A Minimalist Sensor System for Mold Filling

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SUMMARY: Reliable mold filling remains the most critical issue in the commercial application of liquid composite molding. Many techniques of observing the flow are either cumbersome or too invasive for routine service. Combining the sensor output from a single, evanescent wave optical fiber sensor with flow simulation results can provide discrimination between normal mold filling behavior and a variety of flow disturbances. The fiber sensor is operated in evanescent wave mode to provide a lineal signal rather than a point signal, and the flow simulation model is used to design the optimal sensor trajectory through the part.

KEYWORDS: Liquid Composite Molding, Mold Filling, Optical Fiber Sensor, Optimal Placement, Stochastic Design

INTRODUCTION

Liquid composite molding (LCM) has become a widely used polymer composite manufacturing process due to its versatility, fast cycle times and relatively low costs. However, there still remain many indeterminant parameters associated with the process such as local variations in the permeability, due to inhomogeneities in the preform, and preform fit to the mold cavity. Optimization of process conditions is typically achieved by conducting mold experiments [1], which are not only time-consuming but also expensive. Hence, there is a growing interest in the development of other means of both optimizing the manufacturing parameters and enhancing the understanding of how these parameters physically govern the outcome of the part at each stage of the process through simulations and in-situ monitoring [2,3].

To date, there exist a myriad of simulation packages and sensory devices explicitly designed for this purpose. An example of such a sensory system that has been successfully developed is Kranbuehl, et al.'s Frequency Dependent Electromagnetic Sensing system, which is capable of monitoring the progress of cure reactions [4]. The main appeal of on-line sensing is that it enables appropriate corrective measures to be taken during manufacturing and thus, can save the part from being rejected due to manufacturing defects. One of the most frequently encountered problems in LCM is the occurrence of voids or dry spots in the part. These are typically the result of air entrapment in the mold or imperfect impregnation of the preform [5].

By monitoring the resin flow front during mold filling, it would be possible to detect the onset of a dry spot and, possibly, take the necessary steps to correct the situation during the process.

While embedded on-line sensors are one of the best means of assessing what is happening within the mold, they often present additional complications as they themselves can become part of the inhomogeneity in the preform structure. However, these complications can be assuaged by having as few of these sensors present in the mold as possible, ideally only one, and also making them as small as possible.

The evanescent wave fluorescence fiber optic flow monitoring sensor system works on the premise that the fluorescence intensity measured by the sensor is proportional to the length of the sensor covered by the resin. In evanescent wave fluorescence sensing, the standing (evanescent) waves at the fiber-resin interface excite the fluorophores in that immediate vicinity, causing them to fluoresce [3]. This evanescent field arises from the total internal reflection at the interface of the fiber and the surrounding medium. It extends beyond the reflecting interface into the surrounding medium, decaying exponentially in amplitude from that interface [6]. To date, evanescent wave fluorescence sensors have been successfully used in cure monitoring of thermoset polymer composites [3], pH sensors [7] and in antigen- antibody binding studies [8].

In previous work, the fiber optic sensor response for fiber lengths exceeding 1 m was characterized through a series of idealized experiments [9]. The results of these experiments were then employed to conduct a sensor simulation study for LCM in a square mold, with and without inserts. The overall objective of this investigation is to develop an understanding of how to interpret an evanescent wave fluorescent fiber optic sensor response, and, subsequently, how to use it to control the LCM process. Specifically, the goal is to understand these responses and address the issue of sensor placement so as to obtain as much information as possible about the flow pattern within the mold from just a single sensor. An additional consideration in choosing the sensor placement is the probability of flow anomalies occurring in the vicinity of the sensor. A method of assessing such probabilities is presented.

