting success rate will be higher.

Changing the Flow on the Fly - The "Active" Control

The passive control does not quite eliminate the potential for failure, it just dramatically reduces its likelihood. In some cases, the failure is not an option. Either the part is too large to waste or the continuity of the production might suffer too much. In that case, the active control comes to play. In actively controlled filling algorithm, the resin flow is monitored by imbedded sensors. Once the disturbance is detected, the system must determined what is happening and take a corrective measure, such as opening/closing injection ports or regulating the flow rate.

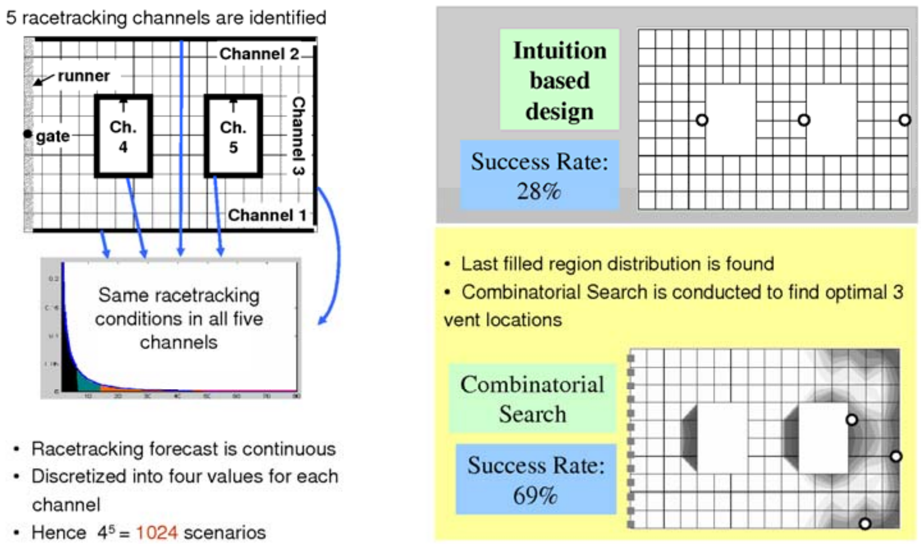

Figure 3. *The RTM part with two inserts. Three vents are used to provide evacuation of air in various scenarios. The intuition based design (top) fails in 72% of cases. The solution based on modeling flow scenarios that account for race tracking improves the success rate by 31%.*

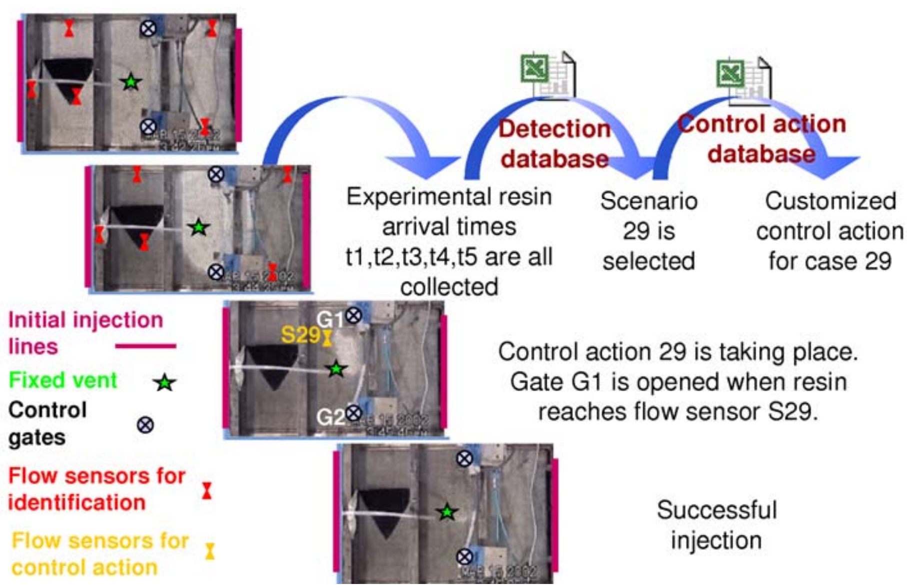

Figure 4. *Actively controlled injection into a plate with triangular insert. Racetracking may exist around part and insert edges. The scenario is detected by sensor triggering sequence and corrective action is taken.*

The current state of the art in Liquid Molding does not allow one to provide detection in real time. Thus, just like in the case of passive control number of scenarios is prepared and modeled. Then, under software control a position of sensors is determined and detection database is prepared to determine the scenario from the sequencing of resin arrival at sensor locations. Optimization algorithm, through automated execution of filling simulations, determines the corrective measures needed to take place to steer the flow to desirable pattern (vent location).

