On-Line / Off-Line Control of Mold Filling in Liquid Composite Molding

Jeffrey M. Lawrence, and Suresh G. Advani,
Center for Composite Materials and Department of Mechanical Engineering
University of Delaware, Newark, DE 19716

SUMMARY: Prohibitive costs are preventing Liquid Composite Molding processes from gaining greater popularity. The high costs are due to lack of automation and repeatability. Variations inherent in the preform cutting and placement process lead to unpredictable resin infusion patterns which form regions devoid of resin. This compromises the structural integrity of the composite and the part scraped. Control during the filling stage of Liquid Composite Molding processes have been shown to redirect the flow providing a greater percentage of acceptable manufactured composite parts. However, many of the current techniques have various limitations. Many off-line control approaches depend on anticipation of problems, and on-line approaches are geometrically limited and can be computationally intensive if executed during manufacturing. The present work combines off-line and on-line approaches to fill the mold containing fabrics in an attempt to eliminate their shortcomings and reduce the limitations. First, off-line computationally intensive control algorithms based on the specific part geometry and locations for the sensors and injection gates are created. Next, on-line control is initiated with the off-line parameter guidelines. The approach will be presented and illustrated with several case studies to demonstrate geometrical independence in a simulation environment.

KEY WORDS: Resin Transfer Molding, Numerical Simulation, Active Control

INTRODUCTION

In Liquid Composite Molding (LCM) processes, a dry preform stack is placed into a mold. The mold is sealed, and a liquid thermoset resin is injected into the mold. The resin flows through the preform, displacing the air in the gaps between the fibers pushing it out through the vents. Once the filling is complete, the resin is allowed to harden, and the final composite part is removed from the mold. Due to the nature of the fiber preform material and the process of cutting and placement in the mold, the flow behavior is complex and may result in dry spots (regions devoid of resin). These mechanically weak regions of the part require the entire part to be discarded. Current research efforts have focused on utilizing fluid flow techniques to ensure that the fluid will entirely displace all of the air in the mold and fully saturate the preform. Slight deviation in preform placement in the mold can cause fiber free channels between the preform edges and the mold walls. The resin can race through these channels as the resistance to flow is much less than within the preform and reach the vent before the complete preform is impregnated. Active flow control will compensate for material and fiber preform cutting and placement variability and help to reduce wastage and increase the yield.

FUNDAMENTALS OF DEPENDENCE MAP CONTROL

The first concept to establish is that of the actual flow front and the target flow front at a given instant. The objective of the controller is to minimize the difference between the actual and target flow fronts. As control is lost (or not taken) the two will diverge. The schematic seen in Figure 1 explains this difference.

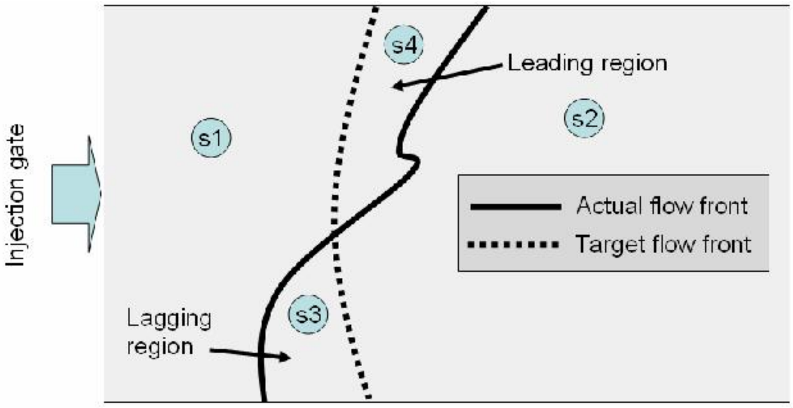

Figure 1: Schematic of disturbance in mold filling depicting the actual and target flow fronts, as well as the concepts of the leading and lagging region

