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Citation: *AIP Conf. Proc.* **907**, 902 (2007); doi: 10.1063/1.2729628

View online: <http://dx.doi.org/10.1063/1.2729628>

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Application of Artificial Vision in flow redirection during filling of Liquid Composite Molding processes

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Abstract. The control techniques applied in Liquid Composite Molding processes have been extensively worked out by many different research groups abroad. In this work, the original use of artificial vision technology in order to redirect the flow path during mold filling appears as a major objective of online control strategy. In this study, a process performance index developed in a previous work [1] is used to define the mold gate opening sequence. The Vacuum Assisted Resin Transfer Molding (VARTM) and Vacuum Assisted Resin Infusion (VARI) have been selected as the main processes of study. The expert system will make use of numerical simulation in order to obtain a previous physical understanding of the flow behaviour in different manufacturing conditions. Some examples of the installation are presented and discussed.

Keywords: Liquid Composite Moulding, VARTM, Numerical Simulation, Artificial Vision, Control.

PACS: 61.41.+e, 61.20.Ja

INTRODUCTION

This investigation aims to develop a methodology to assist in the design of flexible moulds for infusion processes such as VARI (“Vacuum Assisted Resin Infusion”) or SCRIMP (“Seeman Composite Resin Infusion Manufacturing Process”) that are now widely used by industry for the low cost manufacturing of large composite parts. In these processes, the fibrous reinforcement is set in a base mould, covered by a plastic film and sealed, then vacuum is drawn in the cavity and resin is infused in the part at atmospheric pressure. This investigation has two main objectives: (1) simulate and optimize infusion moulds; (2) control the manufacturing process. The natural

CP907, 10th ESAFORM Conference on Material Forming, edited by E. Cueto and F. Chinesta
© 2007 American Institute of Physics 978-0-7354-0414-4/07/\$23.00

extension and complement of process simulation and optimization is process control. With the current state-of-the-art technology, it remains difficult and requires much time to characterize precisely a thickness-varying permeability everywhere in a flexible mould. This prevents an accurate simulation of resin infusion. For these reasons, it is imperious, in parallel to the work carried out in the first objective, to set up a joint investigation on process control. This one is focused on the use of artificial vision and intelligence to monitor and control mould filling.

The process is cyclic and begins with the infusion of the resin into the mold and ends when the resin completes the chemical reaction of curing and the part. Due to the low pressure involved and the relatively large size of the components, the filling time can range from less than a minute to one hour or more for exceptionally large components. As we shall see in this work, a long time can sometimes be useful to control the resin front advancement.

In other Liquid Composite Molding processes the simplest injection systems only permit the injection of resin under the most basic conditions: constant pressure or constant resin flow rate. On the other hand, there are injection systems provided with PLCs that allow the filling stage to be programmed and to modify the filling conditions "in situ". These enable resin inlet and air outlet points to be programmed to open or close, pressure or resin flow rate to be modified at all injection points, resin/catalyst ratio to be modified during filling, etc. It is even possible to monitor the location of the resin flow-front by means of pressure sensors or fluid presence sensors, which allows defining a filling sequence. In this work a CCD artificial vision camera is used to track the flow front shape during filling and only the vacuum gates can be located in different positions depending on the flow front advancement.

To define the optimum gate opening sequence offline, it is necessary to use the numerical simulations models, based on a discretization by FEM of Darcy's equation. It yields proper results for the simulation of LCM processes [1].

USE OF ARTIFICIAL VISION IN FLOW FRONT TRACKING

The success of filling in liquid composite molding (LCM) depends mainly in proper locations of gates and vents. Traditionally the selection of gate and vent locations in mold design is based on experience and trial and error attempts. Recent research studies have been conducted to reduce cycle time by using computer simulation and optimization. Zhang, et al, employed in [2] a process performance index based on gate-distance of the resin located on the flow front at different time steps. A good process should have short filling time and a vent-oriented flow with a desired resin flow pattern, see Figure 1. At a given time step, the distances from the nodes located on the resin flow front to the outlet are associated with the quality of the filling process. The standard deviation of those distances is used to evaluate the shape of the flow front (the smaller the better).

