Role of Filling Simulation in LCM Process Design

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SUMMARY: Numerical simulations of the mold filling process in various Liquid Composite Molding (LCM) techniques, in which the fiber reinforcements represent the porous media and the polymeric resin is the impregnating fluid, have been successfully utilized for over a decade now. They continue to be under dynamic development and their utilization has expanded to design and optimization of the process, control of the impregnation process and adaptation to new LCM techniques such as the Vacuum Assisted Resin Transfer Molding (VARTM). This paper briefly describes the modeling and implementation of these features in a numerical simulation. We discuss these challenges in the framework of Liquid Injection Molding Simulation (LIMS) developed at the University of Delaware with examples that demonstrate its usefulness.

KEYWORDS: Process Modeling, Liquid Composite Molding, Flow in Porous Media, Process Control and Optimization.

INTRODUCTION

The Liquid Composite Molding refers to a number of processes that use liquid resin to impregnate the stationary fibrous preform. The two variations of this process that are of particular interest are Resin Transfer Molding (RTM) and Vacuum Assisted Resin Transfer Molding (VARTM).

During the RTM Process, the preform is placed into the mold cavity, the mold is closed and the resin is injected into the cavity under pressure. Once the liquid resin fills the mold cavity, it cures, during which the resin hardens due to the gelling of the polymer network forming the matrix of the composite, allowing the part to be de-molded. Note that the mold walls are considered rigid and preform is stationary during the injection. This technique is well known and has been traditionally applied to moderately large parts in various applications.

The VARTM process is similar, but the mold is one-sided. The fiber preform is placed on the mold plate. The other face of the preform is covered with a flow enhancement layer known as the distribution media and the assembly of the mold plate, preform and distribution media is encapsulated in a plastic bag. Vaccuum is drawn to compact and to hold the preform stationary. Vacuum pulls the resin into the distribution media and the fiber preform. Once the preform is saturated with resin, the part is cured and de-molded. This process is gaining popularity for manufacturing of larger parts, mainly because of lower tooling costs.

However, the one-sided mold complicates achievement of dimensional tolerances [1], though some heuristic remedies are available.

In this paper, we will address resin injection and preform saturation. It is useful to predict the resin flow during mold filling as it offers guidance for the selection of the injection gate location and the last regions to fill provide the location of vents in the mold to displace the air.

APPLICATIONS OF MOLD FILLING SIMULATION

The physical reality of the manufacturing process dictates what should be taken into account and included in the simulation to describe the process physics. Simulations have to address all significant issues that are encountered during the particular manufacturing process to be of value in manufacturing. In the wide range of LCM processes, different aspects of the impregnation physics become more (or less) significant. The simulation is then called upon to model these physical aspects.

Traditionally, the mold filling simulations were used to find the necessary vent location and to establish process pressure and time ranges [2-8]. This definitively proved to be more useful than the prohibitively expensive method of trial and mostly error to settle on gate and the vent locations to produce a composite structure without dry spots.

Although the introduction of the simulations helped in the selection of gates and vents in the mold during the manufacturing process, LCM processes tend to show significant variability in the input data. The imprecise cutting and placement of the preform is the most significant source of this variability. This makes it necessary to introduce optimization and control in the filling process to increase the yield despite this variability. Thus, the full potential of the simulations can be realized if one can use them for optimization of injection location(s) and other parameters [9-11], and to design robust adaptive injection systems for process control in the presence of variabilities [12].

Combining Elements of Various Dimensions: Distribution Media Model

The question whether a two-dimensional or three-dimensional model should be used to numerically simulate the mold filling has been raised since the first attempts to simulate RTM filling. The majority of LCM manufactured parts are geometrically thin shells. This suggests that simulation of the filling process using two-dimensional shell elements in three-dimensional space will be numerically efficient and be able to describe the flow accurately.

Unlike the plate, beam and solid elements in finite element stress analysis, the pressure and flow computation during the filling simulation allows one to combine 1-, 2- and 3-dimensional elements within a single mesh. Therefore, thick parts can be represented by three-dimensional elements and one-dimensional elements are superior in modeling runners and race-tracking channels. With the introduction of distribution media in VARTM processing, three-dimensional modeling becomes mandatory to capture the flow-front lag in the thickness direction.

