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INJECTION OF A COMPLEX PREFORM BY RTM. OPTIMISATION OF A MOULD DESIGN AND PROCESS PARAMETERS

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ABSTRACT: This work concerns the manufacturing of a composite tube using RTM process. During the preforming stage, a woven braid is laid down and stacked on a mandrel so that reinforcement plies form conical shapes with a defined angle. An innovative experimental preforming procedure has been developed to respect the specific angle. The resin injection step has been studied both experimentally and numerically. In this work a focus is applied on the optimization of the mould geometry and on the way the resin is injected within the preform to prevent the appearance of defects such as displacement of plies and porosity. Different optimization steps are described in this work and a mould geometry is proposed for this specific application and the quality of the part obtained is discussed and analysed.

KEYWORDS: Complex preform, RTM, Process parameters, Simulation, Braid permeability.

INTRODUCTION

This work concerns the manufacturing of a composite tube with 3D braided reinforcement by the RTM process. Specifically the influence of the preforming stage of the process on the resin injection is studied. Three-dimensional braided preforms were recognized as the most promising materials because of their low delamination tendency. Furthermore, the near-net-shape manufacturing, out-of-plane stiffness, strength, impact tolerance and ablation resistance recommend these materials [1]. Because braiding has the potential to produce complex shapes with fibre continuity at the edges and around holes and branches [2], braided structures are also used in several other applications, such as medical, automotive or sport equipment [3]. Classically, fibres are braided directly on a cylindrical mandrel with a conventional braiding machine. This process is an ancient technique, but as it could be automated, it is suitable for manufacturing reproducible preform for RTM process. The prediction of the fibre position along the mandrel as a function of the process parameters remains difficult. Consequently a lot of studies [4-6] concern the development of models which compute the characteristics of braided preforms. These characteristics could be the braid angle, the yarn volume fraction, the covering factor and finally the influence of these parameters on the permeability of the braid [7-8].

In this work application, each ply of fibre must have a specific orientation with the axis mandrel. As a consequence, a conventional braiding machine cannot be used. From specific 3D carbon braided reinforcement, an innovative experimental preforming procedure has been developed [9].

Three main properties have to be respected on the final composite part. First, the angle between plies of braid reinforcement and the tube axis must be equal to a specific value. Secondly, the preform has to present an important fibre volume ratio with a homogeneous distribution along and in the part. Thirdly, the level of macro porosity should not exceed the defined value to meet aerospace specifications (2% is a classical value).

From the 3D-braided reinforcement the experimental procedure consists in realizing one preform constituted by several plies [9]. Each ply must have a specific angle, (denoted α on figure 1.a) with the mandrel axis, and the preform must have a specific diameter given by the closed mould for the resin injection step. To realize this preform, a cylindrical mandrel with a conical base (figure 1.a) is used. The braid length depending on the expected fibre volume fraction can be estimated and weighted. The braid is first slipped into the cylindrical mandrel and tied between two threads on a length which will define the ply. The first ply, with the expected orientation, is obtained by folding up the braid on the conical base of the mandrel. By using the same principle, the others plies can be superimposed on each other. A preform (figure 1.b) contains approximately 120 plies, for 200g of carbon braided reinforcement.

In a second step the mould is closed and placed on the preform so that the resin can be injected (figure 1.c) under pressure or flow rate conditions, with a specific device developed at Orleans [10]. The outside flow front evolution can be measured as well as the time required to fill the mould.

This paper proposes to analyse the steps that led to the optimisation of the mould and particularly to the way the resin is injected in the preform in conjunction to the required quality of the part.

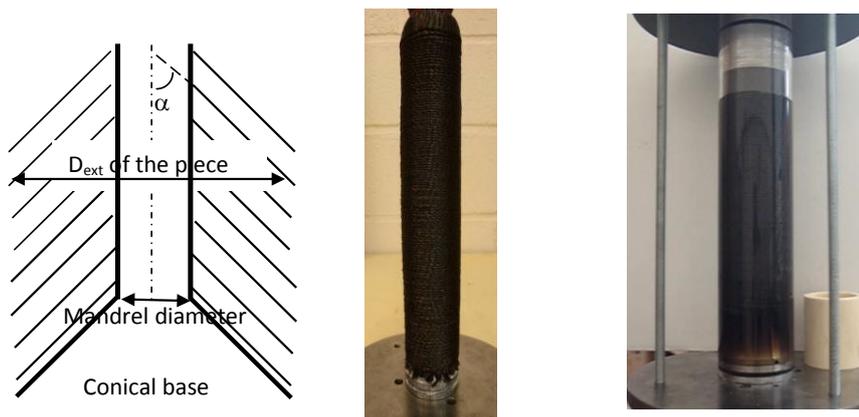


Fig. 1 (a) Scheme of the preform; (b) Final preform; (c) Resin evolution

Optimisation of the mould design and injection conditions

As mentioned in the previous section, the ply angles as well as a fibre volume fraction along the length of the tube should be homogeneous. The level of macro porosity should also be kept to a minimum value (below 2% for this application).