SIMULATION OF SENSOR RESPONSE

Previous work demonstrated that a linear response may be expected for evanescent wave optical fiber sensors for lengths up to approximately 1 m [9]. While that work did not address important issues such as fiber bending, advanced optics employing gratings and coatings are expected to mitigate nonideal responses. The important issues to address for the case of a single sensor in the mold are:

(i) Can the sensor response distinguish between a defect-free mold filling and one with an anomaly such as race tracking?
(ii) Can the sensor response distinguish between different flow anomalies?
(iii) Can flow anomalies be detected early in the mold filling process?

These issues were addressed by analyzing the simulated sensor responses in a number of different simulated mold filling situations using the Liquid Injection Molding Simulation (LIMS) package developed at the University of Delaware [10]. The times at which the flow front reaches certain points lying along a predetermined sensor trajectory were noted. The sensor response was simulated using this information and the experimentally determined linear relation between the measured fluorescence intensity and length of the sensor covered. The sensor

response was then graded according to the three criteria listed above.

A flat, square mold of size 1 m x 1 m x 0.01 m, with double inserts, was used for the simulations reported below (Fig.1). First, the mold filling of an isotropic preform was examined, followed by simulations of mold filling with race tracking. The injection gate is located at the center bottom edge and each mold filling simulation was performed under constant inlet pressure. Three race tracking cases, indicated in Figure 2, were studied.

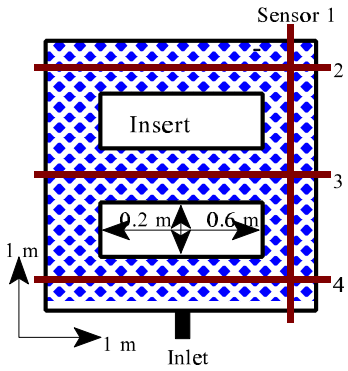

Figure 1. Double insert mold

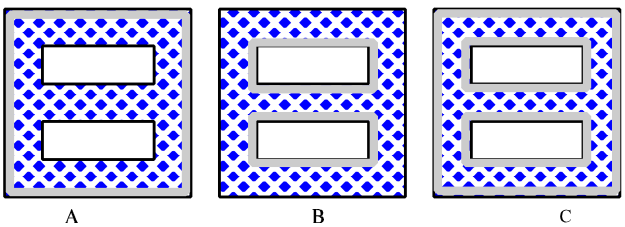

Figure 2. Race tracking simulations were conducted with simulated sensor for three cases. A. Race tracking on outer edges, locations. B. On insert edges, and C. on both sets of edges.

The responses from the sensors in various race tracking scenarios will be compared to their response in the idealized mold filling case. Figures 3 and 4 illustrate the flow patterns and sensor responses. In several of the cases, the sensors cannot clearly distinguish all three race tracking cases from the ideal case with no race tracking.

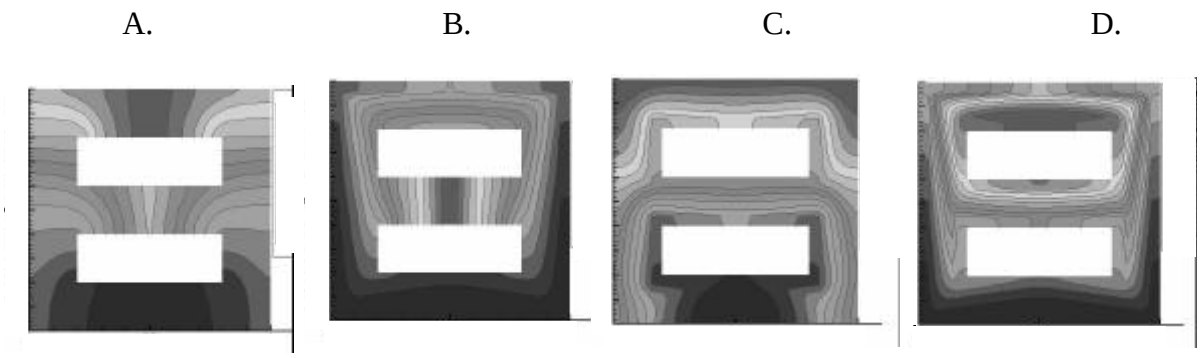

Figure 3. Flow patterns for A. No race tracking, B. Race tracking on outer edges, C. Race tracking on insert edges, and D. Race tracking on all the edges.