The actual action of active control is demonstrated in Figure 4 for the case of a flat panel with a triangular insert injected from line gates on both sides (Figure 4) with a vent in the middle. In this case, the scenarios included 2 different strengths of race tracking around the edges and the insert and the control action steers the flow towards the vent location.

First, the resin triggers the installed sensors. From the order of sensor activation, the flow pattern and existing disturbance(s) are determined by lookup in pre-prepared database. For the case shown in Figure 4, it determines strong race tracking along the bottom edge of the part. The data base also offers the pre-determined corrective action which is triggered by another sensor input. Opening the auxiliary gate steers the resin flow towards the inlet and no void is formed. Figure 5 shows the comparison of experimental flow, captured through the acrylic mold top, and the simulation predictions made for the corrective action.

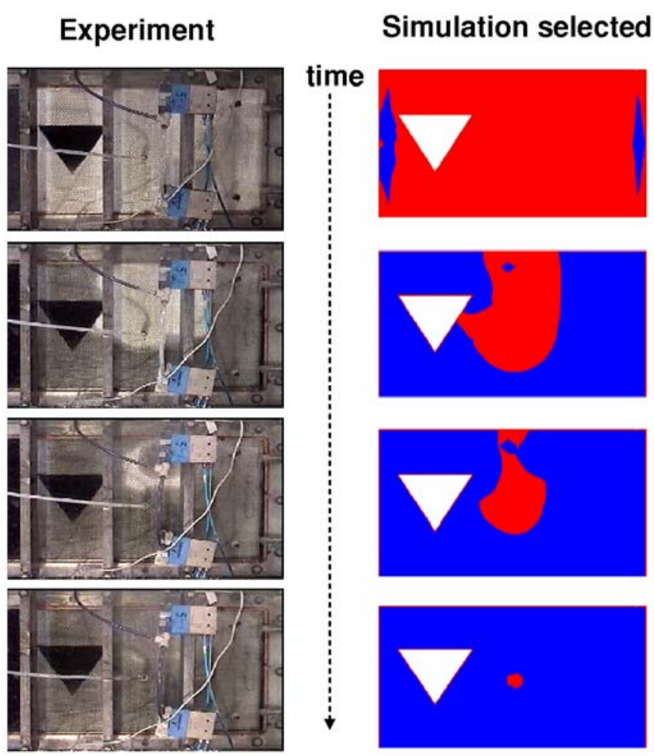

Figure 5. *Comparison of experimental flow patterns during actively controlled injection with the predicted patterns.*

Such verification is necessary in developing the flow control schemes. As all this is controlled with a computer, the operator does not have to reproduce his lay up for the next part. This approach to automated manufacturing in which the variations in the material handling and process is corrected with sensors and simulations will consistently improve the yield.

CONCLUSIONS AND FUTURE OUTLOOK

The resin injection in LCM process is not entirely repeatable because of (a) the variability in material parameters and (b) the geometrical inaccuracy of preform preparation an lay up. The existing simulation capabilities allow one to include both these effects. Thus, the simulation user can determine in advance the flow pattern during injection under various scenarios and design a robust injection scheme to achieve successful mold filling in most if not all scenarios.

In many cases, risk reduction benefits may be reaped even by manually executing the simulation for several values of material parameters, usually by executing the simulation for the lowest and highest possible values. However, to fully harness the simulation capabilities, one must address the material variability and introduce coupling of process modeling with optimization programs because of the large number of permutations involved.

Designing a simple passive control approach, such as providing a couple of extra vents, is relatively straightforward and greatly reduces the risk of injection failure. Active control is more involved, but allows one to design risk-free injection scenarios even with variable material and preforming. In order to design an active control, additional software tools are needed to determine sensor locations and design the control action. These software tools depend on repetitive execution of process simulation to accomplish their goal. The future role of simulations in addition to predictive modeling and a design tool will be to integrate with conceptual design and with a controls system on the shop floor to improve the yield and reduce the time for prototype development as shown in figure 6.