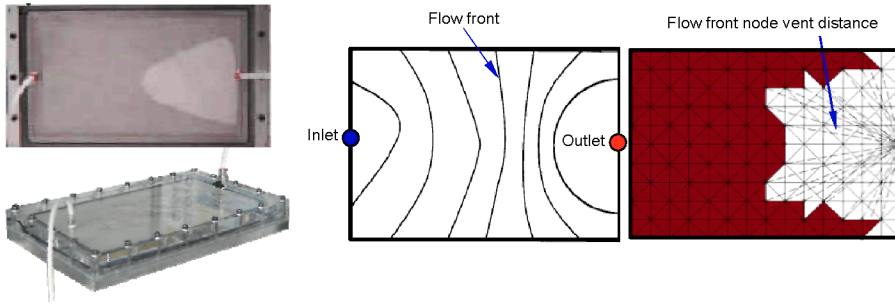


FIGURE 1. Mold (left), Flow front shape and distances between flow front nodes and vent (right).

In the last decades, artificial vision is used for industrial applications such as quality control inspection. This device also can be used as a sensor in control systems. For our particular application of VARTM and Infusion processes, camera vision has main relevance because the pixels can be directly associated with simulation meshes. The camera sensor (CCD) has a rectangular form. The pixels are uniformly distributed in the CCD. In this sense, an amount of pixels must be associated with each mesh. It permits to calculate the percentage at which the mesh is filled. This concept permits to guarantee the correspondence between both processes, see Figure 2.

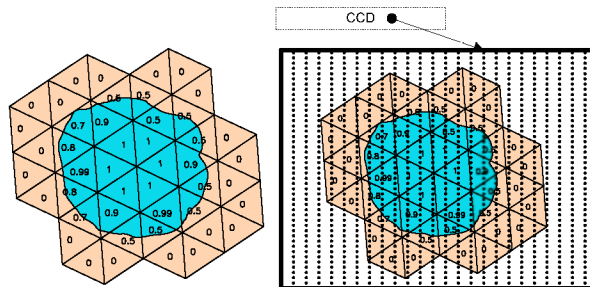


FIGURE 2. Control Volume fixed mesh used in numerical simulation to track the flow front advance during filling (left) and associated pixels of the CCD camera device (right)

Although it can be used to validate the simulation results, our main objective is to use this correspondence to flow front redirection to the proper vent during filling. Camera vision is allocated in a certain distance that permits to see the entire mold. The position of the camera depends on the optical parameters. In particular, the focal distance determines the position of the camera. The selection of this parameter depends on constructive limitations. The loop control system used in this application is depicted in Figure 3.

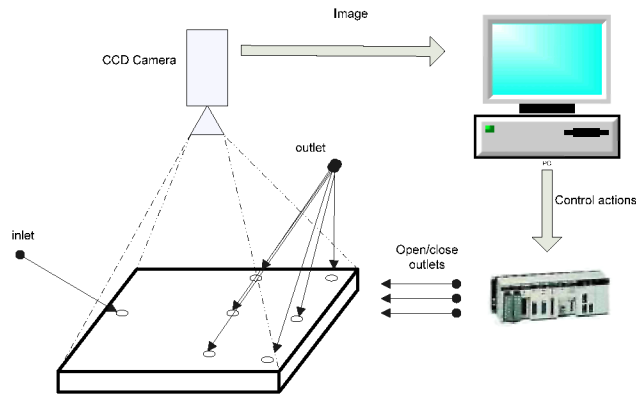


FIGURE 3. Used Mold and loop control system

The image is processed in a PC. Flow front is detected and the performance index is calculated for each candidate vacuum outlet. The outlet with lowest index value is selected as an ideal outlet. The control actions are executed in the PLC closing and opening the corresponding vacuum gates. This application has then two main steps:

Step 1.- when the application is started, a rectangle containing the region of interest must be selected. In this region, is automatically searched the mold limits, vacuum outlets and the resin inlet gate. It permits to work in an image avoiding unnecessary translations.



FIGURE 4. Selection of region of interest (left) and detection of gate inlet and vacuum outlets

Step 2.- When step 1 is completed, the fiber perform must be allocated in the mold and the application is ready to be executed. When it occurs, the application detects the resin flow front during filling and calculates the index for each candidate vacuum (see Figure 5).

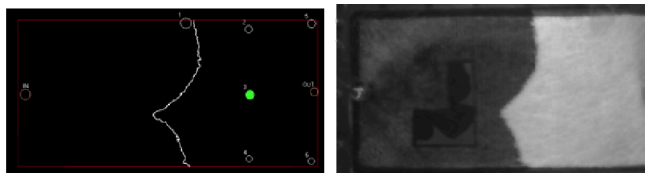


FIGURE 5. Flow Front recognition and gate selection (left) and real filling (right)

