Robust Design of RTM Process with Statistical Characterization of Permeability and Flow Simulation

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ABSTRACT

The resin transfer molding (RTM) process has gained extensive attention for its capability of producing complex structural parts, which has resulted in a rapid growth in RTM applications. However, this process is still underutilized relative to its potential. One major barrier is that the reproducibility of the finished parts is often lower than expected, which increases the cost for RTM components. In the RTM process, major quality problems come from unbalanced resin flow in the mold filling process. Fiber preform permeability is a key parameter that influences resin flow behavior. However, due to variations existing in raw materials and processing, the preform permeability varies across regions within a part or from part to part. This variability results in reduced reproducibility of the finished RTM components. This research studied the statistical properties of the typical race-tracking permeability in RTM processes. Based on this statistical characterization, a robust design approach was developed to help design RTM processes to be insensitive to preform permeability variations coming from materials and processing, thereby consistently manufacturing higher quality composite components.

Keywords: **Resin Transfer Molding (RTM), Process simulation; Flow-modeling**

1. INTRODUCTION

In the RTM process, resin flow is governed by a number of process parameters, such as fiber reinforcement permeability, resin chemistry, rheology, injection pressure/flow rate, mold complexity and human factors. Among these parameters, preform permeability, which can be described by Darcy's law, plays a crucial role in the RTM mold filling process. The primary sources of quality and reproducibility problems in resin flow are induced defects, voids and dry spots. These defects are often caused by unbalanced resin flows, which are directly related to fiber preform permeability variations. Improper fiber preform preparation/loading and fiber deformation are leading causes for permeability variations [1]. Therefore, precise characterization of preform permeability is key to the success for both flow simulation and actual manufacturing processes. RTM manufacturers require a process that is insensitive to the material variations to achieve robust design.

During the past decade, many studies have reported on permeability characterization and RTM process design optimization [1-4]. These research studies have provided a fundamental understanding and some experimental results for fiber permeability and optimum design of the RTM process.

However, these permeability studies only investigated bulk/average permeability of fabrics in RTM processes. Quantitative and statistical analyses of local permeability variations, such as race-tracking effects, are lacking in current RTM literature. In addition, most current RTM process design optimization studies did not consider the effects of local permeability variations. In this research, a comprehensive study investigated the statistical properties of typical race-tracking permeability in RTM processes. With the statistical analysis results, a robust RTM process design method was introduced and illustrated.

2. METHODOLOGY

2.1 Statistical Characterization of Race-Tracking Permeability In RTM manufacturing, since the injection gates are often positioned at the edges of the mold, edge effect or race-tracking may be encountered. Characterizing the permeability in the race-tracking areas in imperative so that the RTM process can be designed and controlled properly. This research establishes a correlation between race-tracking permeability and average permeability with the assistance of RTMSim, a flow simulation software developed by the authors based on a control volume/finite element method (CV/FEM). In experiments, no special care was exercised in transporting, cutting or laying up fabrics in order to make the experimental environment as close as possible to actual manufacturing process, and inevitably produce race-tracking. Repeated experiments were performed under the same circumstances. To obtain race-tracking permeability, an inverse approach was employed. Simulation results were used to infer the race-tracking permeability. With different distribution assumptions (gamma distribution, Weibull distribution and lognormal distribution), ratios indicating the severity levels of race-tracking permeability were fitted by statistical models. Then a goodness-of-test was employed to compare the fitting performance of different distributions to find the best statistical model that describes the statistical properties of race-tracking permeability data.

2.1.1 Determination of Race-Tracking Permeability In this study, one-dimensional permeability measurement experiments were designed to study the statistical properties of permeability. WR24-5X4 woven fabrics (surface density = 810g/m^2 and solid density = 2500kg/m^3) from Owens Corning Company were used as the test material for these experiments. In repeated experiments, the average permeability values of fiber preforms at the regions in the whole mold cavity where the test liquid flowed slowest were calculated using Darcy's Law. With the assistance of flow simulation, race-tracking permeability was obtained by several trial runs through an inverse approach. The permeability for the central region and estimated rack-tracking permeabilities were input into the RTMSim software to obtain a flow pattern. Simulated results were compared with the flow processes recorded by a digital camcorder. Both filling times and flow patterns located in a similar range of the actual race-tracking permeabilities for both edges were acquired. Comparing the experimental flow process with simulation results, a pair of race-tracking permeabilities was obtained. This procedure was repeated 46 times, resulting in 46 pairs of permeability values.

