ASSESSING THE RELIABILITY OF FILLING SIMULATIONS FOR RTM: CRITICAL COMPARISON OF THEORETICAL AND REALISTIC PERMEABILITY OF TYPICAL CURVATURES ENCOUNTERED IN RTM PREFORMS

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Abstract

Fiber reinforced polymeric composites manufacturing by Resin Transfer Moulding (RTM) is sensitive to filling defects depending conditions, materials and geometry. In the past scientific work has focused on identifying the behavior of filling both in theoretical and practical level; models that describe fluid flow through porous media have been applied in filling simulations while flow sensors and instruments (permeameters) that determine the in-plane permeability of virgin textile based fiber preforms have been developed. In 3d-shaped components instead of virgin textile structure draped preforms are given. This paper focuses on the permeability of typical curvatures found in RTM: Flow sensors compatible with curvatures are used in a RTM process. A model is developed for the measurement interpretation to curvature permeability and the differences from in-plane permeability or theoretically expected draped permeability are discussed.

1. Introduction

Filling in closed mold RTM manufacturing is a process in principle not visible which makes the identification of filling behavior and defects difficult. The issue of understanding filling is solved by using filling simulations [1]. For simple shapes, i.e. flat plates, optical monitoring by transparent tools [2], or sensor-based monitoring is also possible. The latter has been achieved by mounting sensors in the tool [3,4] or embedding them in the part [5]. All of the above approaches have certain disadvantages: Simulation quality is heavily dependent on critical inputs (e.g. preform permeability), transparent tools create deflection which was found to affect filling [6], the electrical isolation techniques of electrical mould-mounted sensors from carbon fiber either increase the Fiber Volume Content (FVC) locally (e.g. if a glass film protection is used) or create additional cavities (by intentional misalignment of the sensor from the cavity surface) [7] and finally the bodies of material embedded sensors may disturb the flow depending on their geometry [8]. However there are ways to make the above disturbances negligible: Inserting realistic inputs in simulations minimizes considerably the error from reality, weights on the transparent tool material minimize deflection [2],

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choosing non-electrical flow mould-mounted sensors eliminates the need for electrical isolation and finally material embedded sensors of very small diameters (comparable to the fiber diameter) minimizes possible disturbances. When the purpose of monitoring is to determine permeability, oil is most often used instead of uncured resin while filling occurs at room temperature. As long as viscosity is comparable to real processing conditions, only minor deviations from reality is assumed. However, in practice it has been found that certain conditions do affect permeability (e.g. low compaction, high injection pressure or both allow preform deformation from the flow front itself, thus distorting permeability measurement.

In the study at hand the focus is on monitoring an actual RTM process aiming to get measurement data based on realistic materials, tools, conditions and geometries; polymeric matrix instead of oil, metallic (non-deflecting) tools, high process temperature and single curved part shape, more complex than a plate. For that purpose material embedded sensors were employed. The measurements were interpreted to permeability by an appropriate model and the observed differences from theoretical expectancies were quantified and discussed.

2. Theoretical Background

An analytical correlation between the flow time within a draped zone and permeability is based on the solution of Darcy's law for radial injection on the x-y plane [9] (Eq. 1).

$$K_i = \frac{\eta\varphi}{6Pt_i}\left[\frac{2i_f^3}{R_0} - 3i_f^2 + R_0^2\right] \tag{1}$$

where i is the in-plane axis (x or y), φ is the porosity, P is the injection pressure, i_f is the flow front along the i-axis, R_0 is the inlet radius and t_i is the time needed to achieve i_f. Transforming Eq. 1 for the fluid movement between two points A and B along the i-axis where $i_{fA} > i_{fB}$, yields Eq. 2.

$$K_i = \frac{\eta\varphi}{6P\Delta t_i}\left[\frac{2}{R_0}\left(i_{fA}^3 - i_{fB}^3\right) - 3\left(i_{fA}^2 - i_{fB}^2\right)\right] \tag{2}$$