At the instant pictured in Figure 1, a disturbance (unknown) has caused the fluid to flow faster in some regions of the mold, and to flow slower in other regions. The areas where the actual fluid is flowing faster then the target flow pattern will be called the leading regions and those where the actual fluid is flowing slower than the target pattern will be called the lagging regions. In LCM, the only way to correct for a lagging region is by opening an injection gate near that lagging region. The only way to correct for a leading region is to close any open gates near the leading region. The vents in this case have no influence on the fluid flow. Since the only control available for each gate is to either be open (allowing fluid to inject) or closed (preventing fluid from injecting), the controller has to determine which of the gates to open and which to close. Gates near a particular flow region will influence the flow in that region [1]. Therefore, qualitatively, gates near leading regions should be closed in order to slow the flow and gates near lagging regions should be opened to accelerate the flow. This however is an ambiguous solution, as gates near both lagging and leading regions need a clear command as to what to do. Therefore, a quantitative approach needs to be developed. First, each sensor in the mold will tell the system weather or not the fluid has reached that point. Then, the virtual sensor status is checked from the target flow front. Then, each sensor is classified as lying in a lagging (s3 in Figure 1), leading (s4 in Figure 1), or no-action region (s1 and s2). Figure 2a assigns a sensor state value for each of those conditions.

		Target	
	Ideal Actual	Fluid	No Fluid
Actual	Fluid	0	-1
	No Fluid	1	0

(a)

$$q = \frac{1}{\int_{gate}^{sensor} \frac{1}{K} ds}$$

(b)

Figure 2: (a)The comparison of the sensor status for the actual and target flow fronts for the sensor state value (0, 1, -1). (b) The flow conductance (q) is the inverse of the integrated permeability (K) of the preform

With the sensor state value, the sensors have a way of communicating to the gates weather the fluid needs to be accelerated (by opening) or retarded (by closing). In order to decide which sensors to respond to, each sensor must be weighted according to its relationship with the gate in question. This will be accomplished through the flow conductance (q), which is qualitatively defined as the effect a particular gate will have on a particular location in the mold, and quantitatively defined by the equation in Figure 2b. The flow conductance is calculated from the gate in question to each sensor in the mold. The path that is used to calculate the flow conductance is optimized by using an A* algorithm [2, 3]. To determine the ultimate state of the gate, the sum-product between the sensor state value and the flow conductance is taken, which results in the action value. If the resultant action value is positive, the gate will open, and if it is negative it will close. In the balanced case that the action value is exactly zero, the gate will remain in its current state (opened or closed). This same process is then repeated for every gate in the mold. When this is done, the flow conductance will be calculated between each gate and each sensor. The matrix of these flow conductance values is called the dependence map. After these calculations, the fluid advances, and the analysis is repeated during each time step of the entire filling process. There are a few auxiliary rules that are amended to the general construct above. The first rule is that gates that are not covered by fluid should not be opened. This prevents multiple flow fronts, weld lines, and other unfavorable flow conditions. The second rule is that once a gate has been opened and closed, it may not be re-used. This is to prevent "dead" gates that will no longer provide controllability to the system from being used. The third, and final rule is that if a situation exists where all of the gates in the mold are set to be closed, the single gate with the lowest action value is to be opened. This is to temporarily allow the filling to continue, until a target gate is found.

VALIDATION

With the control approach fully defined, it is now necessary to validate the approach. In order to have better control over the processing parameters, virtual experiments will be used in the validation. The virtual experiments will be done using computer simulation of the filling stage using the computer simulation software Liquid Composite Molding Simulation (LIMS) [4].

In order to conduct the virtual experiments, a finite element mesh must be prepared, a nominal permeability distribution must be applied to the elements in the mesh, and initial injection gates must be selected to generate the target flow pattern. The mesh with the initial and control gates along with the target flow pattern can be seen in Figure 3.

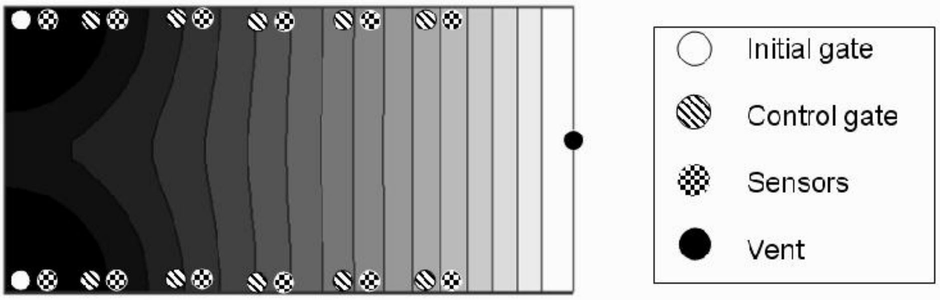

Figure 3: The initial injection gates, target flow front pattern, and control gates and sensors

Now that the target flow pattern is defined, the dependence map containing the flow conductance values between each gate and sensor is generated with the A* algorithm. With these two tasks complete, the off-line portion of the control strategy is complete. To perform the on-line portion of the control, disturbances are added to the system.

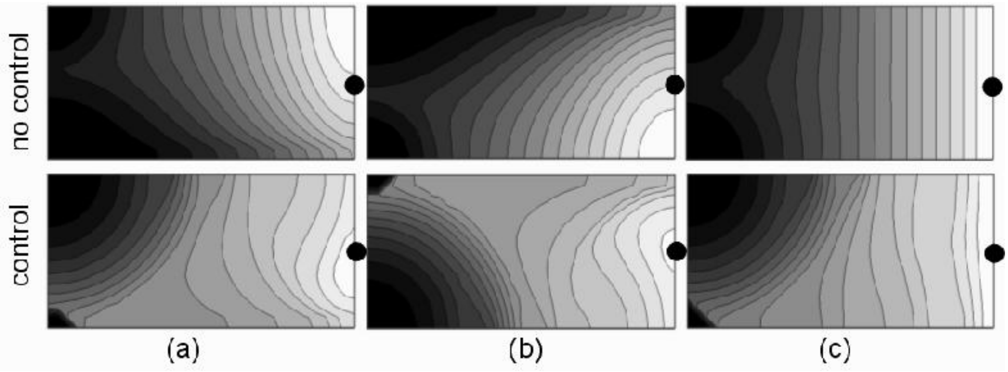

Figure 4: Examples of the controller's effect. The top shows the flow progression with no control applied and the bottom pictures show the same cases with flow control. The vent is indicated by the black circle.

The most common flow disturbance that occurs in the RTM process is race tracking, where fluid flows faster along air gaps created along mold edges [5].Three virtual experiments will be conducted for this validation. Case (a), will contain a race tracking channel along the bottom edge of the mold. Case (b) will perturbed with a race tracking channel along the top edge of the mold. Case (c) will be the nominal case, with no disturbances present. This last case will test the robustness of the system to be sure that flow control is maintained when there are no disturbances. Each case is run with and without control using LIMS.

The resultant flow front patterns can then be examined to see if the controller maintained the flow front progression according to the target pattern. Next, the on-line portion of the control is used, where the action values are calculated, and the results checked against the three auxiliary rules. This control technique does not depend on pre-classifying the disturbances. Therefore, no additional effort or modification to the controller is needed for any case. Figure 4 show the resultant flow progression with no control and then with control for all three cases (a-c). As seen in Figure 4, in each case, the flow patterns were restored to resemble those in the target case. These examples validate the control approach and demonstrate its flexibility to handle any disturbance in the mold.

CONCLUSIONS

A new approach was developed to apply control to the filling stage of LCM processes. The controller was built with the goal in mind that the system would be transferable to an actual composites manufacturing operation and will add versatility to the range of disturbances that the controller could correct. The technique was developed, based on the concept of a dependence map. An example was presented that demonstrated that the system was able to maintain control of the flow progression despite several unpredicted and unplanned disturbances.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the Office of Naval Research (ONR) under Grant Numbers N00014-02-1-0811 and N00014-03-1-0891for the “Advanced Materials Intelligent Processing Center” at the University of Delaware.

REFERENCES

1. Gokce, A. and S. G.Advani, *Gate effectiveness in controlling resin advance in liquid composite molding processes.* Journal of Manufacturing Science and Engineering, 2003. 125(3): p. 548-555.
2. Sharai, Y. and J.-I. Tsujii, *Artificial Intelligence: Concepts, Techniques and Applications*. 1982: John Wiley & Sons.
3. Al-Hasan, S. and G. Vachtsevanos, *Intelligent Rout Planning for Fast Autonomous Vehicles Operating in a Large Terrain.* Robotics and Autonomous Systems, 2002. 40: p. 1-24.
4. Simacek, P. and S.G. Advani, *Desirable features in a Mold Filling Simulation for Liquid Molding Process.* Polymer Composites, 2004. in press.
5. Bickerton, S. and S.G. Advani, *Characterization and Modeling of Race Tracking in Resin Transfer Molding.* Composite Science and Technology, 1999. 59(15): p. 2215-2229.