Optimization of Mold Filling Parameters during the Injection Compression Molding Process

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SUMMARY:

The Injection Compression Molding process is a variant of the Liquid Composite Molding group, and requires careful specification of processing parameters if the potential benefits are to be realised. A method has been developed for determining optimal processing parameters for reduction of resin injection pressures, total compaction loads and process cycle times. Response Surface optimization Methodology was applied, providing an efficient method for identifying optimal solutions without the requirement of an exhaustive search of the design space. A 2D Finite Difference flow simulation has been applied to predict the transient resin injection pressures and total compaction forces that are generated during Injection Compression Molding processes. Two optimization scenarios are presented, where different weightings have been placed on the importance of minimizing clamping force, injection pressure and cycle time. The results illustrate how optimum processing parameters can vary depending on the specific requirements of different manufacturers.

KEYWORDS: Injection/Compression Molding, Liquid Composite Molding, Optimization

INTRODUCTION

The Injection Compression Molding (I/CM) process is one of the many Liquid Composite Molding processes that have been developed over the past few decades. I/CM involves liquid resin being injected through a porous fiber reinforcing preform, held within a partially closed two-piece rigid mold. After the required volume of resin has been injected, the mold cavity is reduced to its final thickness. This final phase of compaction forces the resin to flow through the remaining dry areas of the preform and compacts the fiber reinforcement to the designed fiber volume fraction. The resin is then cured, allowing the final composite part to be demolded. I/CM is similar to the more recognized Resin Transfer Molding (RTM) process, where resin is injected into a porous fiber reinforcing preform held in a mold cavity at the final part thickness. Relative to RTM, I/CM can provide reductions in required clamping forces or cycle times. To realize these potential benefits, careful specification of the processing parameters is required [1,2].

In specifying an I/CM process, several design variables must be selected. The choice of the injection flow rate, mold cavity thickness during resin injection, and the rate of compression during the final compaction phase are critical. Non-optimal processing parameters can result in excessive manufacturing cycle times or the requirement of oversized injection and compaction machinery. Through optimization of design variables considering both physical and economic requirements, an ideal processing solution can be identified for a specific mold geometry. To allow for efficient optimization of the I/CM design variables, a Response Surface Methodology (RSM) optimization algorithm has been adopted and coupled with a finite difference process simulation. The results of this study illustrate the strong dependence of any optimal solution to the specific requirements of a particular manufacturing scenario.

PROCESS SIMULATION

A 2D Finite Difference simulation has been developed to predict required resin injection pressures, total vertical compaction loads and process cycle times. This simulation is applicable to any axisymmetric part geometry where the resin is injected at the center of the mold. The resin pressures generated within the mold cavity have been modeled using Darcy's law, requiring the permeability of the intended fiber reinforcing material to be known. Several permeability tests were completed on a chopped strand mat material, to allow a realistic approximation of permeability to be applied. The reinforcing material compaction behavior has been modeled using a "mixed elastic" compaction stress model where the effects of stress relaxation, compaction rate dependency and resin lubrication effects are accounted for. The total clamping force applied to the mold is calculated, being composed of forces due to reinforcement compaction and generated resin pressure. Full details of the process modeling development have been presented elsewhere [3,4].

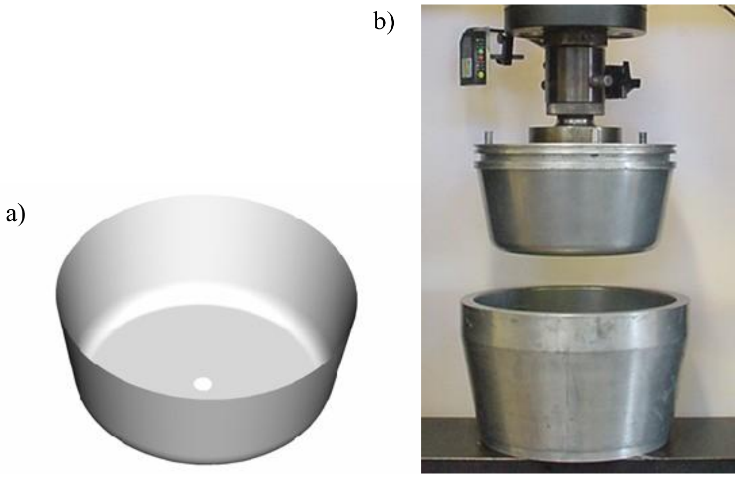

Fig. 1 a) Model of part geometry addressed in experimental study. b) Mold installed for experimentation.

