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A new computational tool for liquid composite moulding process design based on configuration spaces

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ABSTRACT

This paper aims to define a new configuration space, called flow pattern configuration spaces (FPCS), as a new computational tool for LCM process design. The most relevant aspect when using these spaces is the definition of a new coordinate system which relates the process parameters to the flow, instead of to the traditional Cartesian coordinate system. These spaces are commonly used in mobile robots which use wheeled turning radius, path length, velocity, etc. as parameters, enabling a better understanding of the process and inherently reducing the computational costs in decision tasks. The proposed configuration space defines a mould mesh discretization using an alternative coordinate system based on two variables. One of these coordinates is based on the radial flow behaviour. Hence, the angle defined between an interest point, such as the nozzle injection or the vacuum vent, and the location of the evaluated point is selected as a fixed parameter of the FPCS. This liberates the other parameter so that it can be selected depending on the application of the FPCS.

The first FPCS proposed in this paper is based on the node to node distance criterion, which has been extensively used in the literature. The resulting space is called flow pattern distance space (FPDS). The second space is based on the node filling time. Then, through Finite Element simulation, the normalized filling time is used as a criterion for the FPCS development. The resulting space is called flow pattern time space (FPTS). When we apply the normalized unidirectional flow model equations to different filling techniques, constant flow rate or pressure, the flow in the FPTS has the same behaviour as in the unidirectional case. Both spaces reduce the dimensionality of the problem to 2D or 1D allowing a simpler set out of the LCM optimization and control of problems. The concept of configuration spaces is a powerful tool to solve complex problems for LCM processes in a simple manner. To the authors' knowledge, this is the first time that this concept has been applied to LCM processes. Some examples of applications are presented at the end of this paper.

1. Introduction

Liquid composite moulding processes (LCM) include different techniques which can be divided in two main groups: techniques that need positive injection pressure like resin transfer moulding (RTM), Fig. 1 (left), and techniques that require negative injection pressure such as VARI (vacuum assisted resin infusion), VARTM (vacuum assisted resin transfer moulding) and SCRIMP (Seemann composite resin infusion moulding process), Fig. 1 (right). This second group is commonly known as resin infusion processes (RI), and consists in dragging the resin into the mould. It also determines the adequate filling strategy as well as the optimal location and shape of the resin gate inlets and vents. In RTM, vents and gates are points located in the mould whereas in RI processes the vent, gate or both can be either points, lines or in many cases be in the contour of the mould. For instance, in VARI, the vent is frequently located in the mould contour and the gate inlet in the inner part of the mould whilst in VARTM they are located the opposite way.

The LCM processes, which need positive injection pressure, entail a correct clamping of the mould and the use of rigid tooling. This fact makes the suitability of the creation of large composite parts nearly impossible as it is not a cost-effective solution. The techniques which need negative injection pressure do not require this correct clamping. This allows the top half of the mould to be made of a flexible material, making therefore possible the production of large composite parts such as the construction of a boat hull or an airplane fuselage.

The correct clamping of RTM processes limits the possibilities of the vent and gate location. This is due to the necessity to drill holes in the upper rigid part of the mould, reason why in RTM processes, vents and gates are usually points. In resin infusion processes, the top half of the mould is made of a plastic bag. For this reason, it is

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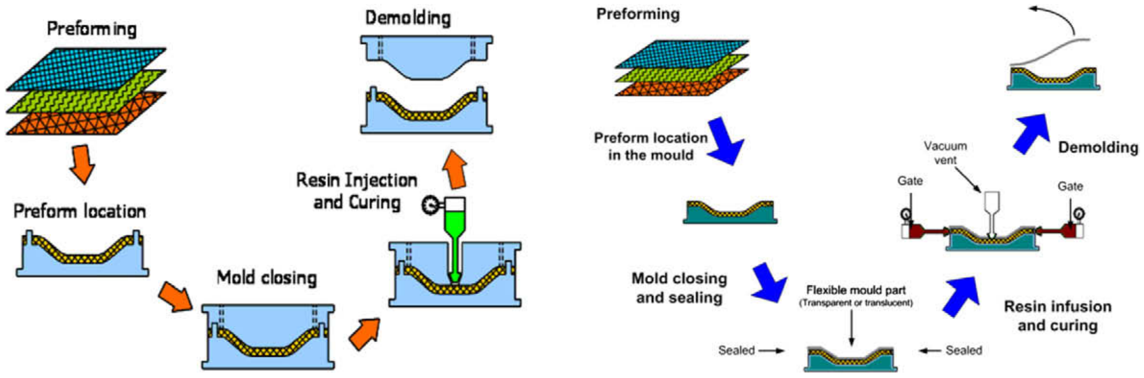

Fig. 1. LCM processes: RTM (left) and resin infusion (right).

easy to introduce vents and gates, which are not points, like pipes and runners.

