A GENERAL METHOD FOR OPTIMAL PRESSURE SENSOR PLACEMENT TO DETECT RACE-TRACKINGS AND PREDICT THEIR CRITICALITY IN THE RESIN TRANSFER MOLDING PROCESS

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Abstract

A common disturbance encountered during composite manufacturing is gaps between the preform and the mold wall, where resin can flow easily giving rise to the race-tracking (RT) phenomenon. Race-tracking is unavoidable in the Resin Transfer Molding (RTM) process and can lead to entrapment of air pockets which results in parts being discarded as scrap. In this study, a simplified cost effective simulation-based methodology is proposed to assist manufacturing engineers in the design and development phase of the RTM process to make it more robust whatever the occurrence of RT. A numerical methodology is presented to distinguish between the critical and non-critical race-tracking scenarios. The detection methodology is based on the use of pressure sensors and the computation of the pressure evolution over time during the injection process. The novelty relies on the superposition of the computed pressure gradient maps in the numerous RT cases investigated. Sensor locations for a simple rectangular shape up to parts of complex shapes are identified using a general rule that a complex geometry can be represented as a combination of simpler ones.

1. Introduction

The main goal of this study is to reduce the risk associated with RT flow disturbances and improve RTM process robustness. The race-tracking (RT) phenomenon is difficult to prevent and is not repeatable hence predicting the flow pattern in a closed mold is increasingly becoming a challenge for manufacturing engineers [1]. Development phase is the most crucial stage in RTM composite parts manufacturing [2]. However, it is costly and time-consuming. The risk increases with the part complexity and the expected level of accuracy. A new methodology is developed to assist manufacturing engineers throughout the development phase in detecting race-tracking during the injection process and determining the level of its criticality. This methodology will support the decision-making process on selecting the best injection strategies, and highlighting the riskiest scenarios which they may face later in the production phase. The fundamental requisites of the methodology are that it must be simple and easy to apply but should be robust and reliable. In addition, it must be a cost effective methodology that uses only pressure sensors for race-tracking detection in the mold filling.

2. Simulation Environment

LIMS (Liquid Injection Molding Simulation) developed at the University of Delaware (UDEL) and experimentally validated is used as a solver for carrying out RTM process flow simulations [3]. LIMS is a a finite element/control volume based mold filling simulation, and has the capability of providing scripting in LBASIC which allows to implement some changes to LIMS UI extending its capabilities. GMSH and MATLAB were used for geometry and mesh creation as well for post processing of the results.

3. Approach

The approach is based on finding the optimum number of pressure sensors for any mold geometry for RT detection using a mold filling simulation. Minimum number of sensors will be found and placed for a simple mold geometry, then the geometry will be extended with more features. Then a new failure criterion will be defined for RTM parts which will flag the riskiest scenarios for void entrapment.

3.1. Selection criteria

The selection criteria will be based on minimizing the number of sensors required while obtaining maximum possible information and be able to distinguish between different race-tracking situations.

3.2. Framework

Injections are made at a constant flow rate with a line injection on the left side of the mold and a line vent is placed along the right edge of the mold. This injection and vent strategy was chosen to avoid any possible discrepancies that could result from irregular flow front shape due to point injection or vent. Different predefined race-tracking scenarios were proposed based on some fixed and variable parameters reported in **Table 1**:

Table 1. Fixed and variable parameters

Variable	*Definition*	*Unit*	Type	
			Fixed	Variable
L_y, L_x	Mold length and width	m	✓	
K	Preform isotropic permeability	m^2	✓	
K_i	RT permeability	m^2		✓
L_1, L_2	1st and 2nd RT lengths	m		✓
ρ_i	RT strength	-		✓
H_1, H_2	1st and 2nd RT widths	m	✓	
i	RT edges (1 and 2)	-		✓

RT along the upper and lower edges can vary in the range [0, Lx]. The race-tracking strength which is defined as the ratio between the RT permeability K_i and the preform permeability K is assumed to vary between 10, 100 and 1000. The initial mold geometry, boundary conditions and race-tracking location and dimensions are illustrated in Fig. 1.

