Variability in Liquid Composite Molding Techniques: Process Analysis and Control

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SUMMARY:

The present work aims to develop tools to understand and control the manufacturing repeatability in LCM processes such as resin transfer molding (RTM) and vacuum infusion (VI a.k.a VARTM). One major cause of flow repeatability is studied: the natural variation in reinforcement permeability. This is done by implementing a Monte-Carlo solution to the problem of flow through porous media. Reliability improvements are proposed by using this "real-life" virtual flow environment to design the appropriate active control strategies. In addition, the reliability differences between VI, where the flexible tooling induces transient thickness and permeability, and standard RTM, are explored. It is shown that specific models are required to analyse the impact of variability in different LCM techniques and how different control techniques affect the probable outcome of an injection.

KEYWORDS: Liquid Composite Molding, Statistical Methods, Monte-Carlo, Computational Modeling, Control.

INTRODUCTION

Modeling real flow through porous media is statistical in essence. It is commonly accepted that superficial density and compaction properties of textile reinforcements vary. It is also known that permeability exhibits a statistical nature, although these and other sources of injection risk are not normally taken into account [1]. The approach followed is based on the Monte-Carlo technique which, insofar as this work is concerned, can be outlined as a method involving the repeated simulation of the same case with different statistically generated properties. The main outcomes are the probabilities of specific flow occurrences such as final filling points, times and expected deviations from the ideal scenarios. Through these results one can characterize the efficiency of different filling strategies and produce control development tools. It can also be shown that ideal simulations of flow can overlook filling problems and, while sensible strategies can be used to avoid them, some might also result in longer filling times then are necessary.

Variations in permeability of reinforcements are therefore expected to promote differences in fill time, flow front perturbations, and cause incomplete mold filling. The same can be said for fiber angle or surface density of textiles for example. Hence, the fact that these properties are averaged in standard simulations involves a simplification of the physical process, which can be critical for the manufacturing of large series or expensive components. While sensible strategies can be used to prevent problems, they are often associated with operator expertise and can sometimes be overlooked in the design stages. The ability to quantify possible flow errors statistically could therefore be used as a manufacturing-design tool. Furthermore, computer assisted design of control schemes can only be done if one can understand and simulate natural variations in flow. The global objective of this work, which stems from which stems from past publications on this topic [1], is therefore to examine some scenarios where flow modeling, monitoring and control can be used to advantage to address some of the real-world difficulties.

BACKGROUND

Most background literature on statistical variations in flow deals with the problem of race tracking. Simply put, it is not possible to ensure that the cutting of textile reinforcements is perfect nor is their placement in the molds. Flow must therefore be controlled in order to achieve consistent production and prevent filling problems. This field has seen a significant amount of research, from the bulk-permeability work by Hammami *et al* [2] and Bickerton *et al* [3] to the control of of real cases by Mathur *et al* [4] and Hsiao *et al* [5] and experimental characterization work by Devillard *et al* [6].

A number of other factors can also influence LCM flow: experimental work published by Rudd *et al* [7] and Smith *et al* [8] explored, for example, the effect of textile draping on the permeability tensor and the mechanical properties of resulting laminates. As with most results found in the literature, these present a degree of scatter but the statistical nature of flow or mechanical properties is not explored since their work focussed on the fundaments of average behavior. Rudd *et al* [9], Lai *et al* [10] and Long *et al* [11] are examples of modeling approaches for draping, and of the draping effects on permeability: again, not investigating the nature of statistical variations as a possible origin of flow disturbance.

One other significant source of parameter variations is reinforcement permeability, which, as Bickerton *et al* [3] and Hoes *et al* [12] propose is not a constant value but follows a statistical distribution. A typical result is shown in Table 1, which contains the data used in these examples.

Table 1 – Statistical permeability data (Hoes *et al,* [12]).

Type	Matl.	Manuf.	Ref.	No. tests	Orient.	Mean	σ / *mean*
Plain woven	E-glass	Syncoglas	R 420	86	*x*	1.23×10^{-11}	14.1
					y	2.62×10^{-11}	21.7
					$ln\ (K_x/K_y)$	0.32 -	$\sigma = 0.08$

This statistical nature of flow properties of textile reinforcements is fundamentally different from the literature models of fiber orientation and fiber volume fraction used in the draping analysis, which are deterministic (a function of idealized textile architecture and mold geometry).

Note that this is not the case in recent race tracking studies where the stochastic nature of channel formation is integrated in the analysis. Given the importance and widespread use of flow simulation software in mold design and optimization, these input parameters are crucial to their accuracy. Consequently, real LCM flow does not follow the idealized scenarios but presents variations due to the statistical nature of the flow properties and geometry of the preform. These references are currently the main source of statistical permeability characterization data.

The effect of statistically distributed flow properties is discussed briefly in the following section through an implementation of the Monte-Carlo method.

IMPLEMENTATION OF NATURAL VARIABILITY IN FLOW MODELING OF LCM

Useful process models should reflect permeability variations by predicting the distribution in possible outcomes from any molding process. To model the effects of permeability and compaction variations on flow, predicted or measured distributions in properties must be incorporated in LCM simulations. In the present work, this is achieved by Monte-Carlo FE simulation which involves solving the same geometric problem a significant number of times insuring, each time, that the model contains different element properties (permeability and compaction). This is achieved by generating properties, by random selection from the relevant inverse probability distribution function (PDF), thereby resulting in them being normally distributed across a significant number of elements replicating experimental measurements and making all resulting models different and non-ideal. This procedure is repeated for all elements within the model: each will have a different permeability tensor and/or compaction properties, but permeabilities over a large number of analyses conform to the experimental normal distribution. Figure 5 shows the Monte-Carlo algorithm used.

