EFFECT OF SURFACE COATING ON THE CHARACTERIZATION OF THE PROCESS DYNAMICAL BEHAVIOUR DURING MOLD FILLING IN LIQUID RESIN INFUSION

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ABSTRACT

The material characterization and measurement of fibre preform permeability and resin cure kinetics is one of the main issues in liquid composite processing since it plays a key role in process design and control. It allows predicting the flow behaviour in porous media with numerical simulation. The appropriate material modelling is a critical input parameter needed by simulation. In spite of using accurate computer simulations, the modelling and characterization of the materials is usually a tedious and extensively work in industry. The appropriate computational resolution of the flow kinematics during filling allows one to relate the local material properties such textile permeability and resin viscosity with the flow motion under dynamic behaviour.

In this work, a mixed numerical/experimental technique based on artificial vision is used for estimating the induced effect of the surface coating curing in the laminate impregnation and the flow front advance during filling under controlled conditions. The procedure computes local material parameters and is proposed based on the aim of matching the empirical data with the simulation. For that purpose, the method iterates the value of the material parameters in the simulation until it matches the evolution of the experimentally measured flow front.

That approach can be used to obtain an analytical demonstration of the correct convergence of the method in 1D. Finally, different tests with empirical and simulated data have been shown. These tests show the ability of the algorithm to detect different surface coatings.

1 INTRODUCTION

Resin Infusion (RI) process is frequently used for large composite parts production. This method uses vacuum pressure to shape a transparent plastic bag as a counter mold. Once a complete vacuum is achieved, the resin is sucked into a dry preform textile laminate via placed tubing. This process is increasingly used in most transport applications, and aeolian energy systems where low weight and high mechanical performance materials are demanded. Resin infusion process can be operated in low cost open molds with vacuum bags due to its low-pressure conditions. Moreover, in many applications like wind turbine blade manufacturing the in-mould coating plays a key role in the product performance. It is often required an optimum interphase adhesion and surface finish for mechanical performance or durability reasons [1][2]. Since the coating is usually painted or sprayed onto the mould tool before the dry preform is laminated, it is also necessary to address measurement of part quality in terms of different reasons such are: completed filling, proper resin impregnation, and also, interphase coat-laminate mechanical characterization [3][4]. In this work, distinctive testing are shown in order to assess the macroscopic flow behavior of the resin laminates and its relation with the coating and the manufacturing conditions.

Measurement and characterization of material properties such as the fibre preform permeability is one of the main issues in composites process, since it plays a key role in process design and control. In fact, simulation is a valuable tool that allows guaranteeing a suitable design and the success of the process, and the permeability is one critical input parameter needed by simulation. That is the reason why in industry, it is needed that the simulation and the reality are as close as possible, and so, the permeability estimation must be as precise as possible. However, in practice, permeability measurement is not a trivial task. In the literature of fibrous media permeability [9][10][11][12][13], large variations in permeability values have been reported even in well-controlled 1D or 2D flow experiments. It is found that the permeability can vary largely from case to case because of variations in preform microstructures and handling conditions, both of which may come from non-uniform raw material quality, improper preform preparation/loading, and mold assembling. Moreover, the variation of the permeability can be caused not only in different process with similar conditions, but also in the same process. That means, the permeability may not be constant in every place of the preform.

In [5] a promising technique to measure permeability is proposed, called the inverse method. This is based on mixed numerical/ experimental technique (MNET), with the aim of matching the empirical data with the simulation. For that propose, the method iterates the value of permeability in the simulation until it matches the evolution of the experimentally measured flow front.

On the other hand, in our previous works [6][7][8] the Artificial Vision (AV) has been used as a tool to monitor LCM process, since by means a digital camera it is possible to define the pixels as nodes and associate them as Finite Elements. This fact allows one using all the FE tools with the mesh defined by the camera. With this, mixed numerical/experimental technique (MNET) is proposed to the computation of the discretized space observed by the camera as FE domain using a fixed mesh [16]. With the camera, it is possible to measure the arrival time at which the flow achieves each node. Moreover, it is possible to measure the updating of the volume fraction of each element and also the flow front velocity by means of a Level Set numerical technique based on a geometrical distance approach. It permits to calculate the velocity field during filling. The pressure of each node cannot be measured but can be computed, given our possibilities to develop our MNET. As the measurements are “directly” the expected results of the simulation the proposed method is called “direct method”.