The combination of two-dimensional element modeling of the distribution media and some geometric features, such as ribs, with the three-dimensional model of the preform allows one to resolve issues that arise due to large element aspect ratios (Figure 1).

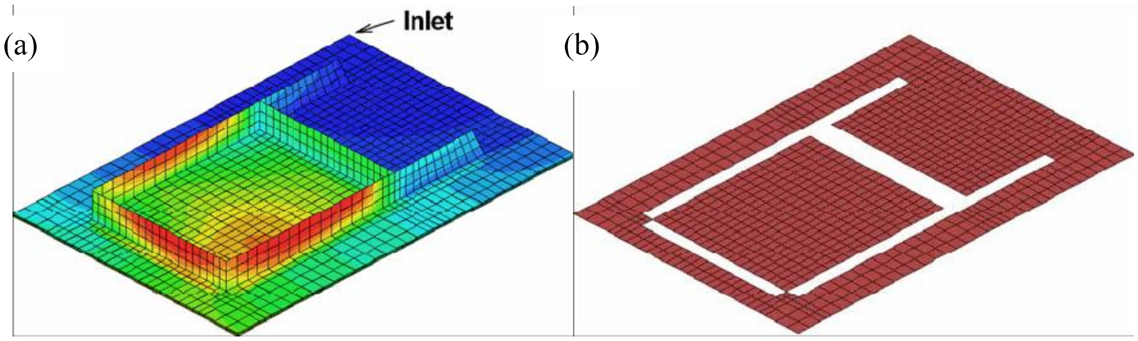

Figure 1: VARTM infused panel (modeled as 3D) with 2D ribs: (a) Simulation results (b) Two-dimensional model of distribution media that was placed on three dimensional mesh representing the fiber preform.

Combining Elements of Various Dimensions: Fiber Tow Saturation

In typical textile preform, the pores between the fiber tows are much larger than those within fiber tows. Consequently, the pressure driven flow fills them first, leaving unsaturated fiber tows behind the flow-front partially filled (Figure 2a.), where they act as a sink term until they are fully saturated. The phenomenon can be simulated by modeling the sink term by appending one dimensional element to each node in the mesh as shown in Figure 2b. The properties of this element are set to capture the behavior of the fiber tows, while the porosity of the original mesh is reduced to compensate for the volume of intra-tow pores. Simulation is run as usual, with the fill factor in the new nodes corresponding to the fiber tow saturation. The complete process may be automated using the scripting language within the simulation, since the material parameters are readily accessible. While the size of the system increases and the simulation performance somehow decreases, it is still possible to simulate injection into large and complex parts in very short (minutes) time frame as shown in Figure 2c, a box consisting of flat two-dimensional panels, with low level of race-tracking along the corners. Contour plot show the saturation of fiber tows. The lag between macroscopic flow-front and fully saturated fiber tows is emphasized [13

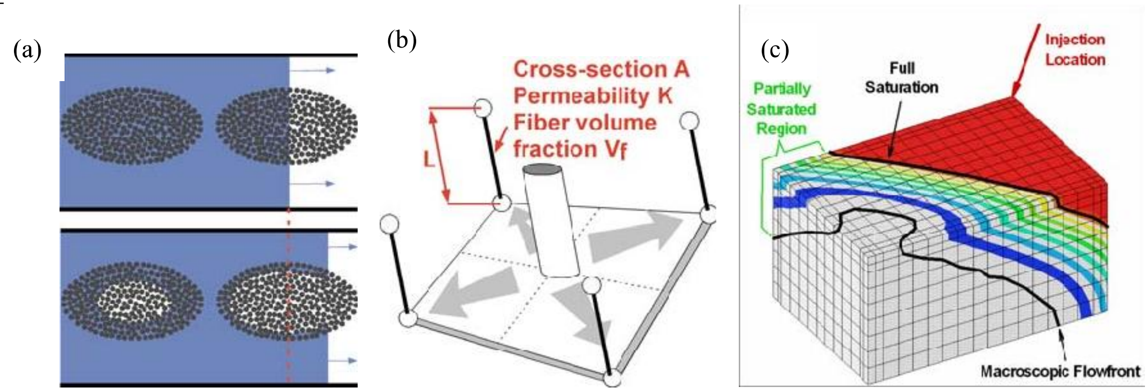

Figure 2 (a) Fiber tow saturation (b) Modeling fiber tow saturation with one dimensional elements appended to the mesh (c) Fiber tow saturation in a box mold with racetracking [13].