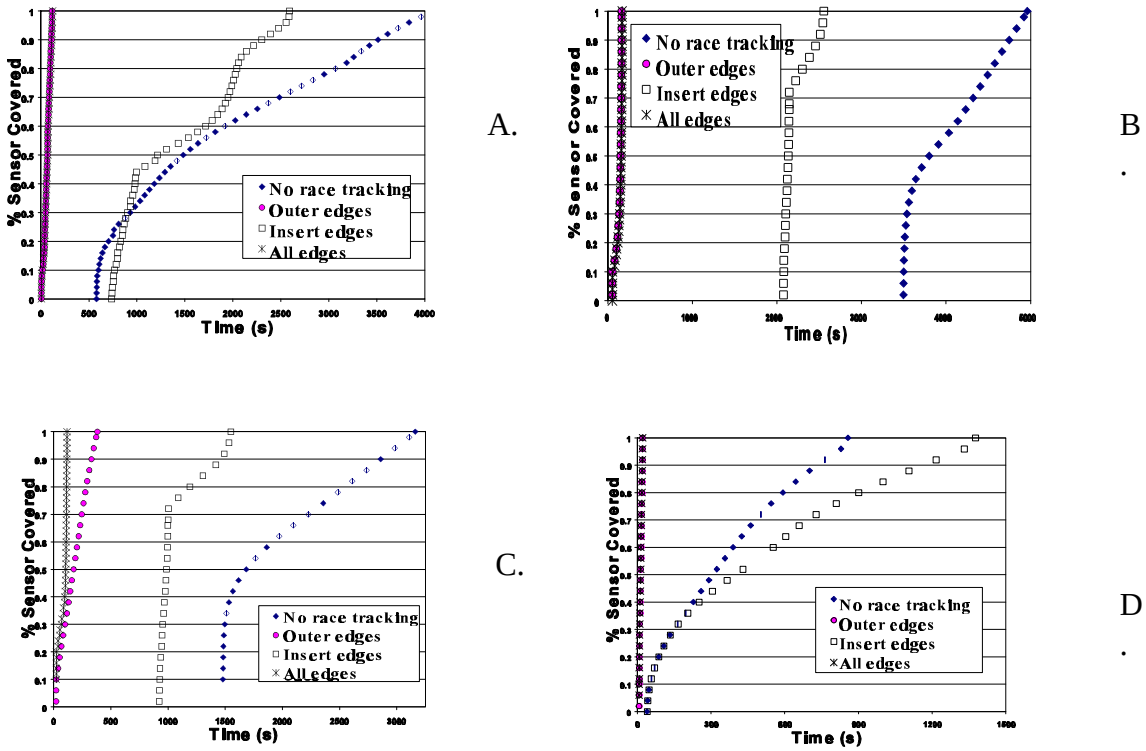

Figure 4. Sensor responses to flow patterns for A. Sensor 1, B. Sensor 2, C. Sensor 3, and D. Sensor 4.

The resin initially reaches Sensor 3 (Fig.4C) earlier in all three of the race tracking cases, as compared to the defect-free scenario. For race tracking along only the insert edges, Sensor 3 was 70% covered within 10 seconds after the resin first reached it, indicating the flow front is largely parallel to the sensor. For race tracking along the outer edges or along all the edges, the first 10% of Sensor 3 was covered instantaneously. The rest of the sensor was then covered rapidly. As all of the responses are clearly different from the normal one and also from each other, Sensor 3 scores highly relative to the first two issues identified above. And since these departures from the norm were distinguishable before the mold is half filled, Sensor 3 also scores well on the third criterion.

