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Determination of the optimal impregnation velocity in Resin Transfer Molding by capillary rise experiments and infrared thermography

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ABSTRACT

Void minimization is an important issue in Resin Transfer Molding (RTM) because concentrated porosity can significantly decrease the quality of final composite parts. The injection stage is critical, since the impregnation of the fibers can generate voids by entrapment of residual air. The optimal velocity of the flow front in RTM injections can be determined by capillary rise experiments carried out through the fibrous reinforcement. Classical wicking investigation techniques are based on the visualization of the liquid front during the capillary rise, which can be enhanced by fluorescence. However, this technique can only be applied to transparent fibers such as glass. For this reason, a new approach based on InfraRed Thermography (IRT) is proposed in this paper for non-transparent carbon fibers. An inverse algorithm is used to estimate the optimal velocity of the flow front during resin injection from the thermal images obtained by IRT. This new experimental method was validated by comparison with capillary rise experiments carried out by fluorescence through glass fibers, after which it was applied to carbon fibers in order to determine the optimal impregnation velocity.

1. Introduction

The quality and the mechanical properties of composite parts are strongly affected by the void content [1,2]. In Resin Transfer Molding (RTM), most of the voids are formed during mold filling and result mainly from the dual porosity structure of most engineering textiles, which include microscopic and macroscopic pores [3,4]. Several techniques have been used to reduce void content, such as bleeding or applying a consolidation pressure to the composite before resin gel. However, most of these methods are expensive and cannot be easily implemented in parts of complex geometry or very large pieces. The main purpose is not so much to eliminate completely porosity (which is hardly feasible), but rather to make sure that no local void concentration exists in the part. In order to do so, a numerical optimization technique was proposed by Trochu et al. [5] and implemented in Ruiz et al. [6] in 2006. This approach is now increasingly used for high performance RTM composite applications. It consists of controlling the injection flow rate so that the average velocity is constant and equal to an optimal value that minimizes voids in the part. This is why controlling the velocity of the flow front during mold filling, also called the "impregnation velocity", represents a key issue in RTM. As shown in Fig. 1, the void content in composite samples describes a "V-shaped" curve as a function of the flow front velocity. Macroscopic voids are formed between the fiber tows when the velocity of the flow front is too low (flow driven by capillary forces), whereas microscopic voids appear inside fiber tows when the velocity is too high (flow driven by viscous forces). It was proven that an intermediate optimal flow velocity range exists that minimizes void formation during resin injection [6,7]. This velocity range is specific of each combination of resin and fabric. The optimal velocity range can be determined by capillary rise experiments, namely by filling the fibrous reinforcement at low impregnation velocity.

2. Materials and method

2.1. Capillary rise experiments

Capillary rise experiments aim to study the impregnation of porous materials. It is used in different fields such as textiles, porous media and soils. The principle of this approach consists of dipping the sample material in a recipient containing the infiltration liquid and measuring the evolution of the impregnation in time. Classical measurement techniques record the mass of the absorbed liquid and/or the height of the capillary front. Different

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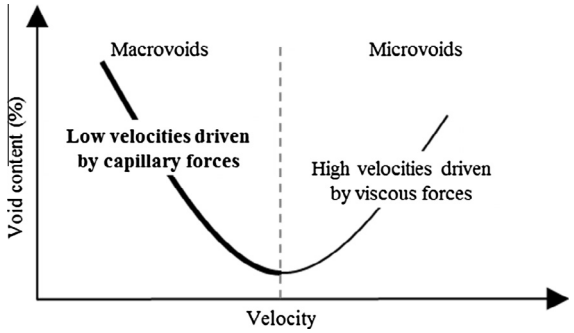

Fig. 1. Theoretical void content as a function of the impregnation velocity in composite parts made by RTM.

visible techniques exist to measure the height of the fluid front. It consists of recording images during the capillary rise and determining the positions of the capillary front by image processing. A powerful optical method using a fluorescent dye has been developed for glass fiber reinforcements [8–11]. The optimal impregnation velocity can be determined by the following relation:

$$v = \frac{B_h}{L_c} \tag{1}$$

where L_c is the characteristic length (m), i.e., the center-to-center distance between two fiber tows and B_h ($m^2\,s^{-1}$) is the slope of the flow front square height evolution as a function of time, also known as the Lucas–Washburn model defined by:

$$z^2 = B_h \cdot t \tag{2}$$

where z is the flow front height (m) and t the time (s).