In this work, the method is used with the objective of exploring the induced effect of the surface coating curing in the laminate impregnation and hence in the flow front advance during filling. The tests are conducted with the same computational method as in [16] but with different coating curing degree instead of textile permeability variations.

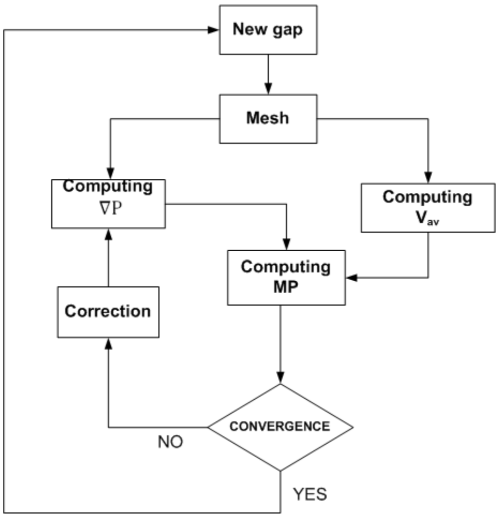

Figure 1. Schematics of the used direct method.

2 A MIXED NUMERICAL/EXPERIMENTAL TECHNIQUE (MNET) BASED ON ARTIFICIAL VISION FOR THE DYNAMICAL BEHAVIOUR CARACTERIZATION DURING FILLING

As stated before, our MNET works as follows: for one hand, computed velocity by the camera and the pressure obtained by the FEM simulation is combined in the darcy′s law to obtain the material properties, see Figure 1.

2.1 FEM Numerical Velocity Computation

A previous work [14] shown how can be solved the numerical simulation of RTM mould filling. This method is used here in order to compute the pressure gradient in the fixed triangular mesh generated through the artificial vision discretization. Darcy's law can model the resin flow through a porous medium:

$$\vec{V} = -\frac{\underline{\underline{K}}}{\phi \cdot \mu} \nabla P \tag{1}$$

where $\vec{V}$ is the velocity vector, ϕ is the porosity, μ is the viscosity, P is the pressure and $\underline{\underline{K}}$ is a permeability tensor.

The fluid flow problem is defined in a volume Ω,

$$\Omega = \Omega_f(t) \cup \Omega_e(t) \tag{2}$$

where the fluid at time t occupies the volume $\Omega_f(t)$ and $\Omega_e(t)$ defines at that time the empty part of the mold. Assuming fluid incompressibility, the variational formulation related to the Darcy flow results

$$\int_{\Omega_f(t)} \left(\nabla p^* \cdot \frac{\underline{\underline{K}}}{\phi \cdot \mu} \nabla p \right) d\Omega = 0 \tag{3}$$

where p* denotes the usual weighting function.

The prescribed conditions to impose on the boundary of Ωf (t) are:

- The pressure gradient in the normal direction to the mold walls is zero.
- The pressure or the flow rate is specified at the injection nozzle.
- Zero pressure is applied on the flow front.

The flow kinematics can be computed by means of a conforming finite element Galerkin technique applied to the variational formulation extended to the whole domain Ω

The location of the fluid into the whole domain Ω is defined by the characteristic function I defined by

$$I(\underline{x},t) = \begin{cases} 1 & \underline{x} \in \Omega_f(t) \\ 0 & \underline{x} \notin \Omega_f(t) \end{cases} \tag{4}$$

The evolution of the volume fraction, I, is given by the general linear advection equation:

$$\frac{dI}{dt} = \frac{\partial I}{\partial t} + \underline{v} \cdot \nabla I = 0 \tag{5}$$

with I=1 on the inflow boundary.

So that, the resolution scheme is based in solving the three steps:

1. Obtain the pressure field using a finite elements discretization of the variational formulation given by equation (3) and imposing null pressure in the nodes contained by an empty element (i.e nodes 4, 5 and 6 in Figure 2).

2. Compute the pressure gradient and the velocity field from Darcy´s law
3. Update the element volume fraction, I, integrating the equation (5)

In our proposal, the meshing algorithm is developed in order to include all the control volumes that are completely filled, so that I=1. That information is obtained directly from the artificial vision as stated before. So in the method proposed, the updating of the volume fraction is not calculated with equation (5). This equation, and hence step 3, is only used in terms on the numerical evaluation of the proposed method.