The other sensors were not able to distinguish the different flow scenarios from each other as clearly as Sensor 3. The sensor responses were of a more even quality on the other two criteria,

detecting a difference in the flow relative to a perfect fill pattern, and detecting differences early in the mold filling. A numerical comparison of the sensor responses was obtained by grading the sensor responses in each of the three criteria on a 3 point scale, with a score of 3 representing excellent performance. Table 1 summarizes the ratings for each sensor trajectory. This sensor rating method is quite subjective, and a more quantitative evaluation system is being developed to objectively assess sensor performance. Despite the subjective nature of the current scoring system, it is clear that Sensor 3 is the best choice to detect race tracking in the example of a mold with double inserts.

Table 1. Scores for several single fiber trajectories in a mold with double inserts.

Sensor Trajectory	Detect Anomaly	Distinguish Anomalies	Early Detection	Total Sensor Score
1	2	1	2	5
2	3	2	2	7
3	3	3	2	8
4	3	0	3	6

PROBABILITY OF EDGE-EFFECTS

Rating the sensor response to various anomalous flows does not account for the probability of occurrence of those anomalies. The example below, on a flat plaque with one slightly curved side (Fig.5), illustrates a scenario where probability can affect mold design and sensor placement. Since detailed knowledge of the preform fit cannot be known in every case, a statistical approach to placing the injection ports and vents is called for. We wish to find the port and vent locations that minimize the number of rejected parts, while still maintaining an acceptable processing rate. Once the possibility of imperfect preform fit is admitted, we can define a probability that a gap of width H will exist along a mold edge. Detailed data on the probability may not exist, but simple models can be developed, numerically solved, and used to design molds robust to flow behavior deviations. As an example, even a flat plaque geometry may be expected to have preform fitting problems, especially along a curved edge. From experience with similar parts, a manufacturer may know they can always fit such curves with gaps smaller than 1 mm; thus, the probability of having a gap larger than 1 mm is essentially zero. However, gaps always occur to some extent so the probability of having a gap is essentially 100 %. Along straight edges gaps larger than 0.25 mm are never seen but some gaps also always occur.

If we ignore possible correlations between the gaps on one edge with gaps on another edge, a simple model for the probability P^{+} that a gap is larger than or equal to a specific size H can be formulated as

$$P^{\%}(H/M) \;\; ' \;\; a\,e^{\&H/M}\,\%b \qquad \textbf{(1)}$$

with

$$P^{\%}(H/M\,'\,0)\ '\ 1$$
$$P^{\%}(H/M\,'\,1)\ '\ 0 \qquad \textbf{(2)}$$

where M is the maximum value of H. Analytical models for edge-effects often scale the gap by the square root of permeability, but for manufacturing purposes models such as Eqs.(1-2) may be more practical. For the hypothetical case above,

$$P_1^{\%}(H_1/M_1)\ '\ \frac{e^{\&H_1/M_1}\&e^{\&1}}{1\&e^{\&1}} \qquad M_1\ '\ 0.1cm$$
$$P_3^{\%}(H_3/M_3)\ '\ \frac{e^{\&H_3/M_3}\&e^{\&1}}{1\&e^{\&1}} \qquad M_3\ '\ 0.025cm \qquad \textbf{(3)}$$

where the subscripts 1 and 3 refer to the curved and straight edges, respectively.

Flow behaviors predicted by models using the gap widths expected in the manufacturing process may now be assigned probabilities of occurrence using the probabilities of occurrence for the gap widths. Assigning an entire flow behavior a probability is not very helpful since the flow behavior occurs over time and occupies the entire mold. A scalar quantity that captures the essence of the flow behavior, and which can be assigned a probability may be used more conveniently for design purposes. For the purpose of locating gates and vents, a useful quantity is the mold fill fraction. More precisely, the mold fill fraction at the point in time the fluid flow front first reaches a mold vent quantifies the quality of the mold filling. The importance of edge-effects for filling the plaque with a curved side can now be easily shown in terms of the mold fill fraction when fluid first reaches a vent. For background, Fig. 5 illustrates the mold filling pattern for the case of a preform with a highly anisotropic permeability tensor and with no edge-effects.