VENT-GATE SELECTION BASED ON BEZIER CURVES

In order to reduce the redundant information of the flow front, an approximation of the flow front points is applied. In particular, the points are approximated to Bezier curves. This curve, originally developed by Pierre Bezier in the 1970's, is the most common form to represent planar curves for CAD/CAM applications. It has the formulation:

$$P_B(u) = \sum_{k=0}^N C_k \cdot \frac{N!}{k!(N-k)!} \cdot u^k \cdot (1-u)^{N-k} \quad (1)$$

where

- C_k Bezier control points.
- u Intrinsic parameter. $[0...1]$.
- N Order of the Bezier equation.
- $P_B(u)$ Points of the Bezier curve

In order to approximate the flow front to bezier curve, it is necessary to normalize the distance between the points of the flow front in the range of the intrinsic parameter $[0...1]$, that is

$$u_k = \frac{n_{k-1} \cdot \sum_{i_k=1}^{n_k=k} \sqrt{(x_{i_{k+1}} - x_{i_k})^2 + (y_{i_{k+1}} - y_{i_k})^2}}{\sum_{i_k=1}^{n_k=n_k} \sqrt{(x_{i_{k+1}} - x_{i_k})^2 + (y_{i_{k+1}} - y_{i_k})^2}} \quad (2)$$

With this, it is possible to obtain one linear equation for each point of the flow front,

$$P_f(u_k) = C_0 \cdot B_0(u_k) + C_1 \cdot B_1(u_k) + \dots + C_N \cdot B_N(u_k) \quad (3)$$

Where P_f are the points of the flow front and $B_k(u_k)$ is the k th Bernstein basis function, which is:

$$B_k(u_k) = \frac{N!}{k!(N-k)!} \cdot u_k^k \cdot (1-u_k)^{N-k} \quad (4)$$

The resulting linear equations can be expressed in the matrix form as:

$$\begin{bmatrix} P_f(u_1) \\ \vdots \\ P_f(u_{n_k}) \end{bmatrix} = \begin{bmatrix} B_0(u_1) & \dots & B_N(u_1) \\ \vdots & \ddots & \vdots \\ B_0(u_{n_k}) & \dots & B_N(u_{n_k}) \end{bmatrix} \cdot \begin{bmatrix} C_0 \\ \vdots \\ C_N \end{bmatrix} \quad (5)$$

$\mathbf{P} = \mathbf{B} \cdot \mathbf{C}$

Least squares methods can be used in order to compute the Bezier control points,

$$\hat{\mathbf{C}} = (\mathbf{B}^T \cdot \mathbf{B})^{-1} \cdot \mathbf{B}^T \cdot \mathbf{P} \quad (6)$$

The error committed in the approximation can be calculated as:

$$\sigma^2 = \frac{1}{n_k} \cdot \left[\sum_{k=1}^{n_k} \left(P(u_k) - \sum_{k=0}^N B_k(u_k) \cdot C_k \right)^2 \right] \quad (7)$$

With this simply methodology, the points of the flow front are dramatically reduced. In order to obtain the minimum control points, it is necessary to indicate the tolerable error in the approximation. The order is increased since the error is less than tolerable error. Figure 6 shows some approximations with different flow fronts.

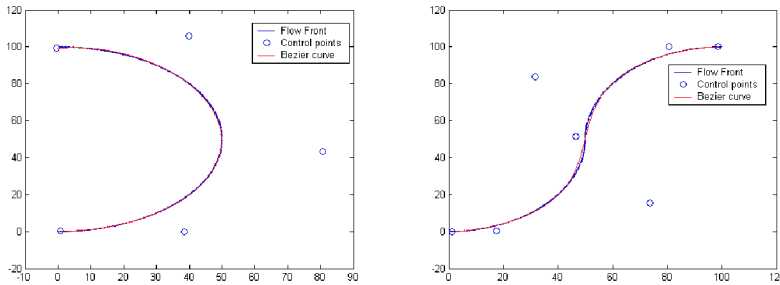


FIGURE 6. Flow front approximations with Bezier curves

The use of this approximation technique has two main advantages:

1. Eliminates the unnecessary oscillations of the flow front.
- 2.-The order of the Bezier curve determines the complexity of the flow front.

The resulting order of the Bezier curve determines minimum representative number of points that are necessary to take into account in the index. For this reason, the resulting Bezier curve is resampled. The intrinsic parameter is selected to $u_k = 1/N$. With these points, the control index is calculated for each outlet. The minimum index determines the optimal outlet for each time instant. Obviously, the outlets allocated in a filled zone are no longer candidates to be the appropriate vacuum gate and the flow front is optimally redirected.

ACKNOWLEDGMENTS

This research work is supported by Generalitat Valenciana, Project GVA05/209 and by the project PRUCHB06/24 of the University CEU Cardenal Herrera.

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