4. Methodology

A total of 15 scenarios were generated for a rectangular mold to address the permutations possible due to the various RT strengths, locations and length (Fig. 3). The scenarios were intuitively selected to identify a variety of lengths, strengths, and locations. RT lengths ranged from 0 up to the full length (60 cm), the strength ranged from 10 to 1000 and the location could be either near the inlet, at the centre or near the outlet.

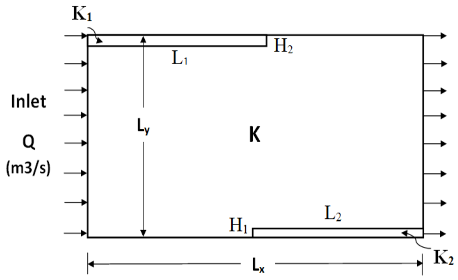

Figure 1: Assumptions

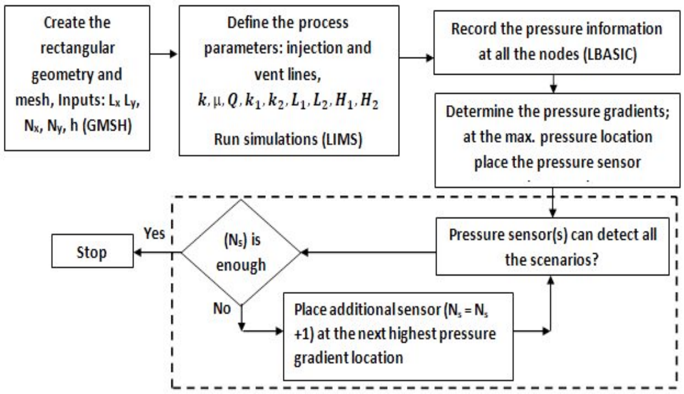

Figure 2: Methodology for sensor placement

Figure 2: RT scenarios used to build the methodology

The numerical methodology using LIMS UI, GMSH, MATLAB and LBASIC was developed and is presented in Fig.2. First the mesh was created in GMSH or MATLAB, then it was imported into LIMS UI, the process parameters were defined then the LBASIC script was modified to enable recording the pressure at all the nodes by the end of the injection. The pressure gradients at each location were calculated and the pressure gradients zones were identified. The location of the highest pressure gradient was selected as the 1st sensor location, then the pressure evolution with time was computed at this sensor location to test if this sensor can detect the most possible RT scenarios. If that sensor was not sufficient, then the second sensor was introduced at the next highest pressure gradient. This process was continued until the minimum number of sensors that could detect different scenarios was obtained.

5. Results and discussion

The pressure contours at the end of injection for all the scenarios were used to calculate the pressure gradients in both the x and y directions, then the norm of these values was calculated and used to plot the pressure gradient map for each scenario.

5.1. Sensor location for simple geometries

The general rule assumes that all the complex shapes can be represented as a sum of simpler ones, as follows; sensor locations will be determined for simple geometries, then more complex geometries that can be represented as a sum of simpler ones are explored.

5.1.1 Rectangular geometry

The pressure gradient matrices of all scenarios were superimposed in a contour plot as shown in figure (Fig. 4a). A minimum of 3 sensors marked with dark dots are necessary to detect and distinguish between all the 15 RT scenarios. Sensor 2 and 3 are symmetric; they are located exactly at the centre of the part length, 2-3 cm from the RT edges. Sensor 1 is located at the top of the left edge because the pressure gradient at this location is very high; it is due to the fact that many RT scenarios are proposed with an RT scenario that starts near the inlet given that it is the most critical scenario, the scenarios with the race-tracking starting near the outlet are less risky. Unfortunately, the location of sensor 1 will limit the number of scenarios detected by this sensor as the race-tracking could happen at each of the edges; for that reason, sensor 1 will be shifted to middle of the left edge, this shift will not affect the pressure order of magnitude because it will also be located in a high gradient zone (yellow) which is not that different from the red one. Hence, the best sensor locations are shown in figure (Fig. 4b).

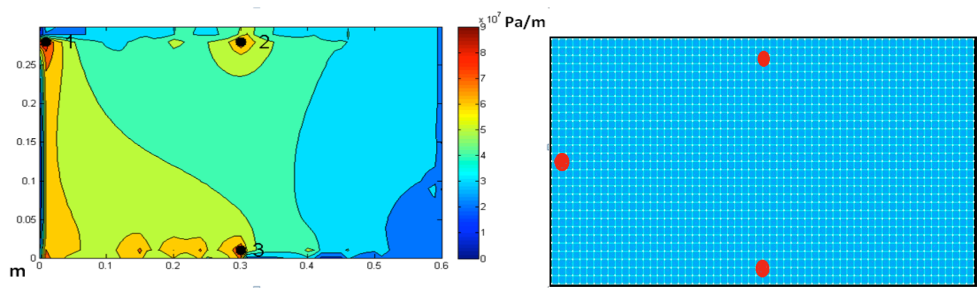

Figure 4. a Pressure gradient maps **4.b** Sensor locations

Sensor locations were validated by observing the evolution of pressure at those locations. It was found that that sensors can distinguish between the 15 scenarios, resin arrival time to each sensor is an additional parameter to distinguish between the scenarios.

Sensor location testing

Sensor locations were tested with new scenarios which were not among the database used to select the locations. This step is necessary to evaluate if these sensor locations will also recognize race-tracking under other conditions. The evaluation was carried out for the following cases:

- New race tracking locations,
- Anisotropic permeability,
- Different aspect ratio of the rectangular geometry and
- Curved edges.

For all the tested scenarios, it was found that sensor locations are robust wherever the RT location, and that they are independent of the preform permeability anisotropy or the edges shape [4].

5.1.2 L shape geometry

This geometry was chosen because it is a combination of two rectangles and it contains additional geometrical features. Following the same methodology of the rectangular geometry, the L-shape is injected with a constant flow rate point injection and vented from one node, and the fabric has an isotropic permeability K equals to 10^{-11} m^2. The simulation was conducted for 15 different race-tracking scenarios, the scenarios were selected to be as representative as possible to cover most of the potential and diversified RT scenarios, for a variety of RT lengths and/or locations.

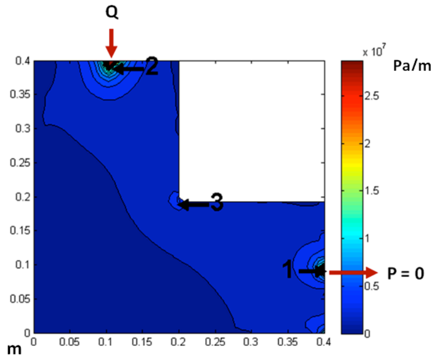

Figure 5: Superimposed pressure gradients map for the 15 scenarios for an L-shaped mold and sensor locations: 1,2 and 3. Dark blue is low pressure gradient value

The sensors were located according to the highest gradients zones as shown by in Fig.5: one sensor at the inlet, one sensor at the L-shape corner, one sensor close to the vent. The results show a clear agreement with the previous rectangular shape. The riskiest RT scenarios are the ones occurring around the corner; which is an important zone because the pressure measurement there will be a contribution from two crucial RT edges.

5.2. Sensor location for more complex geometries

In order to generalize the rule, next, we introduce the more complex geometries shown in Fig. 6. For simple cases (i.e. the rectangular and the L shape geometries), sensor locations are derived from pressure gradient calculations, while for complex ones sensors are placed from the rules inferred from the simpler geometries.

5.2.1 Cross shape

The cross shape was proposed because it can be viewed as a combination of both the rectangular and the L shapes, and it can be folded into a box shape into three dimensions. Sensor number and locations were determined following the rule: 1 sensor at the inlet, 1 sensor per corner and 1 sensor per race-tracking edge, then, 5 simulations were run for different RT scenarios and the sensor locations were validated. The cross shape can be viewed as a rectangle plus two squares on the top and the bottom of the rectangle. Hence, the results suggest 3 pressure sensors for the rectangular geometry and 1 sensor per additional geometrical feature.