2.1.2 Statistical Analysis Results To obtain more precise analysis results by avoiding truncation or rounding errors, the following ratio was defined for quantifying a severe level of race-tracking permeability:

$$Ratio = \frac{race - tracking\ permeability}{average\ permeability} = k_r/k_a$$

The ratio data were calculated from the 46 experiments. These ratio data were analyzed instead of original race-tracking permeability values. To obtain the statistical properties of the permeability ratios, hypothesizing a distribution family for observation data was structured and the results were compared to determine the best model. Three continuous distributions were selected to fit the k_r/k_a values: Gamma distribution (*gamma(..)*); Weibull distribution (*Weibull(..)*) and Lognormal distribution (*LN(,)*).

In this study, the maximum-likelihood estimation (MLE) method was selected to derive the distribution parameters. The candidate distributions were estimated as *Gamma(2.48, 2.759); Weibull(1.638, 7.6829)* and *LN(1.71, 0.6869).* Since none of these three distributions perfectly fit the data, the authors closely examined the distributions to determine the one that best represented the true underlying distribution for the k_r/k_a values. The goodness-of-fit is an effective method for evaluating the fitting of a distribution to the data. In this study, the Chi-Square test was performed as goodness-of-fit hypothesis test [5]. From the hypothesis test, the Weibull distribution was found to perform the best. Therefore, the Weibull distribution was determined the best for representing the k_r/k_a values. It should be noted that the assessment was case specific (for woven fiber, one dimensional experiment setup), and the k_r/k_a values for other fabrics may not necessarily be represented by Weibull distributed variables.

2.2 Robust Design of RTM Processes Locations of gates and vents play a crucial role in RTM process/tooling design. Many studies regarding RTM process design and optimization have been conducted [6-8]. In most of these studies, researchers assumed that permeability of the preform was either uniform/isotropic across the part or deterministic, i.e. no consideration of stochastic nature of permeability. These assumptions are invalid in many actual RTM production conditions, particularly when race-tracking is present. This paper introduces a new concept of optimum RTM process design. This method minimizes the sensitivity of the mold design to uncertain material properties by choosing the appropriate locations of gates and vents, improving the robustness of RTM tooling and processes design.

2.2.1 Robust RTM Process Design Methodology In the RTM process, the major factors that determine the resin flow behavior and final part quality can be grouped into two classes: deterministic factors and stochastic factors. Injection pressure, flow rate, mold temperature, etc. are the deterministic factors, which means they can be measured or controlled as desired. The primary sources of uncertainty include the preform permeability dominated by its microstructure and the variability of rheological and kinetic properties of the resin. Those uncertainties presented by the above factors occur at different magnitudes. Only race-tracking permeability was considered as a stochastic factor in this study.

The same material described in Section 2.1 was used for the robust RTM process design so as to utilize the conclusion that the k_r/k_a values were distributed as Weibull random variables (*Weibull(1.638, 7.6829)*). With the assistance of computer simulation, different combinations of statistically generated input and deterministic parameters can be used as inputs for the flow simulation software to assess tooling designs with well-defined objectives. Therefore, the robust design approach involves two components: a virtual experiment and a Monte-Carlo simulation. Figure 1 illustrates the robust process design approach.

Dry spots create major defects in RTM process. Usually, the vent is positioned at the location where the flow entraps the air. Once the tooling design is completed, the vent location cannot be changed during the course of manufacturing. However, for most fiber preforms, permeability variations, especially the variation of race-tracking permeability, vary at the ending locations of the flow. Because of variations in process parameters, the flow does not end where desired. Therefore, to obtain a robust tooling design, the vent should be placed at the location that minimizes the ending locations variations due to uncertainties in process parameters.