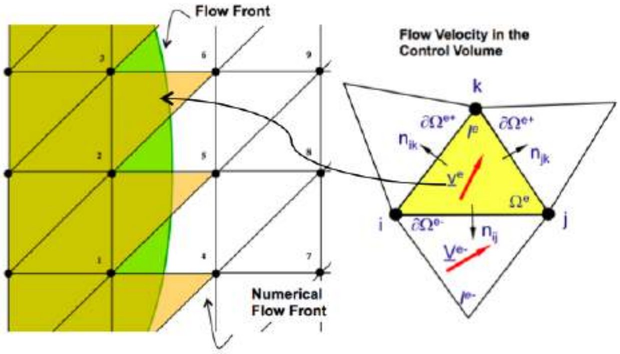

Figure 2. Fixed triangular mesh with control volumes in elements and computation of numerical flow velocities in elements.

2.2 Obtaining the Velocity field by means Artificial Vision and a Level Set Technique

Computation of velocities at flow front can be estimated by means the distance and time between consecutive flow fronts. In this work a level set approach described in [15] is employed to compute the vent distance field of a given composite part. An easy and fast way to compute a distance field, expressed as an implicit function *$\phi(x,t)$,* is to employ a Fast Marching technique that provides very fast results at a minimum computational cost.

The evolution of an implicit function under an external velocity field can be written as

$$\phi_t + \vec{v} \cdot \overrightarrow{\nabla\phi} = 0 \tag{6}$$

where sub-index indicates a partial derivative with respect to that variable. If we assume that the velocity field at the flow front is normal to the implicit function ϕ itself, $v = V_n n$ with V_n constant. We can rewrite (6) as

$$\phi_t + V_n \cdot |\nabla\phi| = 0 \tag{7}$$

See [17] for details on the discretization and integration of this equation. We can define some geometric concepts that will be used in Resin Infusion modeling by computing the distance function $\phi(x,y)$ in the whole domain. In order to clarify its computation, in next figures are shown the results of an experiment carried out in a rectangular rigid mold with a constant pressure injection line on the left. The objective was to obtain the value of V_n from equation (7). Then the flow is assumed to be normal and scaled outwards from previous image, see Figure 3.

The values of V_n are then calculated from equation equation (7) using an upwind technique with the level set functions obtained directly from the images:

$$V_{n,i} = \frac{\phi_i - \phi_{i-1}}{\Delta t \, |\nabla\phi|} \tag{8}$$

Normal velocity values are computed for each mold location on each time instant during filling and give us information in real time of the velocity field during filling. This experiment will be discussed in this paper.

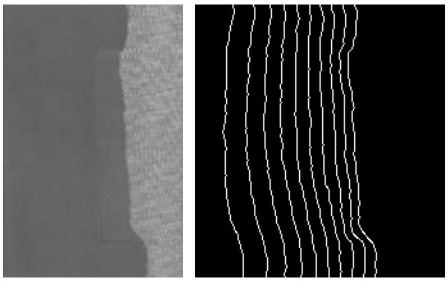

Figure 3. Artificial Vision flow front image (left) and the computed consecutive flow fronts during filling with the same gap, elapsed time (right)

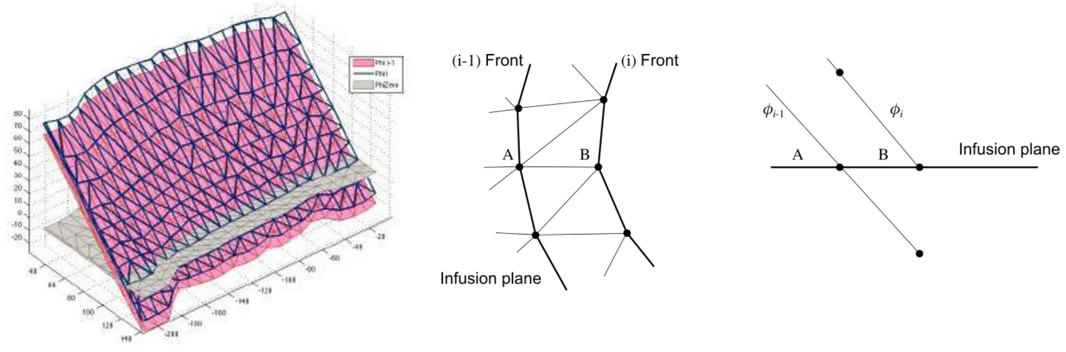

Figure 4. Level set ϕ function for consecutive flow fronts computed in triangular mesh elements