To verify the accuracy of the process simulation, an experimental program has been completed [4]. Both RTM and I/CM Experiments were completed in a conical basin shaped mold having a central injection gate.

The fluid injection pressures and total vertical compaction loads were recorded during a range of experiments, where the cavity thickness during the resin injection phase, the rate of resin injection and the rate of compaction during the final compression phase were varied. The part geometry used in the verification of the mold filling simulation is pictured in Fig. 1. Sample clamping force traces recording during three I/CM experiments are shown in Fig 2, and are compared to simulated force traces. Comparison of process simulation and experimental results have provided good confidence in the application of the process simulation within the optimization study described below.

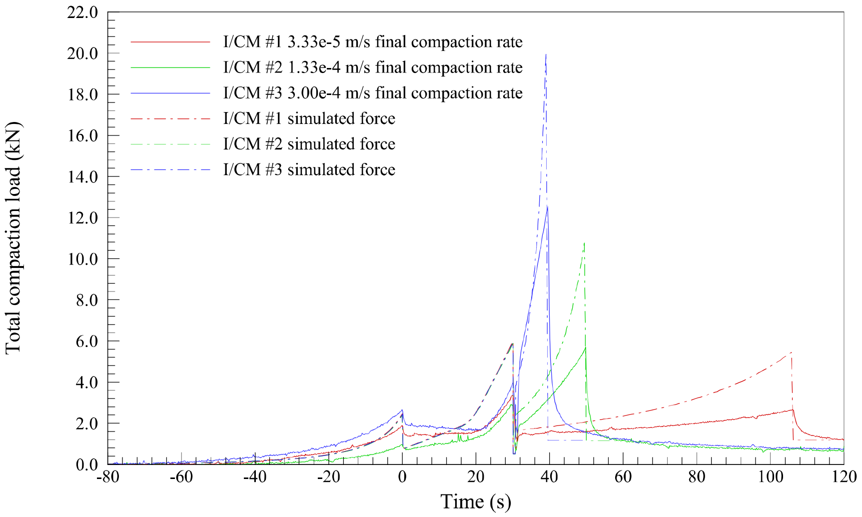

Fig. 2 Comparison of three experimental and simulated compaction force results

I/CM OPTIMIZATION METHODOLOGY

In this study three critical design variables have been varied to achieve an optimized process, the cavity thickness during the resin injection phase, the applied resin injection pressure at the injection gate, and the mold clamping force applied during the final phase of compression. An ideal I/CM process will result in a process with minimal injection pressure and clamping force, that is completed in a minimal process cycle time. These requirements are conflicting as a minimal injection pressure and clamping force will inevitably result in a maximum cycle time. This has prompted the development of a weighted process Performance Indicator (PI), provided in Eqn 1. W_F, W_P and W_t are weighting factors, and can each be set between 0.0 and 1.0, effectively ranking the importance of minimizing the maximum clamping force, injection pressure and process cycle time respectively. The PI developed has been used as an objective function during optimization, with a smaller value of PI representing a more ideal process.

$$P.I. = W_F \cdot \frac{F_{\mathbf{max}\ process}}{F_{\mathbf{max}\ allowable}} + W_P \cdot \frac{P_{\mathbf{max}\ process}}{P_{\mathbf{max}\ allowable}} + W_t \cdot \frac{T_{process}}{T_{cycle\ max\ allowable}} \qquad (1)$$

A Response Surface Methodology (RSM) algorithm has been applied in this study, through the HyperOpt (formally SOSopt) optimization platform.

RSM has been used extensively in the optimization of products and processes where multiple design variables can be altered to improve measures of design performance [5]. RSM is a numerical search method that uses an iterative approach to converge upon an optimal design solution. The concept behind RSM is that given the objective function values of a set of design solutions, a mathematical approximation of the objective function can be formulated. If there are two design variables in the problem then the approximation of the objective function can be visualized as a 3D surface, giving the methodology the 'response surface' title. The mathematical approximation of the objective function allows numerical techniques to be used to approximate the design variables that would result in the minimum objective function value. When a minimum value of an approximated objective function or 'response surface' has been determined then more design solutions can be evaluated in that region of the design space allowing a new mathematical approximation of the objective function to be formulated. As more design points are added to the response surface, the error between the approximated and actual objective function decreases. When sufficient design points are added to achieve a required level of convergence, then the design variables that result in the minimum of the approximated objective function can be assumed to be optimal.

Two optimization case studies are presented here using different weighting factors in the Performance Indicator to represent different manufacturing scenarios that may occur in industry. The geometry studied is the large circular tray of diameter 1.28m pictured in Fig 3. The final part thickness was set at a uniform 4.0mm, producing a target fiber volume fraction of 30% using a chopped strand mat reinforcing material. Resin viscosity was set at 0.13 Pa.s, typical of a low viscosity resin system used in LCM processes.

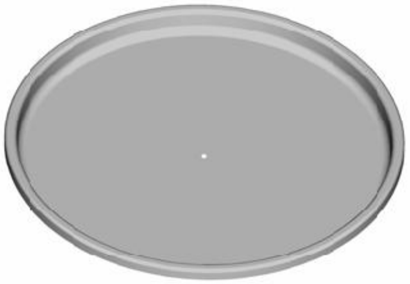

Fig. 3 Mold geometry utilized in the optimization study.

The PI weighting factors applied in each study, and the optimal solutions identified are outlined in Table 1. Study A places a large emphasis on minimizing the clamping force and a moderate emphasis on minimizing the process cycle time with W_F=0.6 and W_t=0.3. Study B places the main emphasis on minimizing the cycle time with very little requirement placed on minimizing the forces or injection pressures with W_t =0.8 and both W_F and W_P set at 0.1.

Table 1. Outline of case study objectives and optimal results identified.

	Study A			Study B		
	W_F	W_P	W_t	W_F	W_P	W_t
PI Weighting Factors	0.6	0.1	0.3	0.1	0.1	0.8
Compaction force (N)	765442			1740370		
Resin injection pressure (Pa)	250597			326417		
Cavity thickness during injection (mm)	16.0			22.9		
Minimum objective function value	0.380			0.2505		
Process cycle time (s)	144.6			56.82		
Iterations required to find optimum	21			22		

During the iterative RSM optimization process, many combinations of possible processing parameters are evaluated such that the effect of changing each can be gauged. The process parameters evaluated as the RSM optimizations progressed in each of these studies are presented graphically in Figures 4 and 5. At each iteration the resulting value of the objective function (PI) found from a set of processing variables is plotted against the primary vertical axis (at left), while the values of the input processing variables are normalized against maximum feasible values and plotted on the secondary vertical axis (at right). The optimization iteration number is plotted on the horizontal axis and it can be seen that as the optimization progresses the PI reduces (more optimal).

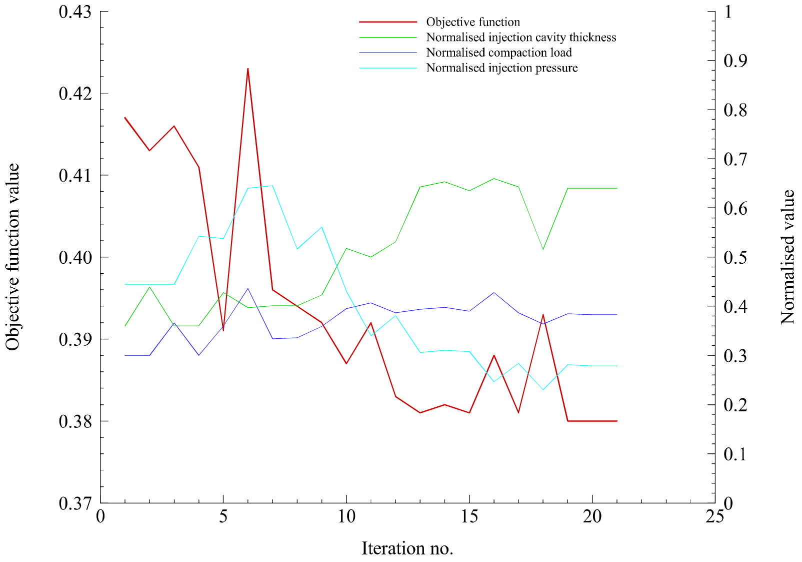

Fig. 4 Processes evaluated during study A RSM optimization.

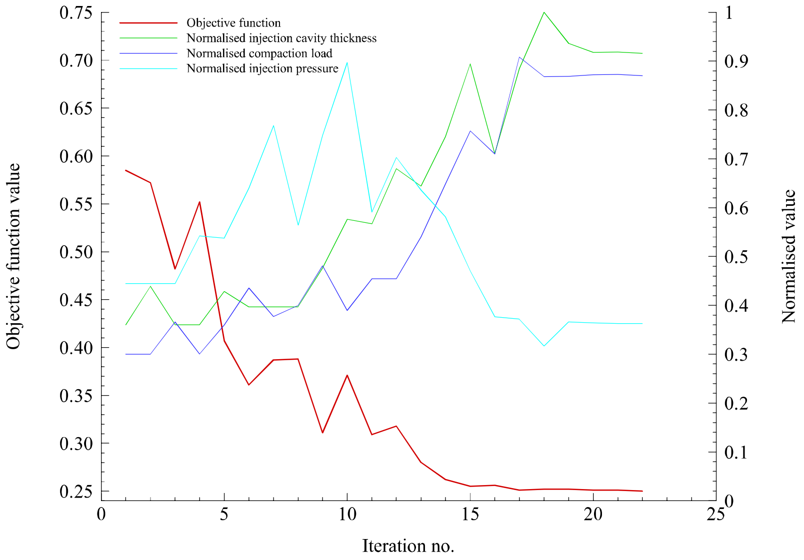

Fig. 5 Processes evaluated during study B RSM optimization.

DISCUSSION

It can be seen in Figures 4 and 5 that as the iterative RSM optimization progressed, the objective function (PI) continually dropped until converging upon an optimal solution. The optimal solution identified in each study was different, as expected with the weighting factors on minimizing injection pressure, clamping force and cycle time being different for each case. The optimal process identified by each study has selected injection pressures, clamping forces and process cycle times that reflect the performance indicator weighting factors that were applied. In study A, the optimal process identified requires clamping forces that are significantly lower that identified in study B. This is because the weighting placed on the importance of minimizing the clamping force is considerably higher in study A than in study B. The optimal process identified in study B results in a process where the cycle time is close to a third of that identified as optimal in study A. This is because the importance of minimizing the cycle time was high in study B.

CONCLUSIONS

This study has shown that for any I/CM manufacturing scenario where the requirements of reducing injection pressure, compaction force and process cycle time can be ranked, then optimal processing parameters for that process can be efficiently identified through the use of an RSM optimization algorithm. As I/CM is increasingly considered as an alternative to RTM, the greater number of process parameters to be specified must be acknowledged (i.e. cavity thickness at initial injection, mold closing speed during compaction phase).

The presented optimization methodology allows for efficient specification of an I/CM cycle that can closely match the requirements of each manufacturing scenario considered.

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