Lucas–Washburn model is obtained by writing the balance of capillary, gravity and viscous forces [12] in Hagen–Poiseuille flow along the vertical direction through a fiber bundle. Note that inertia and gravity can be neglected during capillary rise experiments through reinforcement samples of the size and shape used in the present work [9]. In Eq. (1), L_c is measured by a microscopy analysis. The critical experimental parameter B_h required to estimate the optimal flow front velocity is obtained by optical means during capillary rise experiments. Since this kind of observation is not possible in non-transparent fabrics, another possibility is to write the Lucas Washburn model in terms of mass:

$$m^2 = B_m \cdot t \tag{3}$$

where m is the absorbed fluid mass (g) and B_m ($g^2\,s^{-1}$) is the slope of the square mass evolution as a function of time. Hence the optimal flow velocity can still be calculated by Eq. (1) when B_h is derived from B_m by the following relation:

$$B_m = \left[\rho \cdot w_{fabric} \cdot h_{fabric} \cdot (1 - V_f^{fabric}) \cdot s\right]^2 B_h \tag{4}$$

where ρ is the fluid density ($kg\,m^{-3}$), w_{fabric} and h_{fabric} are respectively the width and height of the fabric sample (m), V_f^{fabric} is the fiber volume content of the fabric sample (%) and s denotes the saturation level (%) of the fabric. In Eq. (4), all the parameters are known except the saturation s, which varies in time. The first option is to estimate saturation as follows:

$$s(t) = \frac{real\ volume}{apparent\ volume} = \frac{m(t)/\rho}{w_{fabric} \cdot h_{fabric} \cdot (1 - V_f^{fabric}) \cdot z(t)} \tag{5}$$

However, this approach cannot be applied to non-transparent fabrics since it requires knowledge of the evolution $z(t)$ of the liquid height in time. The second option is to consider the saturation equal to 1, which means that all the pores are completely filled with liquid. If this can be assumed inside fiber tows and for unidirectional fabrics, it is not true for 2D fabrics because macroscopic voids are created as a result of perpendicular horizontal capillary flows that occur in these materials. Therefore it is not possible to extend the actual Lucas–Washburn mass model to the case of non-transparent textile reinforcements such as carbon fibers. This is why a new method based on infrared thermography was devised to estimate the optimal impregnation velocity.

2.2. Infrared thermography applied to capillary experiments

InfraRed Thermography (IRT) has become a widely used measurement technique in research and engineering, especially in the Non Destructive Testing (NDT) of composites [13]. IRT has already been used for capillary rise measurements in soil samples to detect the moisture absorption [14], or porous media samples [15,16] but only as a visualization tool. This investigation aims to study the possibility of using IRT during the imbibition of carbon fiber engineering textiles as a quantitative technique to predict the optimal impregnation velocity. The experimental setup is shown in the diagram of Fig. 2a. The main experimental difficulty is connected with the thermal signal required to visualize the evolution of the capillary front. If the reinforcement and the infiltration liquid are both at room temperature, no temperature changes occur during imbibition and hence no motion of the capillary front can be detected. Therefore a small thermal contrast needs to be created between the liquid and the fibrous reinforcement in order to visualize the infiltration. The liquid temperature was monitored via a temperature controller and a heated plate (see Fig. 2a). The sample is attached on a laboratory frame which moves vertically to approach the liquid surface. The heated plate and the liquid container are placed on a weighing scale.

The motor allows a very slow approach towards the liquid surface. When a mass jump is detected on the weighing scale, the motor is instantaneously stopped. From experience, a motor speed of 0.1 mm s^{-1} and a mass threshold of 20 mg were set to define the initial time of the capillary rise when the liquid comes in contact with the fibers through a meniscus. These parameters have been selected to prevent the samples from being dipped abruptly into the liquid and avoid buoyancy effects. The motor also allows removing the samples from the liquid after the capillary rise. The whole experimental setup is installed in an insulated dark room in order to avoid air motion, vibrations, external light, and minimize heat transfer. The liquid used for the experiments is hexadecane, a perfectly wetting fluid of well-known physical properties (density, viscosity, contact angle). In this configuration, IR images were recorded during the capillary rise at a frequency of 5 frames per second. Every image is a 2D matrix giving the temperature field in Celsius degrees (see Fig. 2b). The whole sequence of temperature fields is a 3D matrix with time as third dimension. This sequence of images is imported into Matlab software for post-processing. An inverse technique is then used to estimate the velocity from the temperature fields.

3. Numerical method

3.1. Thermal modeling

Inverse techniques are well known in heat transfer problems, and very useful in the case of infrared thermography [17]. In order to retrieve the fluid velocity from the temperature field, a thermal model needs to be introduced. In the case of capillary rise experiments in a 2D fabric, the physical phenomenon can be considered as a two-dimensional heat transfer problem (the thickness is negligible compared to the length and width of the samples). The heat equation can be written in the fibrous reinforcement as follows: