LIQUID COMPOSITE MOLDING: ROLE OF MODELING AND SIMULATION IN PROCESS ADVANCEMENT

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SUMMARY

In Liquid Composite Molding (LCM) processes, liquid resin is injected or infused into a stationary fibrous reinforcement within the mold cavity. The composite part is de-molded after the resin cures. While the part design is dictated by desired service performance, the process scheme has to ensure that the part is manufactured as designed with (i) the resin fully saturating the reinforcement without voids and (ii) the part cures properly. To design the process for net shape and complex composite structures, process models and simulations have provided a virtual manufacturing environment in which processing steps can be executed to explore the process physics, change boundary conditions and material parameters as needed to optimize the process cycle.

The state of the art and the role of modeling and simulation in process design is reviewed. The methodology for development of robust manufacturing schemes and not just for “acceptable” ones are presented by accounting for the variability in the process and material parameters. Resin flow simulations can be coupled with intricate features of the geometry to influence the part design while addressing manufacturing concerns. Simulations can also be used to develop flow control algorithms to manipulate resin impregnation dynamics which can then provide guidance to integrate automation in the manufacturing process. Finally, a case for seamless coupling of the process and part design is made and examples on how this objective can be achieved are presented.
1 INTRODUCTION
1.1 Liquid Composite Molding Process

Liquid Composite Molding (LCM) process encompasses a family of processes in which a dry fibrous reinforcement usually a woven or stitched textile preform is placed within a mold cavity and infused with a liquid resin to cover all the empty spaces between the fibers and fiber tows of the fabric. Once it is completely saturated, resin is cured and the part is de-molded. The original process, Resin Transfer Molding (RTM), uses a rigid mold and highly pressurized resin for infusion. Vacuum Assisted Resin Transfer Molding (VARTM) uses a lighter, one-sided mold, vacuum bag on the other surface and the atmospheric pressure to drive resin into the vacuumed preform. There are numerous other process variants such as RTM Light which uses a compliant mold and SCRIMP [1] that uses a flow enhancement media in a VARTM setting. LCM is widely used as it can produce complex net-shaped parts with excellent properties and good surface finish within a single step. With SCRIMP, very large parts can be fabricated. Its environmental impact can be kept minimal as it is a closed mold process.

In order to ensure that a part can be produced without dry spots or microvoids, both the resin infusion and cure cycle must be carefully designed. This paper concentrates on the infusion part. Two requirements must be satisfied to successfully infiltrate the reinforcement. First, the infusion must be achieved before resin gelling arrests the flow. Second, the flow patterns must allow the volatiles from resin to escape toward vacuum ports at all times. If these are entrapped within the reinforcement, defects (or voids) are the result. These also occur when the resin does not saturate some regions before it reaches a vent and these dry regions can be reduced but cannot be reliably eliminated.

To fill the part within required time and to prevent dry spot creation, one needs to place both the infusion gates and resin vents at strategic locations. As the flow patterns are not necessarily intuitive, this gave rise to mold filling simulation software about a quarter century ago to assist with process design. For correct inlet and vent placement, several simulation tools are available [2-4] to predict the resin filling patterns within the reinforcement.

1.2 Flow Patterns, Process Variability and Flow Disturbances

Ideally, modelling tool is used to ensure that the resin will occupy all empty spaces between the fibers before arriving at the vent and before it gels. The model predicts the flow in the mold containing fibrous porous media, described by its geometry with input of “continuum” flow properties such as permeability and porosity. Accurate description of properties can be expected to provide good forecast of mold filling. However, fiber preforms suffer from inherent variability in its local architecture which will influence the permeability and porosity values. More importantly, this is compounded by the variability introduced during fabric cutting, assembling and placement in the mold (Figure 1). As shown in the figure, a small gap along the flow direction allows the resin to move much faster in in that high permeability channel as compared to the adjacent fabric, creating the “racetracking” effect.

Due to this effect around edges, corners and curved surfaces, the bulk material data is no longer a realistic description of mold filling. This disturbance caused by racetracking can result in improper filling as the resin reaches some locations earlier than expected, possibly blocking air and volatiles from reaching the vent. Additionally, the effects can significantly change from one part to the next for the same set of initial conditions. Features in flow simulations can be introduced to capture this anomaly and methodologies developed to address such variability.
1.3. Coupling Part and Process Designs

The composite part to be fabricated by LCM process begins with the geometric design which is coupled with structural analysis to ensure that the performance requirements are met. Thus, the geometry, materials and detailed reinforcement layup is designed within a Computer Aided Design (CAD) environment. After this design is finalized, the processing design is initiated.

Even if the process design tools can handle flow disturbances described above and fully optimize the injection, there is no guarantee it will be possible to design the process (to find proper injection and vent combinations) so that successful mold filling can be guaranteed. The outcome of analysis may be simply that it is impossible to do so within the limits imposed such as maximal infusion pressure or feasible number of vents. In this case, it is desirable for the process analysis to provide feedback to the designer, so that he can change the part design to improve the manufacturing possibilities. For example, the simulation may suggest elimination of certain geometric feature that introduces risk of flow disturbances.

The CAD systems already provide structural checks to the designer, for example to determine whether some corner creates unacceptable stress concentration. This model based production design can be advanced to couple the functional design with the manufacturing process design. Flow simulations can be integrated within the CAD environment to accomplish this.
2 USE OF FLOW SIMULATION IN LCM PROCESS

2.1 Design of Infusion Strategy

The conventional application of flow simulation is to determine the location of inlet and vents for the infusion process and the time and pressure requirements based on the infusion location. This requires generating the finite element model of the geometry, providing input material parameters such as permeability, fiber volume fraction and resin viscosity and subsequent simulation of the mold filling process. The data − particularly the inlet location(s) may be changed as needed and the simulation may be executed iteratively to explore the effect of changing inlet locations on the flow patterns during mold filling. Vents will be at the locations where resin arrives last. Time to saturate the preform is obtained from the simulation if inlet pressure was specified, and required pressure at the inlet if flow rate was specified.

Figure 2: Finite element model and resin filling patterns for Compression RTM infused automotive body. Last locations to fill (red) require venting.

This approach is usually carried out manually, with numerical trial-and-error method used to “optimize” the gate and vent settings to minimize the fill time under a given inlet pressure or to minimize the pressure requirements for a prescribed flow rate at the gate. The current application of this approach goes beyond commonly used processes such as RTM and VARTM. Any LCM process variation that can be modeled can be analyzed using this methodology, for example Compression Resin Transfer Molding (CRTM) [5] (Figure 2).

2.2 Accounting for Flow Disturbances

While the ability to “virtually” infuse a part is helpful, process disturbances or major inaccuracies in material parameters will invalidate the results. To design the optimal processing methodology in the presence of disturbances, it is necessary to simulate disturbances. Thus, racetracking or material parameter variability must be added to the model description. This process includes modifying the permeability and porosity values and introducing disturbances, highly permeable gaps, in the form of 1D channels. The approach has been described in detail elsewhere [2, 6].
It is generally possible to simulate disturbed flow with available RTM software, though some simulation packages make it easier to create the disturbances on the mesh of the part (LIMS [2]). The effect of disturbances may be very dramatic (Figure 3). The current issue is not so much in modelling the disturbed scenario, but rather how to generate a finite set of scenarios that adequately describe the expected process variability.

2.3 Designing Robust Process

With the conventional process design, the location of gates and vents is determined to provide good infusion behaviour for the expected (“typical”) part configuration. That usually does not consider process disturbances. Skilful analyst can check his process settings against manually introduced disturbances as demonstrated in Figure 3.

We call the infusion process “robust” when it will result in successful infusion regardless of particular variations and disturbances that can occur during the infusion of a particular part. The goal is to increase the yield of the process by ensuring that the resin will arrive at the selected vent last despite the flow disturbance.

To establish robustness, one needs to simulate flow for “all” likely disturbances. As it is impossible to simulate infinite – or even a very large – number of cases, the disturbances are applied in discretized form [6, 7], hence only one or several magnitudes are applied to each possible disturbance and, usually, the disturbance along a certain geometric feature is assumed to extend along the entire feature (edge). For example, along each edge of a part there may be no, small or large empty channel that will determine racetracking along that edge. Each disturbance may have certain probability associated with it, giving each scenario a distinct probability of occurrence [6, 7]. Unfortunately, at the current state of knowledge, educated estimate is the best data we can hope for but this could be improved by collecting data from actual manufacturing situations and adopting proper statistical analysis.

The number of scenarios to consider may be very large. Even for the simple case in Figure 4, there are 8 outer edges which, with two possible disturbances on each edge (no channel and modest channel gap) results in 256 ($2^8$) possible scenarios. If we use three magnitudes (no, small or large channels at each edge) the number of scenarios balloon to 6,561 ($3^8$). Simulating the filling in each scenario determines the appropriate vent location for that scenario.
Figure 4: Line infusion into flat panel with and without racetracking (three possible scenarios out of 256). Infusion line and racetracking edges are shown in the top figure while the filling patterns in which red is early times and blue is later times are shown in the corresponding bottom figure. Suggested vent locations are labeled. Note how the last region to fill changes with race tracking as shown in the bottom figures.

