Composites: Part A 78 (2015) 223–233

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

A methodology to reduce variability during vacuum infusion with optimized design of distribution media

Hatice S. Sas, Pavel Šimáček *, Suresh G. Advani

Department of Mechanical Engineering and Center for Composite Materials, University of Delaware, DE 19716, United States

ARTICLE INFO

Article history:
Received 19 March 2015
Received in revised form 2 July 2015
Accepted 10 August 2015
Available online 22 August 2015

Keywords:
E. Resin flow
C. Numerical analysis
C. Computational modeling
E. Resin transfer molding (RTM)

ABSTRACT

Seemann Composites Resin Infusion Molding Process (SCRIMP) is a widely used version of Vacuum Assisted Resin Transfer Molding (VARTM) in which a highly permeable layer (distribution media) is placed on top of the dry preform to distribute the resin with very low flow resistance to reduce the filling and hence the manufacturing time. The flow patterns during filling may vary from part to part due to the variability associated with the material, part geometry, and layup of the assembly, which may result in race-tracking channels. The process is considered as reliable and robust only if the resin completely saturates the preform despite changing filling patterns caused by flow disturbances.

The resin flow pattern can be manipulated with a tailored distribution media layout as it does impact the flow patterns significantly. The continuous distribution media layout over the entire part surface works well for very simple geometries with no to little potential for race-tracking along the edges. In this study we address complex cases, which require placement of an insert within the assembly, which will introduce race-tracking along its edges, and hence uniform placement of distribution media over the entire top surface will fail to yield a void free part. We introduce a methodology using a predictive tool to design an optimal shape of distribution media, which accounts for the flow variability introduced due to race-tracking along the edges of the inserts. This iterative approach quickly converges to provide the placement of distribution media on selective areas of the preform surface that ensures complete filling of the preform despite the variability. This approach has been validated with an experimental example and will help mitigate risk involved in manufacturing complex composites components with Liquid Molding.

1. Introduction

The term Liquid Composite Molding (LCM) is used for closed mold processes in which a dry fibrous preform is placed in the mold cavity and the mold is closed [1]. Then, a liquid resin is impregnated through the preform to fill the empty spaces between the fibers in the mold cavity. Resin Transfer Molding (RTM) is one of the most commonly used process in which the resin is impregnated within the empty pores of the preform in a two-sided closed mold. The Vacuum Assisted Resin Transfer Molding (VARTM) is the other commonly used LCM process because of its ability to manufacture large scale, low cost composites. In VARTM, the preform is placed on a one-sided tooling surface and the other side is sealed with a vacuum bag. Vacuum is applied at the vent line to remove the air from the mold cavity, which induces fiber compaction under atmospheric pressure and draws resin into the mold cavity through the injection line. After resin arrives at the vent, the injection is discontinued but the vacuum is maintained until the resin cures allowing one to de-mold the final composite part [2]. To speed up the process, a highly permeable material called as the distribution media (DM) is placed in between the top layer of the fabric and the vacuum bag in the process SCRIMP. The use of DM decreases the fill time because the resin first flows through the DM layer and then impregnates through the thickness direction [3,4]. Thus, SCRIMP eliminates the disadvantage of long fill times for VARTM. However, SCRIMP might lead to formation of voids (especially at the leading edge of the flow front) and for complex geometries and parts containing impermeable inserts [5].

To ensure successful impregnation of the resin to cover all the empty spaces within the dry preform and manufacture composite parts without macro-scale voids (dry spots), process models and simulations have been developed to predict the process parameters (inlet/vent locations) [6–8]. These process models are based on resin flow through porous media governed by Darcy's Law [9,10] which relates the pressure gradient to average resin velocity within the preform

* Corresponding author.

http://dx.doi.org/10.1016/j.compositesa.2015.08.011
1359-835X/

$$\bar{u} = -\frac{K}{\mu} \cdot \nabla P \quad (1)$$

where $\bar{u}$ u is the volume averaged velocity, K is the permeability tensor that describes the fiber preform resistance to the flow of impregnating resin in various directions, μ is the viscosity and ∇P is the pressure gradient experienced by the resin. The permeability of the preform can be numerically predicted, or experimentally measured.