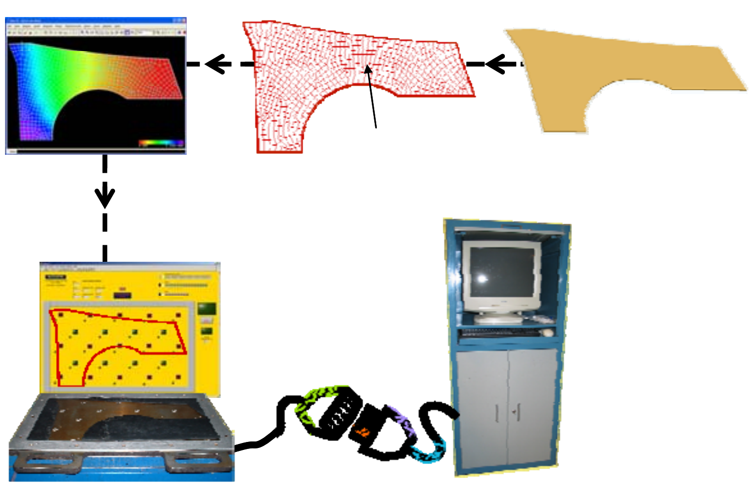

Figure 6: *Seamless integration from Design to Product Manufacturing*

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DISCLAIMER

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research.

REFERENCES

1. U.S. Pat No. 4902215, 1990, W.H. Seemann.
2. Bruschke, M. & Advani, S.G., "A Finite Element/Control Volume Approach to Mold Filling in Anisotropic Porous Media," *Polymer Composites* 11, (1990): 398-405.
3. Lewis, R.W., Usmani, A.S. & Cross, J.T., “Finite Element Modeling of Mold Filling,” *Finite Elements in the 90’s,* ed.by E. Onate, J. Periaux and A. Samuelsson, Springer-Verlag/CIMNE, Barcelona, 1991.
4. Voller, V.R., & Chen, Y.F., "Prediction Of Filling Times Of Porous Cavities," *International Journal for Numerical Methods in Fluids* 23, (1996): 661-672.
5. Ngo, N.D., Mohan, R.V., Chung, P.W. & Tamma, K.K., "Recent Developments Encompassing Non-Isothermal/Isothermal Liquid Composite Molding Process Modeling/Analysis: Physically Accurate, Computationally Effective, And Affordable Simulations And Validations," *Journal of Thermoplastic Composite Materials* 11, (1998): 493-532.
6. Trochu, F., Gauvin, R. & Gao, D.-M., " Numerical Analysis Of The Resin Transfer Molding Process By The Finite Element Method," *Advances in Polymer Technology* 12, (1993): 329-342.
7. Phelan, Frederick. R. Jr., "Simulation Of The Injection Process In Resin Transfer Molding," *Polymer Composites* 18, (1997): 460-476.
8. Acheson, J.A., Simacek, P. & Advani, S.G., “The Implications Of Fiber Compaction And Saturation On Fully Coupled VARTM Simulation” *Composites Part A: Applied Science and Manufacturing* 35, (2004): 159-169.
9. Correia, N.C., Robitaille, F., Long, A.C., Rudd, C.D., Simacek, P. & Advani, S.G., “Use of Resin Transfer Molding Simulation to Predict Flow, Saturation and Compaction in the Vartm Process,” *Journal of Fluids Engineering*, 126 (3) (2004): 1-6.
10. Carpenter, G., Leek, R., Donnellan, T. & Rubel, A. "Simulation Of Resin Transfer Molding For A Cubic Shell Geometry," *Heat and Mass Transfersin Materials Processing and Manufacturing*, ASME HTD 261, (1993): 133-145.

11. Young, W.B. & Chuang, M.T., "Fabrication Of T-Shaped Structural Composite Through Resin Transfer Molding," *Journal of Composite Material* 29, (1995): 2192-2214.

12. Bickerton, S., Stadtfeld, H.C., Steiner, K.V. & Advani, S.G., "Design And Application Of Actively Controlled Injection Schemes For Resin-Transfer Molding," *Composites Science and Technology* 61, (2001): 1625-1637.

13. Devillard, M., Hsiao, K.-T. & Advani, S. G., “On-line Race-tracking Characterization and Flow Control in Resin Transfer Molding,” *34TH International SAMPE Technical Conference*, November 4-7, (2002).

14. Simacek, P. & Advani, S.G., “Desirable Features in Mold Filling Simulations for Liquid Molding Processes,” *Polymer Composites* 25, (2004): 355-367.

15. Gokce, A. & Advani, S.G., “Vent Location Optimization Using Map-Based Exhaustive Search In Liquid Composite Molding Processes,” *Materials and Manufacturing Processes* 19, (2004): 523-548.