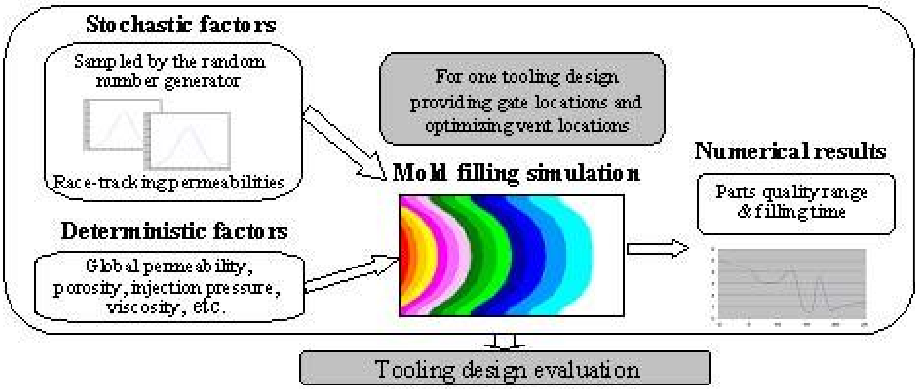
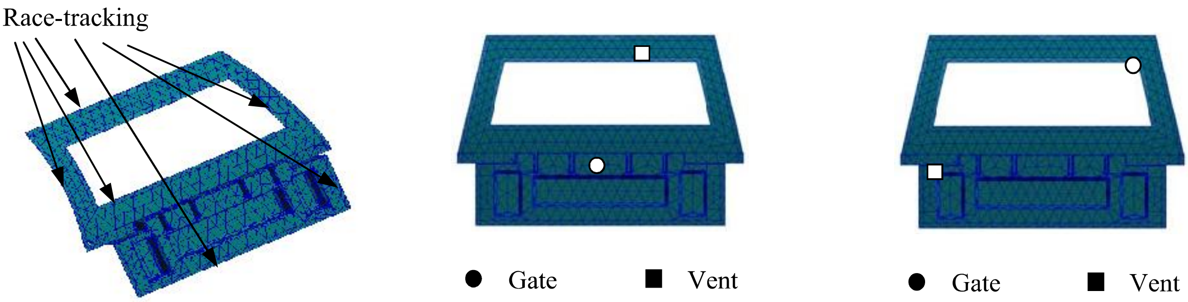


Figure 1: Illustration of the robust process design approach

A vent location dispersion value was defined to quantify the ending locations variation. Using this dispersion value, part quality can be quantified. Usually, the process design with a comparatively smaller dispersion value is preferable. This can be generalized for multi-vent cases.

To illustrate this method, a rear car door was designed and tested, as shown in Figure 2(a). For this case study, it was assumed that the average permeability was constant and the ratios of race-tracking permeability over average value were statistically distributed variables (*Weibull(1.638, 7.6829)*).



(a) Part geometry (b) Tooling design #1 (c) Tooling design #2

Figure 2: Car door example

A typical tooling design for this part is to position the gate at the center of the main region, as shown in Figure 2(b). However, after evaluating other locations of the gate, a smaller vent location dispersion value was found, which indicated a better gate/vent design. For one gate and one vent tooling design scenario, it was determined that they should be located along the length direction of the part (Figure 2(c)). The vent location dispersion value was reduced from 15.64 to 6.06.

3. CONCLUSIONS

This paper reported on two studies: statistical characterization of race-tracking permeability in RTM process and robust design of RTM process. In the first study, sources of variations in RTM processes were analyzed and the most important source of variability – preform race-tracking permeability – was investigated. By repeating one-dimensional permeability measurement experiments and corresponding simulations, race-tracking permeability data were acquired via an inverse method. A ratio of permeability in the race-tracking area to the average permeability of the preform, k_r/k_a, was defined to indicate the severity level of race-tracking permeability. The ratio data were characterized statistically with different distribution assumptions. The Weibull distribution was found best suited for representing the values. The second study involved the optimum design of the RTM process based on the statistical characterization of race-tracking permeability of fiber preform. The optimization objective was to realize robust process design, which makes the process insensitive to the preform material variations. The process design approach was illustrated through an example of RTM processing a rear car door. The result from the example indicated that the robust process design approach was effective in reducing the process sensitivity to preform permeability, as well as the mold filling time.

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