Superimposing the results may determine all necessary vent locations for a robust infusion scheme [6, 7]. The derivation of such scheme requires only (a) the ability to generate a reasonable scenario space for a given part and (b) repetitive simulation of all the generated scenarios. However, the proposed solution may not be admissible, for example, because it would require very large number of venting locations. For such cases one may attempt part redesign that would eliminate the most problematic feature or introduce feedback control into the process.

2.4 Distribution Media Optimization

The placement of additional vents during the injection represents a rudimentary form of passive process control. During the impregnation process, the vents will be closed when the resin arrives at their location. There is a different option available in LCM methods such as VARTM that use flow enhancement media in some form to distribute the resin into the part. A flow enhancement media on top is placed to purposely create race tracking over the entire surface to fill the top surface with resin. The resin then has to penetrate through the thickness which is usually 3 to 5 mm. One still needs to optimize the shape of the flow enhancement media so that the flow patterns are insensitive to the usual disturbances, and flow arrives at the vents last despite presence of any potential disturbances around the edges or inserts.

Thus the distribution media should be placed over the surface selectively to ensure the flow pattern starting at the predetermined inlet arrives last at the desired vent location, regardless of the disturbances. The methodology starts by identifying possible disturbances and dividing the part domain into regions which can (but do not have to) be covered by distribution media. Then, an optimization algorithm [8] finds regions which should be covered by the distribution media that guarantees filling for all scenarios created from all possible permutations of identified disturbances (Figure 5). If this does not result in success filling, the domain is divided into finer region and the process is repeated.
Figure 5: Optimizing distribution media layout to provide robust filling patterns in the presence of flow disturbances [8].

Proper DM layout steers the flow toward the preselected vent location(s) (Figure 6). Note that while the process is robust, the filling time may increase relative to the conventional case in which the entire top surface is covered with DM.

Figure 6: The left side shows resulting voids (black) when the entire surface is covered with the DM and you encounter flow disturbances. The right side shows the flow progression for the same scenario with the top surface covered with designed DM layout (shown in Figure 5). The resin arrives last at the vent even though the flow patterns are different. [8].
2.5 Introducing Active Flow Control

There are other control options available during mold filling. Most importantly, it is possible to open and close resin inlets or to manipulate their pressure and flow rate [9-12]. It is even possible to successfully manipulate the permeability of fibrous reinforcement or distribution media that spreads the resin over the preform surface [8]. This is fundamentally different from the previous cases as now the infusion strategy has to change in-situ as the resin flow progresses.

The active control must embed sensors in the mold to detect and identify what (if any) disturbance are prevalent early during the impregnation process so that an appropriate control action can be initiated with the injection hardware to manipulate the resin flow to arrive last at the open vent. The flow simulation can be used to design the control strategy. Algorithms have been designed with the flow simulation to (a) identify the location of flow disturbances and create all possible flow patterns due to permutations of the identified disturbances (b) select sensor placement locations that will allow one to identify early the current scenario taking place and (c) develop customized control actions that will rectify the situation [9-12].

As with the passive control, the simulation models all feasible deviations from undisturbed filling, but it goes beyond this, as there are additional tasks to address. First, placement of sensors has to be determined to detect the flow scenario in time to take action. Second, additional inlets and their locations need to be decided and placed in the mold to allow for flow-front steering when needed. Last, the timing of the control action is to be established (Figure 7).

The virtual manufacturing simulation can create the corrective actions for each scenario off-line and can be implemented on the laboratory floor to execute the corresponding corrective action once the sensors identify the scenario during mold filling [9]. Thus, this will form the framework for automated manufacturing in which the preform is placed and injection is initiated. The control action is automatically triggered based on sensor feed-back.

Figure 7: Actively controlled infusion into a panel with an insert. Example shows experimental and simulated solution to one of 32 possible disturbance cases.
2.6 Optimization

Similarly, process optimization is made possible by flow simulation tools. The virtual mold filling allows one, for example, to place the inlets so that the fill time is minimized. Methods deployed here vary from ad-hoc trial-and-error execution of simulations with a few randomly selected inputs through exhaustive searches to complex application of genetic algorithms and surface subdivisions [13-17].

The simulation tools are necessary for any non-trivial optimization as they provide the only realistic way to evaluate the cost function, be it minimizing time necessary to infuse the part or the averaged porosity content of the final product. For the usual optimization problem (minimization of time to fill the mold), it is virtually impossible to conduct exhaustive searches as the number of possibilities rises with number of nodes in the mesh raised to the power of number of gates desired. For example, a mesh with 1000 nodes, would require only 1000 simulation to find the best gate for minimum fill time, but will require 1 million simulations to find best locations for two gates and a billion simulations for best locations for three gates using exhaustive searches. Thus, much of the research in this field has focused on finding suitable methods to optimize the infusion strategy [14-15, 17-18]. Figure 8 shows an example of locating three gates on a complex part such that the fill time is below a few hundred seconds. An exhaustive strategy with 5000 nodes would require one to run $5000^{3/6}$ simulations A Voroni based algorithm [18] allows one to complete the optimal gate location with 7 simulations (Figure 8).