If the ply angle globally remains constant and will not be discussed here, figure 2 shows that the fibre volume fraction estimated from density measurements is not constant in a part injected with a pressure of 2 bars. In the first third of the part (from the bottom where the injection takes place), the fibre volume fraction is higher than what was expected. A difference of about 10 % is measured. In the second third of the part, (middle of the part), the fibre volume fraction decreases to reach values lower than what was expected. A difference of about 10% is also observed.

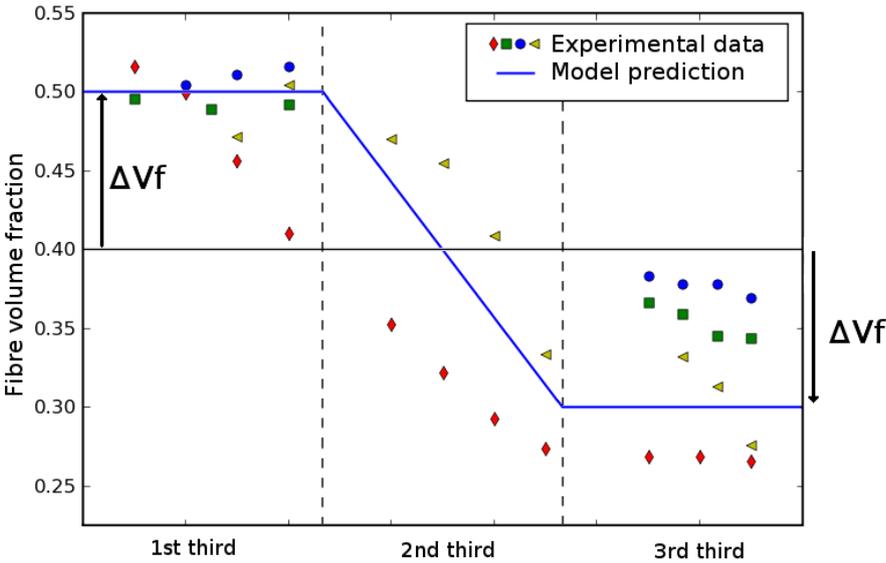


Figure 2: Fibre volume fraction as a function of the tube length

To explain this phenomenon, several hypothesis may be formulated. A first one consists in considering that the preforming was not homogeneous. A second one consists in considering that the injection phase changed the fibre volume fraction homogeneity. Some displacement and compaction of the plies in the first third of the part may have taken place.

As the preform is realized following a rigorous procedure, it is expected that compaction of the bottom plies of the preform took place. To confirm this hypothesis, some paint dots were applied at the extremity of chosen plies, and the movement of these ones was recorded using a video camera. Figure 3 shows that the bottom plies of the preforms do not remain in their initial position. It also shows that the distance between the dots becomes closer.

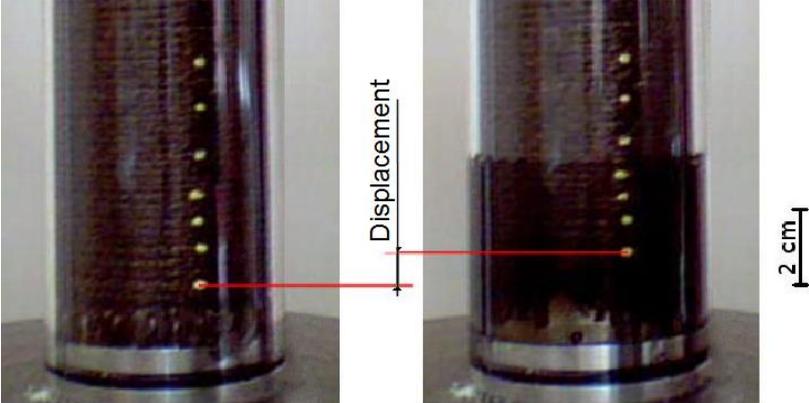


Figure 3: Influence of the fluid injection on the position of the bottom plies of the preform

The displacement of different marks, positioned along the tube axis, were recorded and reported in figure 4.

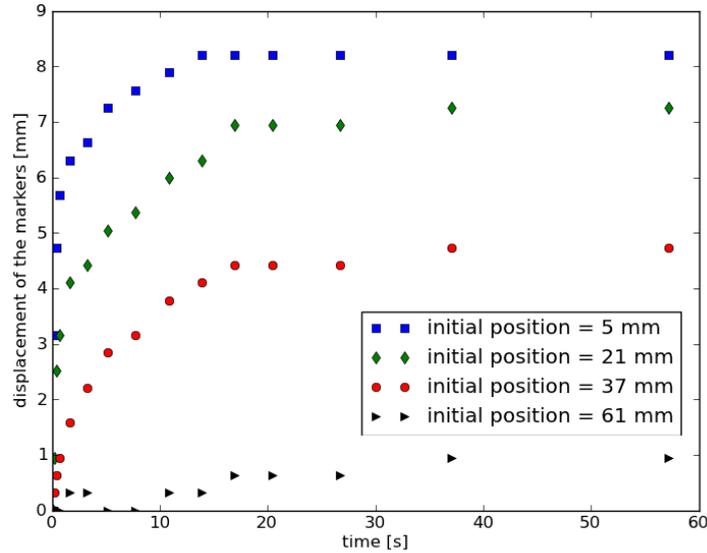


Figure 4: Displacement of the markers as a function of time during the injection

Figure 4 indicates that the displacement of the markers is more pronounced for the ones initially positioned closer to the injection gate. As an example the mark initially positioned 5 mm above the injection gate was submitted to a displacement of about 8 mm, whereas the mark positioned 61 mm above the gate was submitted to displacement lower than 1 mm.

The displacement of the ply and the non uniform fibre volume fraction cannot be accepted. For this reason, a porosity analysis of the part is not presented here as the part cannot be accepted in this state. However, the level of porosity is difficult to control on such a long part as the speed of resin is not constant and not necessarily within a processing window within which the porosity would be minimum. Indeed, different authors used the modified capillary number to define a processing window within which the macro and the micro porosity should not take place [11-14].

The capillary number is defined as follows:

$$Ca = \frac{\mu \cdot v}{\gamma} \quad (1)$$

Where μ is the viscosity of the resin [Pa.s], v is a characteristic velocity of the resin flow [m/s], γ is the interfacial tension between the air and the resin [N.m⁻¹]. These studies [12-14] indicate that below a value of the capillary number of 0.0035 capillary flow dominates and macroporosities are expected to take place. Above a value of 0.0035, flow in macro pores dominates, and microporosity is expected to take place. A processing window between 0.0035 and 0.035 is generally defined.

Simulations carried out using a FEM code for RTM analysis [15] were used to define the capillary number processing window. Results are presented in figure 5. Figure 5 shows that the modified capillary number approach suggests that injection pressure should be raised

above values of 30 bars. This cannot be considered as ply displacement (due to hydromechanical coupling [16]) already takes place for low injection pressure of 2 bars.

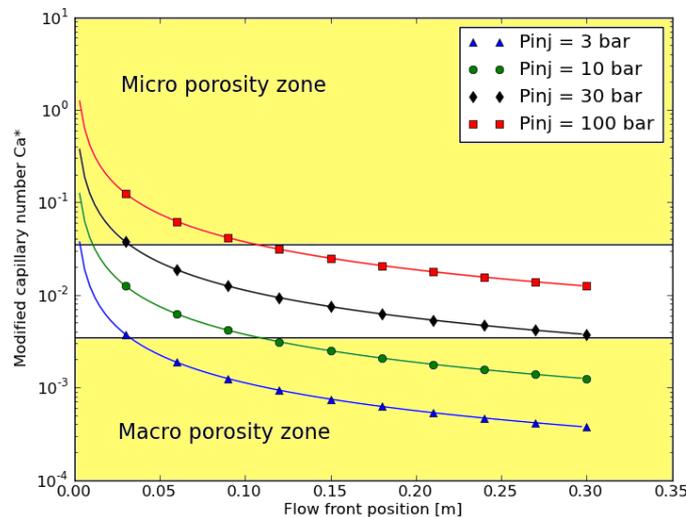


Figure 5: Simulation of the processing window based on the modified capillary number for the original injection mould

Solutions to prevent the displacement of the plies due to the injection of resin have been considered. The first one consists in allowing the resin to flow in a preferential channel along the preform as presented in Figure 6. In this case, the plies are held together by a gridded mesh.