Optimization

Conventionally, one uses the filling simulation to verify existing part and process design and to ensure the cavity is filled without any dry spots. User might utilize the simulation as a tool to optimize the filling process, either to minimize the filling resources (time or required pressure) or to reduce the process sensitivity to expected variations in component properties [11]. In both cases, one usually varies the location of inlets and outlets to minimize the prescribed cost function.

Theoretically, the exhaustive search of optimal solution of the model problem is possible due to its discretized nature, but it is prohibitively time consuming in non-trivial cases. Hence, one either reduces the pool of admissible vent locations [15] or couples the simulation with optimization methods such as genetic algorithms [11,16] or similar techniques. Even then, the number of cases to be simulated is large. To handle this in real time, the simulation code must be very fast and the model must be simple and capture the necessary physics. Also, the input and output data for individual cases must be processed automatically by a computer (Figure 3). This requires a very tight coupling between optimizing code such as a genetic algorithm and the simulation package making it necessary to have an advanced scripting possible within the simulation code or/and runtime control of the simulation by the optimization code.

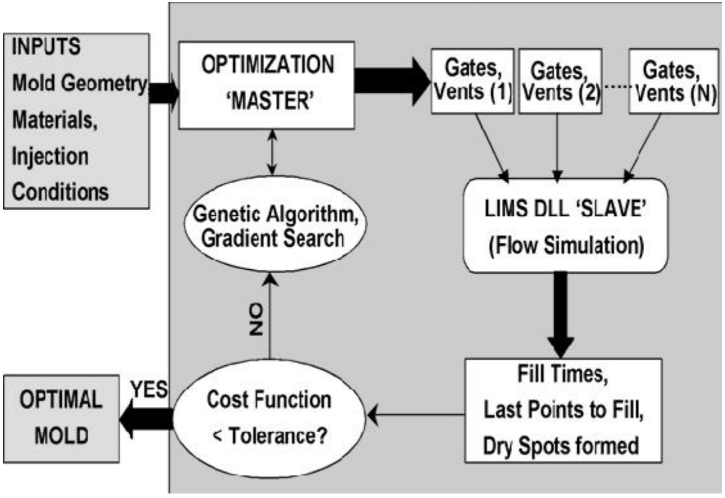

Figure 3: Flow Chart of RTM process optimization [13]

Sensing and Control

The material and process parameters in LCM manufacturing show evidence of variations [14,17-18]. Most commonly, the preform permeability can vary along the edges due to imperfect fit and non-repeatable placement, causing the resin to flow faster along the edges (race-tracking). Such race-tracking effects could significantly change the behavior of the predicted (or experimentally observed) flow front pattern [19]. As race tracking is a function of how the preform is placed and the edge effects, it is difficult to forecast its exact magnitude. To address this issue, one can monitor the situation in the mold via the use of flow sensors [20] and invoke corrective actions according to the sensor output. The corrective actions may include opening or closing inlets or vents or just modifying the injection parameters such as the flow-rates. The simulation is necessary to model possible scenarios, to find the "optimal" control actions and to verify the resulting control strategy.

Figure 4 shows an example of how one can use simulations to develop and test a control strategy to avoid dry spot formation by directing the flow of resin towards the vents by the opening and closing the auxilliary injection gates once the sensors have identified the correct scenario in action. Note that in order to deal with limits on driving pressure during VARTM processing, one commonly applies various sequential injection schemes to reduce the filling time. For such situations, the closing and opening of injection inlets may be triggered by resin arrival at specific locations, so this process can be classified as a rudimentary control.