![Figure 8: Optimization of infusion inlets (three) on composite orthotic part. Efficient simulation is essential but the optimization algorithm still needs to keep the number of simulations low [18].](image)

3 INTEGRATING PROCESS MODELING AND DESIGN

In theory, the process analyst can carry all the above mentioned tasks “by hand”, modifying the model and executing the virtual infusion case by case. However, even with simulation tools such as LIMS [2] where generating a disturbance is as simple as clicking on a part edge, the practicality of such approach ends as the part complexity increases. Even for the part shown in Figure 4 this analysis...
will take days. Designer will have to create a new part model for each of 256 cases by adding the proper racetracking channel and setting its permeability and porosity. Then, the model must be saved and the simulation executed. Finally, designer is left with a set of 256 predicted flow patterns which must be superimposed to find all the possible venting locations, and manually processed for appropriate probability values of individual vents to decide the number and the best location for the vents.

The structural analysis on the other hand may take only minutes or at the most a few hours as no optimization and uncertainty analysis of edge and corner disturbances and their permutations are involved. However, even when conducting flow simulations if one limits the number of possible scenarios to less than 256, as was the case in Figure 4, all the simulations can be completed in less than an hour on current CAD workstation which is of the same order as the structural analysis design. The real obstacle to analyze the part that is being designed is the lack of integration between the functional design and the process design. By integrating flow simulations within a CAD design environment this issue can be addressed. This methodology is being attempted but much work is needed in this area for it to work seamlessly [6].

Figure 9: The integration steps to utilize process simulation efficiently from within composite part design environment. Minimally, the implementation must identify the disturbance locations, generate all possible scenarios, perform the simulations and analyze the results to provide comprehensible feedback for designers.

To utilize the flow simulation from within the design environment for a robust manufacturing scheme, several steps need to be executed seamless as listed below:

1. Part representation must be converted to a suitable format. Geometric features that may cause disturbances must be identified, possible effects estimated and distinct scenarios generated.
2. A suitable LCM process to manufacture the part must be identified and proper inlet positions to inject resin selected.
3. Flow simulation must be performed for all likely scenarios.
4. Results must be analyzed to provide vent location, estimated fill time distribution and yield rate.
5. If the predictions are favorable, design can be accepted. If they are not, possible design improvements (from manufacturing standpoint) need to be identified and designer is notified.

Some of these steps have been previously accomplished [6] (Figure 9). The determination of geometric features conducive to racetracking is possible. Scenario generation is straightforward from the modelling perspective. The data to describe the probability distribution is, however, not readily available. The post-processing of results is currently limited to determination of vent location, the feedback cannot reliably determine the offending disturbance prone geometric features, but this issue can be addressed.

4 CONCLUSIONS

Today, liquid composite molding processes can be modelled using commercial software. While it is generally based on RTM modelling, other variants of the process can be described by these models. Despite simplifying assumptions, the accuracy of this description is reliable if one uses effective material properties and applies certain corrections during the virtual process, mostly to enforce the mass conservation. These models have been used for some time with success to determine suitable infusion layouts.

Flow simulation tools themselves are fairly mature, and well tested. For further process advancement, it is necessary to improve the ways in which simulation tools are applied to the process design, optimization and control tasks and how they can be seamlessly integrated within a design environment and with automation on the manufacturing floor.

The accuracy of numerical models depends on the supplied material data and well defined process description. In the world of composites, both of these exhibit variability. Most importantly, various gaps and channels between reinforcement and mold and inserts – racetracking channels – significantly influence the flow patterns. Modeling can incorporate them in the flow simulation and assist in the design of infusion schemes that are “robust” in the sense that they produce the desired result even when the flow has been disturbed.

The full utilization of the capabilities of flow simulation to improve LCM manufacturing requires automation and integration with other software packages. It has already proven necessary in the fields of optimization and control to deal with large number of possibilities. In designing the robust infusion process – by the means of active or passive control – the automation must examine relation between material data and part geometry and generate a set of scenarios that characterize all practically possible disturbances. Then, it must analyze these scenarios to create the robust process scheme.

Large improvement in such manufacturing processes may be accomplished by integrating the process simulation, automated design of robust infusion schemes and part design. Composite part design provide more flexibility and hence the virtual manufacturing flow simulations can guide the designer to design parts that are easy and inexpensive to make in a reliable fashion.

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7 REFERENCES