Where i_{fA} and i_{fB} are the flow fronts at points A and B and Δt_i is the flow time between A and B. Assuming filling of two planar preforms 1 and 2 where dimensions, A and B coordinates, injection pressure and viscosity are common, but $\varphi_2 = F(\varphi_1)$, mutual division of Eq. 2 written for each preform leads to P, η, R_0, i_{fA} and i_{fB} elimination. Considering that a draped zone can be modeled by an equivalent planar zone under the assumption of negligible gravitational effects, the function correlating the porosities can be derived by the ratio of cross sectional draped and equivalent planar areas [10]. The above approach results into the expression for permeability of curvatures given by Eq. 3.

$$K_{i,d} = \frac{\Delta t_{i,p}}{\Delta t_{i,d}}\left\{\frac{2Lh\left(\varphi_p - 1\right)}{\varphi_p\theta[(R+h)^2 - R^2]} + \varphi_p\right\}K_{i,p} \tag{3}$$

Where φ_d and φ_p are the porosities of the draped and planar zones, $K_{i,d}$ and $K_{i,p}$ the draped and planar permeabilities along a planar axis, $\Delta t_{i,d}$ and $\Delta t_{i,p}$ the time of flow within the draped and equivalent planar zone, L is the zone length, h is the part thickness, θ is the curvature angle and R is the internal curvature radius (Figure 1).

3. RTM Tool and sensors

Eq. 3 requires the flow times in a draped zone and in its planar equivalent (Δt_d and Δt_p respectively). Δt_p is derived by an optical permeameter whose principle of operation and measurement procedure is described in detail in [2]. Δt_d on the other hand is derived by flow time measurements within an actual RTM tool (Figure 2). The tool produces parts with an omega shape. The geometrical description of each curvature as defined in Eq. 3 is R=25 mm, h = 3 mm, L = 22 mm and θ = 45 °. In total 8 vents

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placed on the parting line can be used as entry points for any type of material embedded sensors, venting or both.

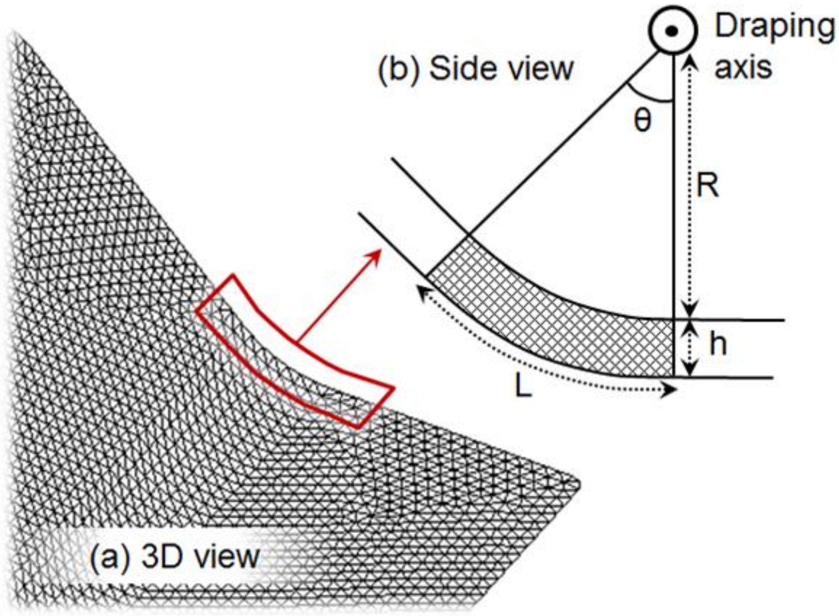

Figure 1. (a) The 3D view of the mesh of a curvature and (b) the side view with the curvature defining parameters.