To simulate sensing and control, the simulation program must provide two mechanisms. First, it should be able to search for the corrective action. This is fundamentally an optimization process. Thus, all of the requirements mentioned above will apply. Tight integration with control program that performs the search is necessary, though advanced built-in scripting can also accomplish the goal. Second, the simulation must provide the "virtual" sensor output during the filling process and allow changes in inlets and outlets during the filling process. This requirement is simple but very important. The coupling of the sensor output and control actions can be provided by an external program, which then controls the simulation, or preferably by an internal script, if the simulation supports any form of scripting.

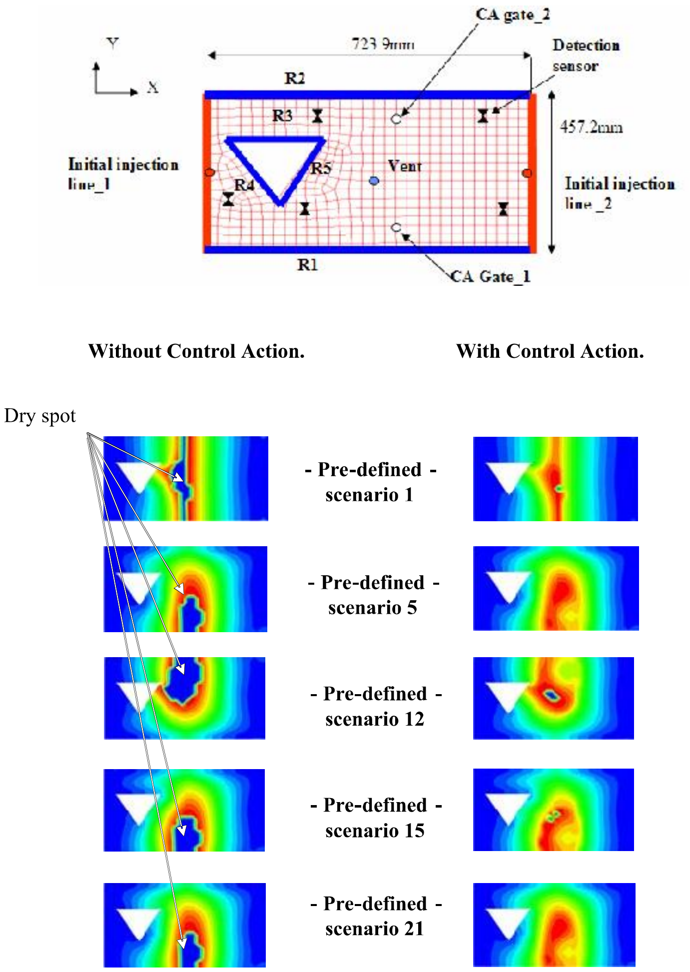

Figure 4: Simulation can evaluate all scenarios with forecasted race tracking and suggest control actions by injection resin from auxiliary gates to redirect flow to avoid dry-spots

CONCLUSIONS

The range of applicability of LCM simulations has significantly widened. This is caused by increasing attempts to optimize the manufacturing process, introduce process control and also because new derivatives of LCM process are being modeled. To successfully address various issues in LCM simulations such as race tracking, variability of material parameters, design of distribution media, prediction of time to saturate all the fiber tows in a preform, preform compression and injection gate and vent design, the simulation has to be flexible, accurate and fast.

It should have the (i) capability to model two-dimensional as well as three-dimensional problems, (ii) capability to include models of one-dimensional entities and be able to combine 1D, 2D and 3D sections in a single model (iii) allow for changes during the mold filling simulation and (iv) provide sufficient time resolution to model control action. Interface allowing for integration into other programs is always desirable.

The speed of computation, accuracy and changes during the mold filling simulation tend to contradict each other. Thus, the simulation package will always present a compromise between individual requirements. The success will depend not only on how the compromise is made but also on the actual use of the simulation that is bound to vary among its users. The simulation package LIMS (Liquid Injection Molding Simulation) has been in a continuous state of development over the last ten years at the University of Delaware. The goal is to keep the simulation flexible and fast, incorporate the correct process physics and validate the simulation with analytic solutions and experiments. It has been used successfully to simulate various aspects of RTM and VARTM injections, including optimization and control. Simulation execution and control from other applications is facilitated by a dynamic link library.

ACKNOWLEDGEMENT

This work was sponsored by ONR under contract number N00014-03-1-0891.

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