3 ESTIMATION OF MATERIAL PROPERTIES

In this section the methodology for estimating the local Material Properties based on Artificial Vision is described. Darcy's law describes the behavior of fluid in a porous medium. However, if the porous medium is isotropic, tensor $\underline{\underline{K}}$ can be replaced by a number since $K_{xx} = K_{xy} = K$ so that, equation (1) can be expressed as

$$\|V\| = M \cdot \|\nabla P\| \tag{9}$$

Where $M = \dfrac{K}{\phi \cdot \mu}$ represents the Material Properties (MP), and the tensorial dimension has been removed since both vectors are collinear. So that M can be computed as follows

$$M = \frac{\|V_{AV}\|}{\|\nabla P\|} \tag{10}$$

Where V_{AV} is the velocity obtained by means Artificial Vision, and ∇P is the gradient of pressure, obtained by means FEM simulation. However in order to compute FEM simulation the value of M is needed, and the equation results as follows

$$M^{est} = \frac{\|V_{AV}\|}{\|\nabla P(M^{est})\|} \tag{11}$$

Equation (11) is a fixed-point equation whose solution is the real MP, since it matches the analytical model and the empirical measures. It can be proved that if the sequence defined in (12) converges, its limit value is a solution of equation (11),

$$M_{K+1}^{est} = \frac{\|V_{AV}\|}{\|\nabla P(M_K^{est})\|} \tag{12}$$

Our proposal consists in meshing the filled zone and then, applying the sequence (12) until its convergence value, in the finite elements that belong to the gap defined between current flow front and the previous flow front (see Figure 4).

Velocity in each FE is computed as explained above, and the value obtained for M is maintained unchanged for the computations of posterior flow front gaps (in elapsed times).

4. EXPERIMENTAL RESULTS

The described proposal has been applied to both simulating and real mold filling. The experiments have been conducted by filling a 2D rectangular mold using 2 different curing conditions for the gel coat. The variances in the coating degree of conversion are defined in order to generate differences in the impregnation and flow advancement of the resin in the dry preform during filling. Coat 1 and coat 2 are characterized previously by performing a measure of the degree of conversion of the polymerization reaction of the polymer matrix. The degree of conversion (α) is obtained by measuring the residual enthalpy **ΔH (j/g)** with a Differential Scanning Calorimetry (DSC) when performing infusion. The total reaction enthalpy is obtained by curing of a gel coat sample in the DSC with equation (13), quantified in table 1 and outlined in Figure 5,

$$\boldsymbol{\alpha\ (\%) = \Delta H_{res} / \Delta H_{total}} \tag{13}$$

Coat	$\Delta H_{\text{exothermic peak}}$ (J/g)	α (%)
Total reaction enthalpy	329,296	0
Coat 2. 40' a 45 ºC	134,12	59,3
Coat 1. 24 horas a 25ºC	5,891	89,7

Table 1: Coat degree of curing characterization with DSC.

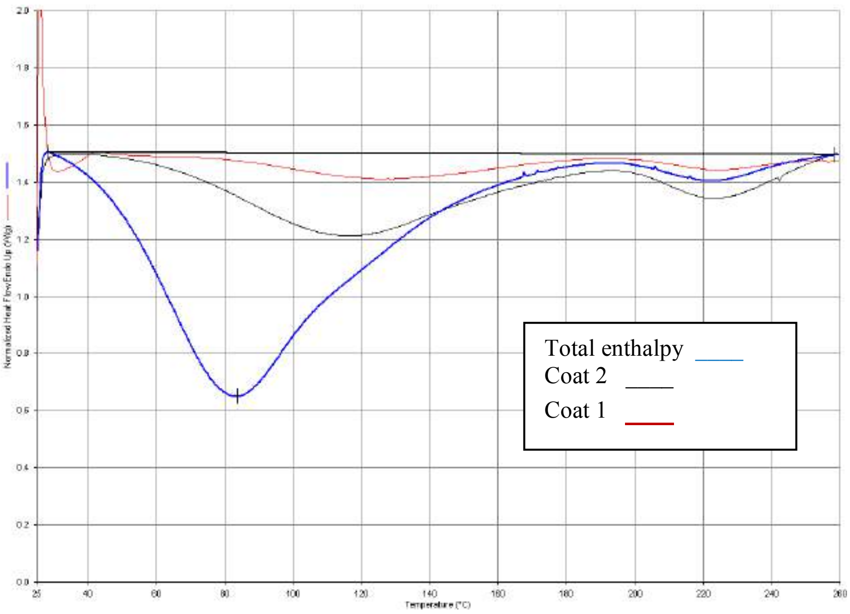

Figure 5. Coat reaction entalphy measured with DSC.