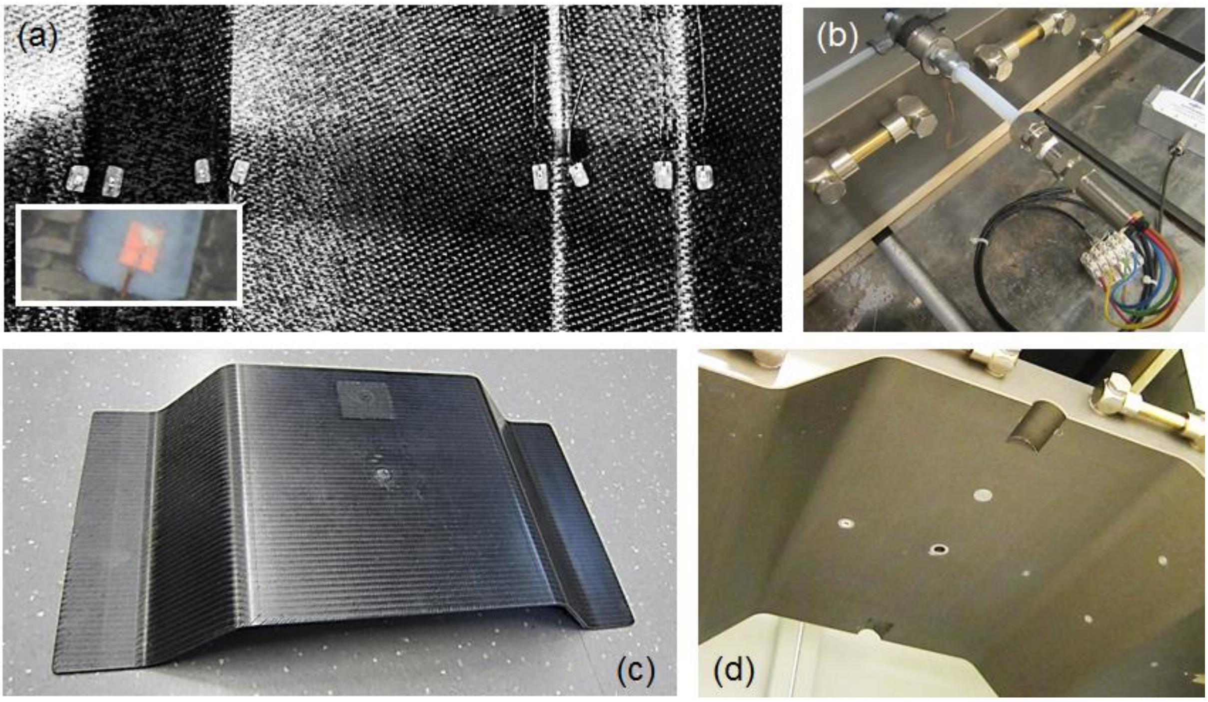

Figure 2. (a) Bottom surface of the produced part (image processing was used to make the sensors visible), (b) A vent being used as entry point for 4 EMFS, (c) the produced part and (d) the top RTM tool (mould-mounted sensors visible).

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Despite a variety of mould-mounted sensors in the tool, in this study, Electrical Microwire Flow Sensors (EMFS) that enter the RTM tool from existing vents and are fixed on the cavity surface, were employed to investigate flow on curvatures. Variations of the particular sensing technique have been used in the past for flow monitoring [5]. Here it was selected mainly due to its compatibility with curvatures (in contrast to optical detection or mould-mounted sensors). It is based on detecting the electrical resistance on the wire tip: when measuring a dry spot of the preform the sensor indicates a very high value (open circuit) while a sudden drop of electrical resistance indicates matrix arrival. To prevent contact with carbon (conductive) fibers, the tip can be electrically isolated with a thin glass wrap. EMFS are characterized by various attributes but for this study special attention was paid to two particular issues:

- The sensors themselves might disturb the flow. Preliminary tests were conducted to identify flow disturbance from the sensors. Filling the tool with and without EMFS where the flow was detected by the tool-mounted sensors, showed that the times of matrix arrival on the latter remain within the preform structural uncertainty in both cases when certain conditions were met: a) wire of small diameter (200um was finally chosen), b) small number of sensors (which is acceptable due to the focus only on curvatures and not the whole part), c) distances between the sensors are maximized. It is important here to discriminate between structural disturbance and flow disturbance: Although a wire with a diameter larger than the fiber diameter can pose a threat to the structural health of the part, it still might not disturb the flow significantly (e.g. due to wire nesting in the tows).

- There might be error in the sensor tip final positions compared to the intended ones. The tip co-ordinates are difficult to be accurate (due to manual placement or shifting caused by the flow itself). The error in positioning the tips was taken into consideration by fixing the tips on the cavity surface. This resulted in integrating the sensor on the part surface (not the interior) thus making the sensor tips visible post manufacturing. As such, precise measuring of the tip final positions was possible and minor shifting was accounted for (e.g. by examining the exact same co-ordinates in the required simulations).

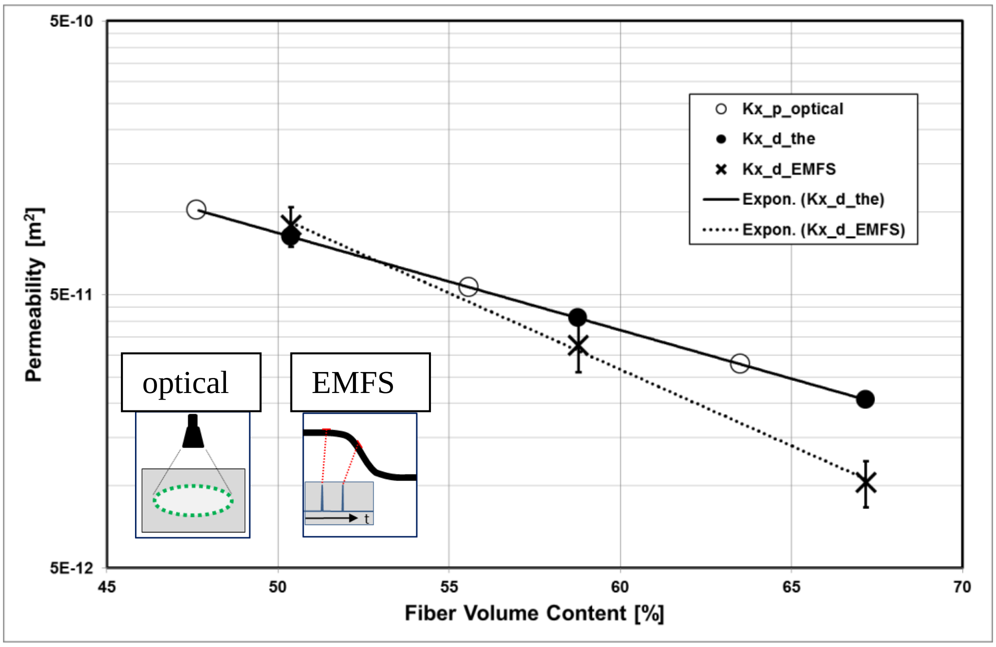

Figure 3. The permeability along the preform main axis (coincides with x-axis due to orthotropy) versus FVC for the planar zones of the RTM tool gained from an optical permeameter ($K_{x\_p\_optical}$), the draped zones as approximated theoretically ($K_{x\_d\_the}$) and experimentally measured using EMFS sensors ($K_{x\_d\_EMFS}$).

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4. Experimental and Results

Experiments in an optical permeameter were used to identify the in-plane permeabilities which were then used as inputs to simulations in order to derive the Δt_p needed in Eq. 3. The permeability of the draped zone along the x-axis derived experimentally ($K_{x\_d\_EMFS}$) is finally calculated by Eq. 3 where the Δt_d is measured in the Omega RTM tool.

RTM experiments involved filling of 3 different preforms of the same textile & local orientation with a polymeric matrix while preheating/ cavity temperature was set to 70°C and injection pressure to 5 bars. EMFS were fixed in the cavity along the x-axis at the beginning and end of the curvatures (Figure 2.a). The theoretical expectancy of the permeability in a draped zone ($K_{x\_d\_the}$) can be derived by mapping the increased FVC of the draped zone as defined in [10] to a permeability value, using the fitting line of the in-plane permeability identified by the optical permeameter. The resulting permeabilities vs. FVC are presented in Figure 3. Additional filling simulations where the in-plane permeabilities and $K_{x\_d\_the}$ characterize planar and draped zones respectively, were executed in order to derive the theoretically expected flow time within draped zones (Δt_{d_the}). To compare these times with the corresponding experimental times (Δt_{d_EMFS}), the relative time increase defined as $t_{inc}=[(\Delta t_{d\_EMFS}-\Delta t_{d\_the})/\ \Delta t_{d\_the}]100\%$ was plotted vs. (draped) FVC (Figure 4).