A variety of effects can cause random local variations in fibrous preform porosity or architecture. However this will not change the filling pattern very dramatically [11]. On the other hand, flow disturbances introduced due to race-tracking as a result of open channels created between the mold and preform edges or along sharp bends in reinforcement or between preform and inserts in the mold can change the filling pattern significantly. This potentially could allow the resin to reach the vent line before impregnating the entire preform which will result in a large macro-void (dry spot) within the part resulting in the part being scraped or reworked [12–17]. In RTM, since the mold is a two-sided closed cavity resin racing along the mold edges is more common than VARTM in which one-sided mold is sealed with vacuum bag. In VARTM, race-tracking will be more prominent along the boundaries of the inserts in the mold or around sharp bends. The process design should be able to address the possible effect of the flow disturbances because of race-tracking to manufacture composite structures without macro-scale voids (dry spots). One could manage the flow disturbances because of the race-tracking by placing flow runner channels in strategic locations intentionally [18]. Other approach is to introduce active control algorithms with sensors in the mold that can correct for the flow once race-tracking is detected to ensure successful filling of the preform [20–23]. Also, studies have been performed to identify the disturbance locations and develop scenario-based solutions [24–27] using active and passive flow control. However, actively controlled scenario based solutions require expensive tooling, placement of robust sensors at the strategic locations and complicated hardware for flow control that is integrated with the injection equipment. Also these tools can be readily implemented with RTM as one can direct the resin flow by introducing more injection gates and locally changing the pressure field. This is more difficult to implement in VARTM [28,29]. Hsiao et al. proposed use of distribution media, which is more appropriate for VARTM processing, as a flow control tool and the race-tracking possibility is handled by placing flow channels [19]. This study also proposes a passive control approach by designing a DM layout for that particular case. The tailored distribution media for the part geometry should ensure successful filling despite the presence of race-tracking that might change from one injection to the next for manufacturing the same part. At the same time, it must guarantee acceptable infusion time in all feasible cases. This is presented in this work.

2. Methodology and implementation

First, given the part geometry along with insert locations, one must identify all possible race-tracking locations within the part and create possible scenarios, which take into account all possible permutations of race-tracking that may occur during the impregnation process. To determine a single optimal layout of DM for all these possible scenarios, a discrete optimization method is adopted. Discrete definition is generated by dividing the surface of the preform (where one places the DM) into a finite number of regions. Optimal solution finds the regions where one should place the DM such that for all scenarios the resin will arrive at the vent last after having impregnated the entire preform. Mathematically, this is done by prescribing the cost function that will minimize the region with no resin in the mold. Evaluation of the cost function is performed with an existing numerical simulation called Liquid Injection Molding Simulation (LIMS) [30] which simulates the flow in any complex geometry in Liquid Molding. LIMS output provides the empty region after each fill based on the inputs of preform and DM permeability, race-tracking strengths along the edges and predefined inlet and vent locations. Race-tracking strength, which is defined as the ratio of the permeability of the race-tracking channel to the permeability of the preform in the channel direction, is modeled by generating one-dimensional mesh using LIMS which interfaces with the part geometry mesh. Thus, the permeability of the one-dimensional mesh elements representing the race-tracking channels are set to the value of race-tracking strength multiplied by permeability of the preform along the race-tracking channel direction.

2.1. Tree search algorithms

Gradient descent method is a first-order algorithm to find a local minimum of a function. The method starts with an initial guess of the solution and the gradient of the function at that point is evaluated. The solution is stepped in the negative direction of the gradient and the process is repeated until the algorithm converges to a zero gradient. This method works for the objective functions for which the gradient can be evaluated. If the variables used in the objective function are only a finite or discrete set of values, discrete optimization should be applied. The discrete optimization problem can be defined as a set, S of finite possibilities that satisfies the objective function. The objective function of that provides local minimum, x_{opt} for all elements of the set S,

$$f(x_{opt}) \leqslant f(x) \text{ for all } x \in S \quad (2)$$

Discrete optimization can be used for different problems such as such as VLSI layouts, robot motion planning, test pattern generation, and facility location [31].

The search of the optimal solution with discrete optimization consists of computationally expensive problems. As Koft [32] states there are two parameters that indicates the complexity of the searches: the branching factor of the problem space and the depth of solution of the problem. The branching factor represents the number of the new states that are generated and analyzed at each depth. The depth of the search is the distance between the initial state and goal state. There are two basic tree search algorithms; breadth-first search (BFS) and depth-first search (DFS). In Fig. 1a, a sample tree layout is given and there are two goal nodes satisfying the objective function, H and T which are the two local minimum satisfying the user defined tolerance. BFS expands all the states one step away from the initial state until a goal state is reached and converges to node H, before node T (Fig. 1b). DFS explores a path all the way to a leaf before backtracking and exploring another path. Therefore, only path of nodes from the initial node to the current node must be stored in order to execute the algorithm. DFS will find the node T, before the node H (Fig. 1c) [33].

As the BFS converges, the solution at the minimum depth is found (Fig. 1b). When a DFS succeeds, the solution may not be at the minimum depth (Fig. 1c). For a large tree, BFS may have large memory requirements because BFS stores all possible nodes at each depth. Thus, BFS convergences may take long time to reach the solution, goal node [33]. For the solution for DM layout design the minimum depth is not a concern but the memory is. So, DFS is adopted by generating regions on the preform which represents the finite solution set and the cost function is the unfilled area. Different race-tracking scenarios yield different unfilled regions and our goal is a DM layout design that results in a successful filling without voids for all possible race-tracking scenarios. Thus, the