4.1 Test 1: Unidirectional flow with an abrupt discontinuity in the curing degree of the gel coat

In this experiment, the coatings have been applied on the mold surface in 2 consecutive areas as outlined in Figure 6. The textile was preplaced in the whole domain with a constant isotropic permeability.

The material properties stated previously as $M = \dfrac{K}{\phi \cdot \mu}$ have been computed locally during filling using the above exposed methodology. In Figure 7 are outlined the values of the flow front velocity that characterizes the flow dynamical behavior during filling. The value of M is estimated for each flow front position so it can be observed an abrupt change on it when the coating also changes. This alteration on the coat curing yields a related change on the flow front velocity that the system identifies.

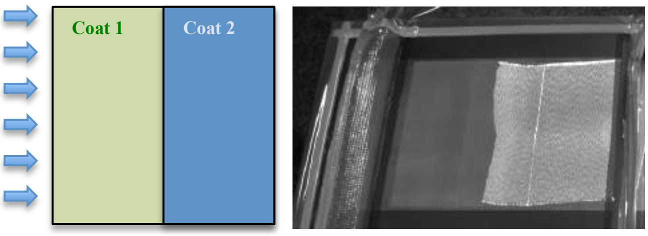

Figure 6. Experimental setup for 1D Material Properties estimation

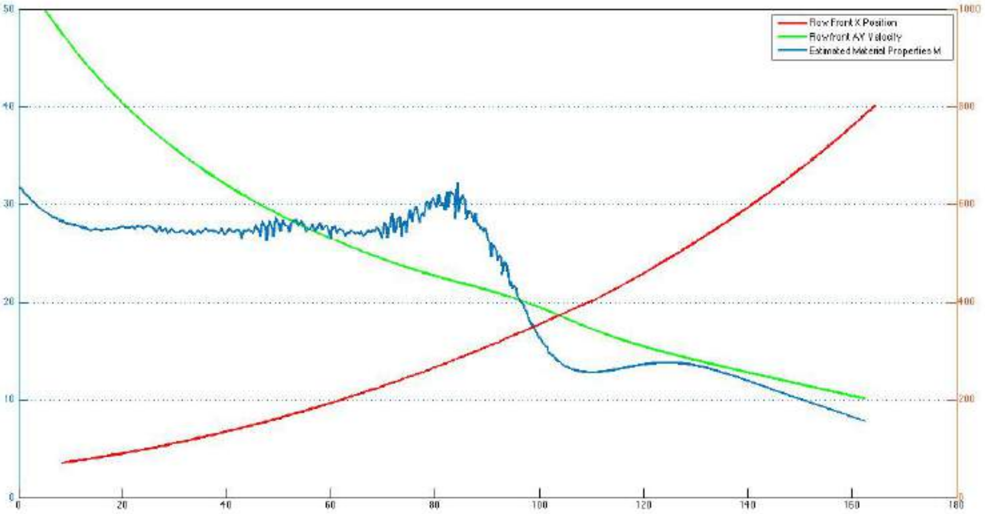

Figure 7. Material Properties Estimation during filling (blue), 1D Flow front position (red) and Flow front Velocity (green)

4.2 Test 2: Bidirectional flow with an abrupt discontinuity in the curing degree of the gel coat

In this other experiment, the coat 1 and coat 2 areas are arranged as depicted in Figure 8 so the flow advancement is not balanced unidirectionally, as can be observed in Figure 9.