In LCM processes, the resin impregnation of the fiber is modeled using the flow through the porous media theory applying Darcy's law. The Analytical treatment of the flowing evolution is difficult except for a few simple geometries. Therefore, numerical methodologies for flow simulation were developed in past decades for RTM, and have extended to other processes more recently. The most common form of flow numerical simulation is the use of a discretization approach with Finite Elements. The use of Darcy's law requires information about the characteristics of the material. A major aspect to model is the preform permeability that characterizes the resistance offered by the porous medium to the fluid flow. Therefore, it is essential to characterize the material involved to obtain an accurate description and design of the process. Moreover, the LCM processes that work with injection pressure are very difficult to design for both their optimization and the design of a filling strategy since it is not intuitive and may vary due to manufacturing conditions. Hence, it is necessary to use real-time control systems for the on-line correction of process deviations.

2. Revision of process optimization and control methods based on gate location

The success of the filling and curing stages in liquid composite moulding (LCM) depends on many variables such as the location of the gates and vents, temperature distribution, flow rate, and injection pressure. Traditionally, the selection of gate and vent locations in mould design has been based on experience and trial and error. In the literature, there are numerous research studies whose main objective was to design RTM processes [1–6]. However, to the authors' knowledge, only one study has been found on resin infusion processes [7]. In general, the proposed optimization algorithms are based on FEM simulation coupled with genetic algorithms. A genetic algorithm, in general, is more likely to locate the nearest global optimum, especially in problems with multiple variables and large search spaces. However, the calculation time of 600 generations with a population size of 30 on a 448 element model took over 75 h. In [1] it was proposed an optimization algorithm coupling flow simulation and genetic algorithms. In that case, only 1% of simulations were necessary for the possible permutations of gates and vents. These models were limited to 2D shapes and the calculation of complex parts was very complicated. The researchers concluded that the excessive calculation time was due to flow simulation. In [2,6] fast alternatives for the flow simulation were proposed. In [2] an artificial intelligence, neuronal network, was trained to create a rapid RTM model. This simulation method coupled with a genetic algorithm is the optimization procedure for the gate/vent location. In [6] a genetic algorithm was also used to optimize the inlet and outlet. However, they replaced the flow simulation for the "mesh distance based approach". This model is fast and can accommodate any complex shape for 2.5D moulds. This work explained that not only flow simulation can be inefficient, but also genetic algorithms. If for example, one inlet was used on a model with 930 nodes, the genetic algorithm would require 1000 trials. For this reason, in [3] a branch and bound search is proposed to improve a genetic algorithm. With this improvement the magnitude of the calculation time is reduced from hours to minutes.

In [7] the most recent work, according to the authors' knowledge, is presented. This study tries to optimize the shape and location of the flow channel distribution in VI process. In this work, a "mesh distance based approach" together with a genetic algorithm was used to find the flow channel position. As the channel is not a point, the distance between each node and the pipe is the minimum distance. Although this work presents some interesting improvements, it also has important limitations. The first one is also the excessive calculation time. The optimal solution of a 2D rectangular mould with 1581 nodes was reached after 17 min on a 2.01 GHz PC. The second limitation is that this study considers the vents as points instead of vent pipes located in the mould contour. The vent channels are used in the contour mould since this allows a more homogeneous vacuum pressure distribution and as a consequence a thickness variation.

The objective functions of most optimization algorithms are based on LCM process parameters such as minimum filling time, dry spot prevention, homogenized curing, and determined flow front velocity. In [8,9] researchers developed numerical indicators called process performance index (PPI) to measure the objective functions and the correct filling stage qualitatively. In [8] an index based on the minimum filling time and a vent-oriented flow front was developed. At a given step, the distances from the nodes located in the resin flow front to the outlet were associated with the quality of the filling process. This PPI index was improved in [9] taking into account the differences in the incubation time values of all the nodes impregnated by the resin. This is not a generic index applicable to any LCM processes as it can only be used for 2D RTM moulds. This is due to the fact that it considers the vent as a point whilst in resin infusion processes the vent is in the mould perimeter. In addition, the Euclidean distance from the flow front nodes to the outlet can only be used in 2D moulds as it does not take into account the mould geometry, as shown in Fig. 2.

For real 2.5D geometries, there exist two possibilities to compute the distance, "*model distance*" and "*direct distance*", see Fig. 3.

The first possibility, "*model distance*", is used in LCM optimization algorithms [6,7], and is known as "*mesh distance based approach*". The accumulated distance on the discretization mesh