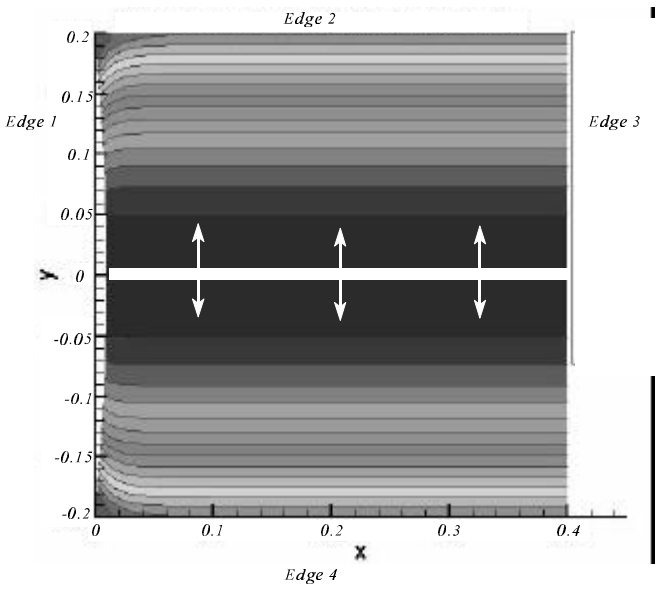

Figure 5. Mold filling pattern in a plaque with one slightly curved side, filled from a fan gate across the waist of the part.

In the case of a central fan gate across the waist of the part, the last portions of the mold to fill are the corners of the curved side. As a design starting point, let us locate the mold vents at those two locations.

Figure 6 illustrates the mold fill fraction, denoted $S(H_1,H_3)$, for several cases of edge-effects. Edge-effects were simulated on only the curved edge and the opposite straight edge for the purposes of illustration, but clearly, more complicated scenarios could arise where edge- effects occur on three or all four edges. The vent locations were chosen based on the filling pattern in Fig. 5, in which no edge-effects were permitted, so that S(0,0)=1.0. The port location chosen, a fan gate across the width of the mold, leads to the lowest injection pressure, in the case of constant flow, and the lowest injection time, for the case of constant inlet pressure. Clearly, edge-effects along straight edge 3 do not significantly influence the results, but even small gaps along curved edge 1 cause large deviations in the mold filling quality.

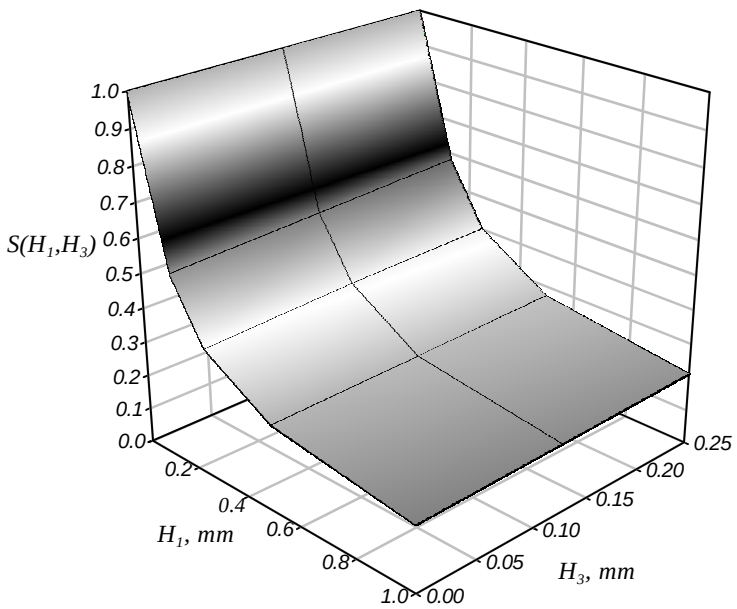

Figure 6. Mold filling quality in a plaque with a slightly curved side, for edge-effects on the curved side of width H_1, and on the opposite straight side of width, H_3.