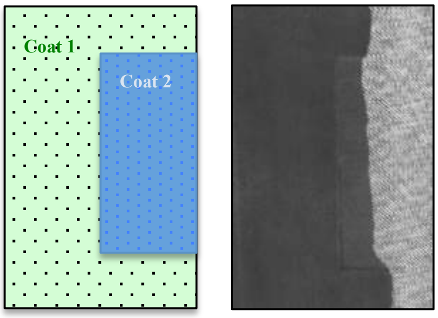

Figure 8. Experimental setup with two different coat areas (left) and intermediate AV image flow front (right)

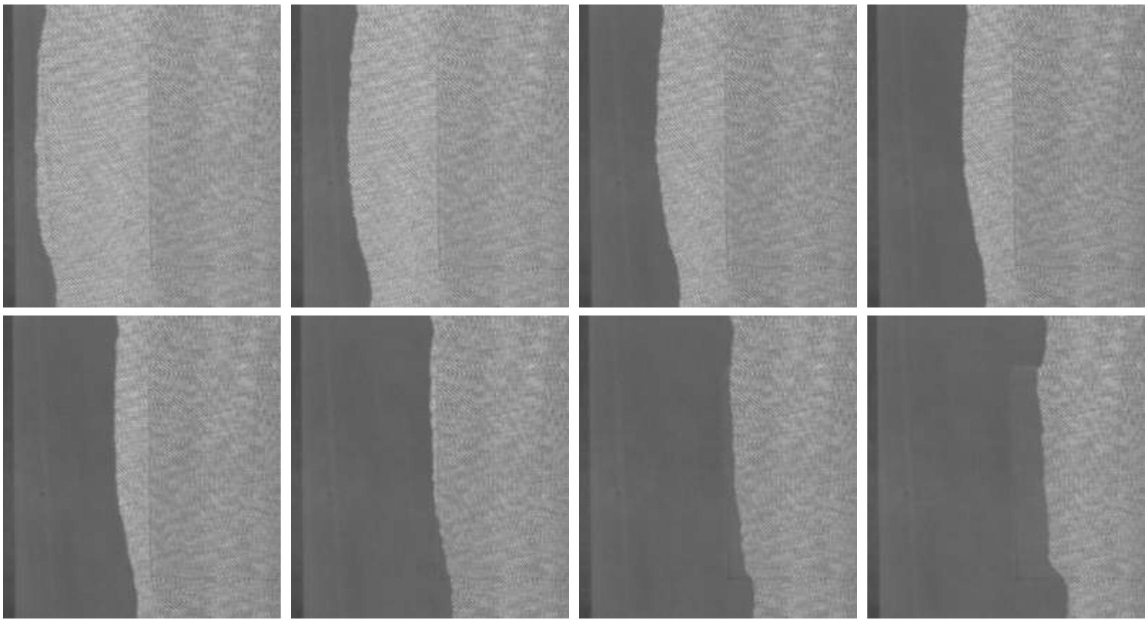

Figure 9. Consecutive Flow front AV images

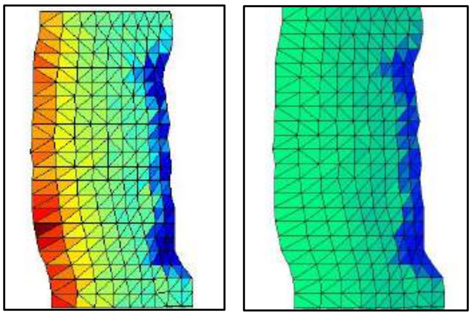

Figure 10. Estimation of Velocity field in elements (left) and Material Properties (right)

In this case, the 2D velocity field during filling is computed in a triangular mesh. The Material Properties estimation M is outlined in Figure 10. It can be observed that the curing degree discontinuity of the coating areas can be identified by means of a deep change on the flow front velocity and hence M can be characterized.

5 CONCLUSIONS AND FUTURE WORK

In this work have been used a novel mixed numerical/experimental technique based on artificial vision for estimating the induced effect of the surface coating curing in the laminate impregnation and the flow front advance during filling under controlled conditions. The procedure computes local material parameters and is proposed based on the aim of matching the empirical data with the simulation. For that purpose, the method iterates the value of permeability, porosity and induced viscosity in the simulation until it matches the evolution of the experimentally measured flow front. Two tests show the capability of the proposed method to characterize the behavior of diverse surface coatings during the mould filling for manufacturing purposes.

A deeper research is being done in order to establish the effect on the materials parameters separately (permeability, compaction, porosity, etc). Up to now, we are not able to conclude about the reasons of the influence on the textile impregnation variations. Nevertheless the procedure regarding to observe the macroscopic flow characterization has been implemented and successfully validated.

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