5.2.2 Double cross shape

The double cross geometry is also a combination between rectangles and L-shapes with additional complexities. An extension of the geometry is introduced to validate the defined rules so far. According to the previous rules; one sensor should be placed at the inlet, one pressure sensor per RT edge, from the L-shape rules; one pressure sensor should be placed at each corner. Following these guidelines, sensor locations are chosen. The pressure evolution at the specified sensor locations is recorded for 5 different RT scenarios and the possibility of sensor redundancy is studied, then sensors are reduced from 14 to 7 due to the similar trend of some curves.

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5.2.3 Geometry with ribs

The 3D part is a rectangular plate with two stiffening panels, to which the guidelines created from all the previous sections are applied. The fabric has an isotropic permeability, resin is injected with a constant flow rate from the upper edge and vented with line vent. Under this injection and vent strategy along with the part shape; there are two remaining potential RT outer edges, the left, and right ones. Sensors are located as follows: 3 sensors for the rectangular bottom plate (1 for the inlet and 1 per RT edge), and one sensor for each additional geometrical feature (stiffening panels). A total of 5 sensors are located to detect all the potential RT scenarios. Five scenarios were run to validate the selection and it was concluded that the number of sensors was sufficient to detect possible RT scenarios.

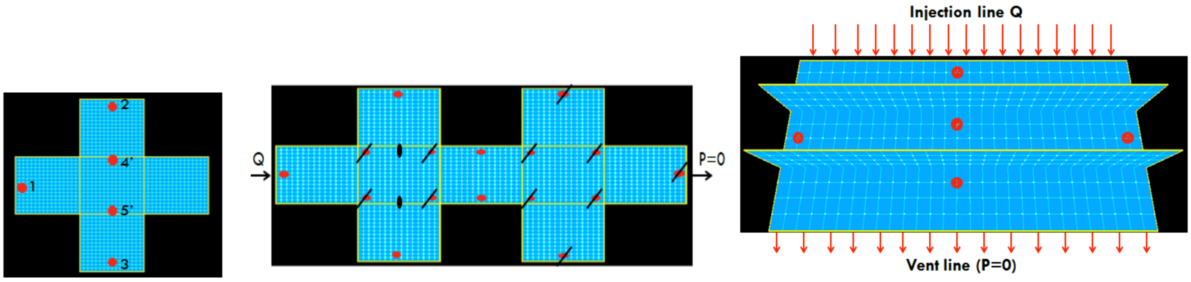

Figure 6: a. Cross geometry **b.** Double cross **c.** 3D geometry

5.3. Guidelines for sensor location

Based on the cases investigated, the guidelines for the pressure sensors to detect RT in any compound or complicated geometry are as follows:

- One sensor should be placed at the inlet.
- One sensor for each potential race-tracking edge.
- Three sensors per rectangle and 1 sensor for each additional geometrical domain.
- All the sensors should be placed inside the 50% of the domain along the flow direction from the injection gate.

We conclude that sensor locations do not only depend on the race-tracking zone, length and strength, but also on the part geometry along with the injection/vent strategy because they are the determining factors in identifying the potential race-tracking edges.

6. Conclusions

This work presented a new, simple, robust and a cost effective methodology for RT detection. The optimum number and location of sensors was found to be dependent on the RT zones, length and strength which is reflected by the superimposed pressure gradients maps. Manufacturing engineers could place pressure sensors following the methodology/guidelines according to the mold geometry, then depending on the injection gate/vent locations. Identifying the flow pattern can support the flow action and control methodologies to correct flow patterns during the injection processes. This methodology will no doubt reduce the time and cost of the development phase, by assisting the manufacturing engineers in choosing the best injection and vent strategies and anticipating the riskiest RT scenarios, it can be considered as a pre-engineering phase for all the RTM parts manufacturing.

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