The results illustrated in Fig. 6 provide a relationship between gap widths H_1 and H_3, and the fill quality S. We can combine these results with the probability distribution of H to find the probability of obtaining certain values of S. Since the gap width H_3 has almost no effect on S, we will neglect H_3 in deriving the probability distribution for S. Note that Fig. 6 shows that S is a monotonically decreasing function of H_1. Therefore, the probability that S # s equals the probability that H_1/M_1 = h, where $s=S(H_1/M_1=h)$. If we define the probability P ˜ as the probability that S # s, then

$$P^{\&}(s) \;\; ' \;\; P^{\%}(H_1/M_1 \, ' \, h) \qquad where \;\; s \;\; ' \;\; S(H_1/M_1 \, ' \, h) \qquad \textbf{(4)}$$

Combining the results for S with the probability P_c^+ from Eq.(3), and using Eq.(4) above, provides the result shown in Fig. 7 for $P^-(S)$.

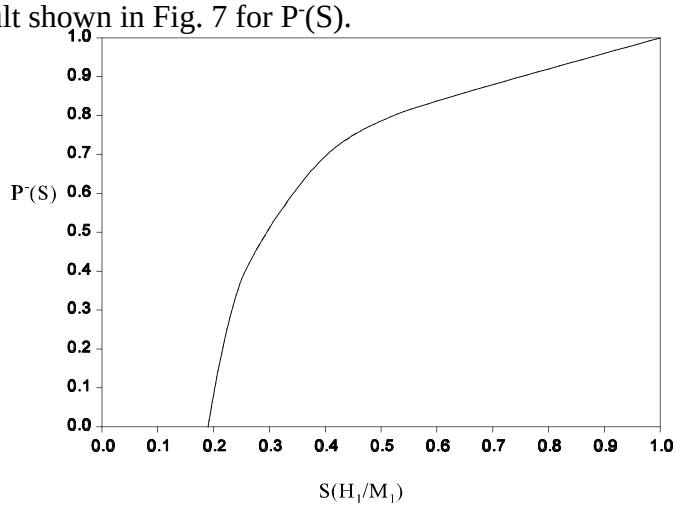

Figure 7. The probability that the fill quality S will be less than a specified value.

This result illustrates that there is a 100% probability that the fill quality S < 1, which means that the initial design of the mold port and vents will not work well at all without active control.

This rather extreme example of edge-effects can be optimized to greatly reduce the consequences of edge-effects by shortening the fan gate so it does not extend all the way to the curved side of the mold. In the optimized configuration, much higher probabilities for high quality fills are obtained at some cost to processing speed. A sensor and control system designed for sensitivity to the highest probability flow anomaly could further reduce mold filling errors past that obtainable from design optimization. For example, in the case above, we have shown that the major problem occurs at the curved side of the mold. Therefore, a sensor trajectory that can quickly detect edge-effects on the curved side of the mold is much more valuable than a sensor trajectory that detects edge-effects at the other mold edges.

CONCLUSIONS

Computer simulations demonstrate the potential to obtain sufficient flow information from a single optical fiber, evanescent wave sensor for mold filling control purposes. A modeling strategy for designing optimal sensor trajectories was outlined where the sensor trajectory was scored based on the ability to distinguish anomalous flows from the correct flow, distinguish anomalous flows from one another, and detect anomalous flows early in the mold filling process. The probability of certain flow anomalies may also impact the choice of sensor trajectory by alerting the designer to those mold filling problems most likely to cause low quality moldings. Analysis of fill quality probability can aid the mold design optimization process as well as the sensor placement process.

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