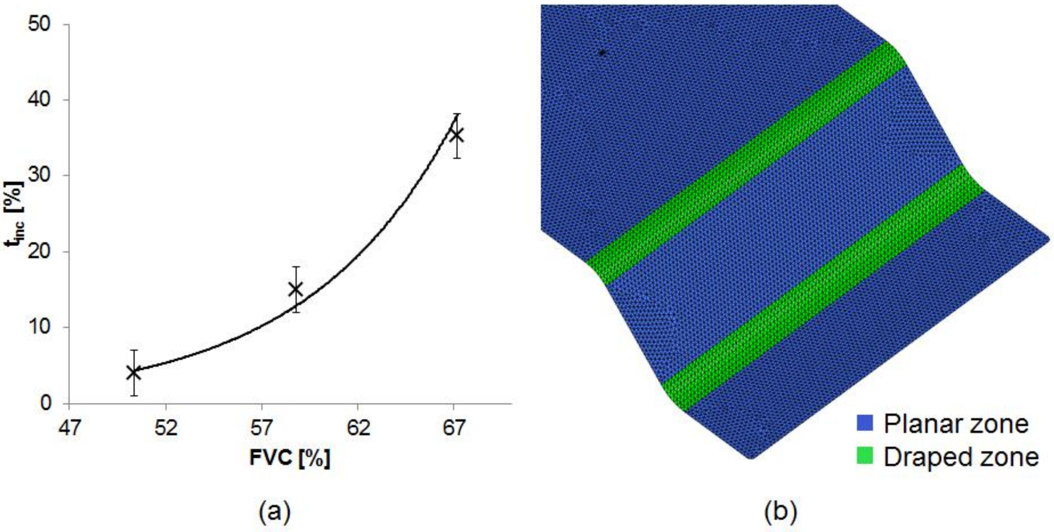

Figure 4. (a) Experimental flow time in a draped zone is higher than the theoretical expectancy and the disagreement rises exponentially with FVC, (b) zones used in simulations to calculate the theoretically expected flow times.

5. Discussion and Conclusion

A tendency towards lower permeability is observed in Figure 3, which however becomes significant only at the highest FVC. This shows that the theoretical expectancy of permeability in a draped zone is in principle in agreement with experimental findings but only for FVCs lower than ~60%. This behavior can be caused by nesting effects that become significant at the high FVC range and are expressed by a drop in the logK=F(FVC) slope. This explanation is supported by the fact that the theoretical expectancy does not take nesting in account while nesting appears experimentally by an increase in Δt_{d_EMFS}. Of course, the theoretical expectancy is derived by the optical permeameter but there nesting would not have been significant as in-plane FVC values are about 3 to 4 % lower than draped FVC values. The discussed difference of theoretically expected and experimentally derived permeability of a draped zone has an impact on the flow time within the draped zone. Figure 4 where the effect is quantified, shows that the theoretical approximation of flow time per curvature is an

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underestimation that becomes significant above FVC of ~55%; t_{inc} increases exponentially and reaches ~35% at FVC of ~67% (3 points are not enough to reveal an exponential relationship but in this case it is not possible to get intermediate values; the 3 FVCs correspond to preforms that differ by 1 layer. The assumption that they follow an exponential fit arises by the fact that Δt is in principle inversely proportional to K (eq.2)). As such, a practical potential of the methods in this study is to shorten the time disagreement observed between filling simulations and actual processes. However, the model has the limitation to be only valid when draping lies along the preform main and secondary axes. In this case it lies along the main so only K_x can be determined ($K_1 \equiv K_x$ due to orthotropic preform). Further investigations will involve methods to derive K_y such as inverse numerical optimization developed in the past [3].

In this study a model to identify the draped permeability was developed. Two measurement types: a) in a typical optical permeameter and b) in a realistic RTM setup were used in the model calculations. The resulting permeability is in agreement with theoretical expectancy at FVCs lower than 60%. Above, a difference possibly associated to nesting appears which is interpreted to flow time increase along the x-axis per curvature as high as 30 to 35 %. Thus, the method shows potential to optimize simulations with respect to flow time agreement with reality.

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