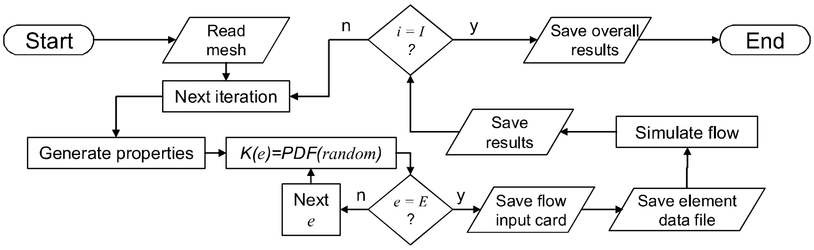

Figure 5 – Monte-Carlo algorithm proposed in this work. *e* and *E* represent the current and total number of elements and *i* and *I* the current and total number of iterations

The input files for these simulations are generated automatically by in-house software. These provide the range of filling patterns that might be expected, and also fill time and last point to fill (guiding gate and vent locations). From this, the likelihood of success for any combination of materials and injection strategy could be determined. Figure 6 illustrates this method by showing the predicted locations for the last point to be filled in a rectangular mold injected from all four corners, obtained from the statistical analysis of 15000 simulations done using LIMS.

Using the same methodology, a 2D LIMS simulation of VI can also be used to study variability for flow through compliant media.

The resulting variable permeability and fiber volume fraction and are shown in Figure 7. As can be observed, these properties are location dependent while simultaneously representing the expected reinforcement variability.

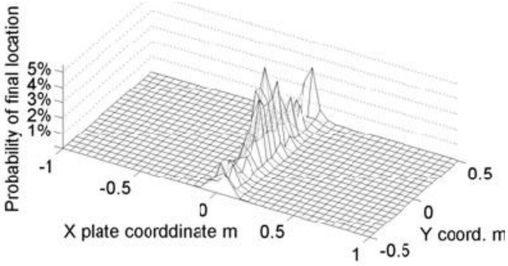

Figure 6 – Probability of final location from 15,000 simulations with Syncoglas RE 420

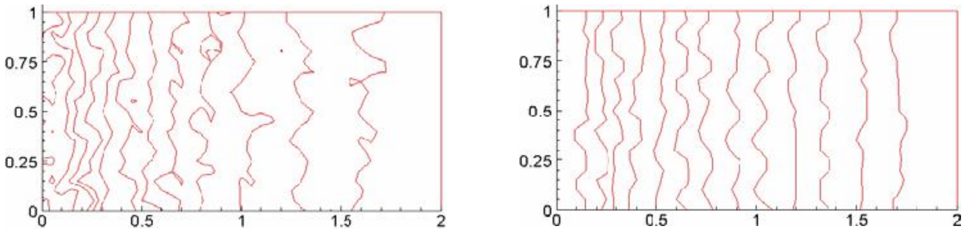

Figure 7 Evolution of permeability. Left) Iso-K lines: 7.75 E-11 m2 to 2.2 E-11m2 in 12 divisions. Right: Iso-vf lines: 40% to 55% in 16 divisions. Flow evolves from left (inlet) to right (outlet).

PROCESS CONTROL

Another application of the Monte-Carlo method is in the computer assisted development of active control systems. The control concept employed in this example uses flow front positions to analyze different control actions: the effectiveness of an action is assessed by computing the difference in saturation between the ideal and the controlled cases. Subsequently, the best control action is activated until the next control step phase is reached. . Figure 8 illustrates the result of a typical five stage virtual on-line control showing the potential benefits of flow front steering through variable inlet pressure at different injection ports.

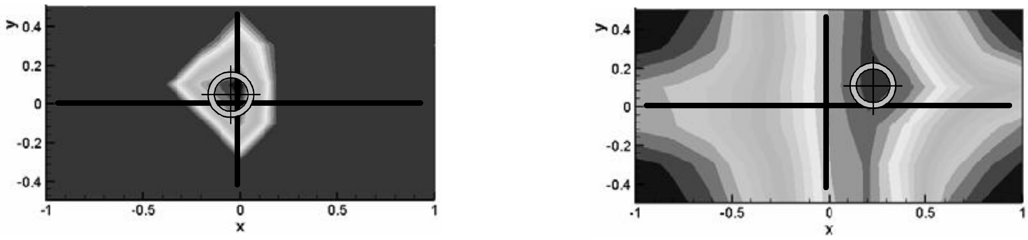

Figure 8 – Controlled injection filling (left) vs isochrones of the non-controlled injection (right)

Note that this is a simple approach to control but that the technique can be expanded, e.g. training neural networks to recognize filling patterns, uniquely quantify the statistical effectiveness of each approach and take the appropriate action.

CONCLUSIONS

This work discusses the developments on flow modeling of LCM processes, which were achieved through the application of the Monte-Carlo method. The method was described and demonstrated for non-compliant porous media case. It was shown that this method can be used to develop complex control approaches as it is able to statistically quantify the effect of different numbers of control steps or injection strategies. The adaptability of this method to different mold geometries and injection strategies also implies that new LCM control and optimisation tools could be industrially deployed. Finally, while the full impact of the statistical distribution of permeability and compaction on LCM techniques continues to require study, the introduction of Monte-Carlo techniques on virtual experimentation / process development could have a vast potential.

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