This solution was tested and showed good results concerning the displacement of the plies. In this case, no displacement of the plies was observed. However, due to the space left between the preform and the mould, the preform thickness does not remain constant after the injection step as shown in Figure 7.

Figure 7 also indicates that macroscopic porosity takes place on the inside of the tube. This is not a problem as this part of the tube needs to be machined in any case to get rid of the yarns used to realize the preform. On the rest of the part, this global view does not indicate the presence of large macro pores, suggesting that the radial mode of injection with resin travelling shorter distances is promising.

An evolution of the concept is presented in Figure 8. It still consists in a radial injection. However, this time, the mould is fitted to the preform size and four small channels are machined in the inside part of the external shells in order to get radial injection.

Coupled to this mould design, an analysis based on the modified capillary number has been carried to optimise the injection pressure that should be applied.

Figure 9 shows that low pressure of about 1 bar or less should be applied to enter the processing window. This injection pressure was tested and a global view of the tube cross section does not show the presence of macroporosity in the useful zone (Figure 10). The large holes on the inside part of the tube are due to the yarn used to maintain the plies during the preforming. As this part is machined, this porosity is not considered as a problem for this application and the design of the mould can be considered as optimized for this particular application.

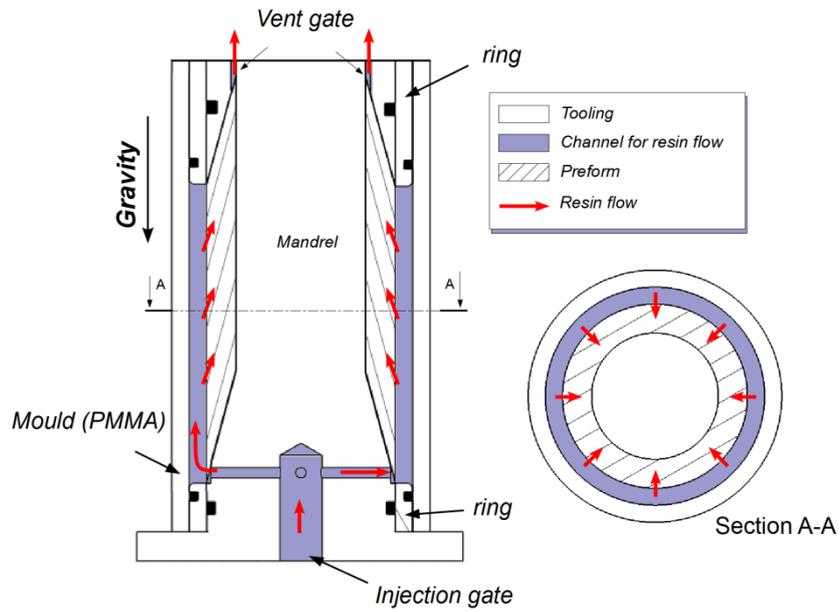


Figure 6: Radial injection mould

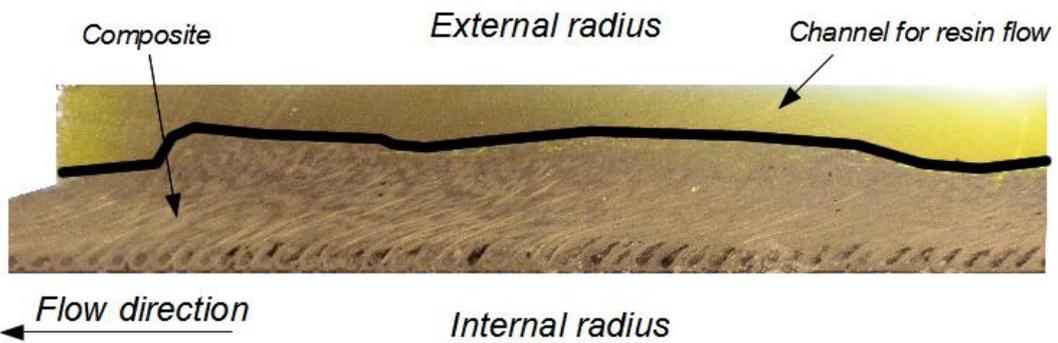


Figure 7: Longitudinal cross section of a tube manufactured by radial injection moulding

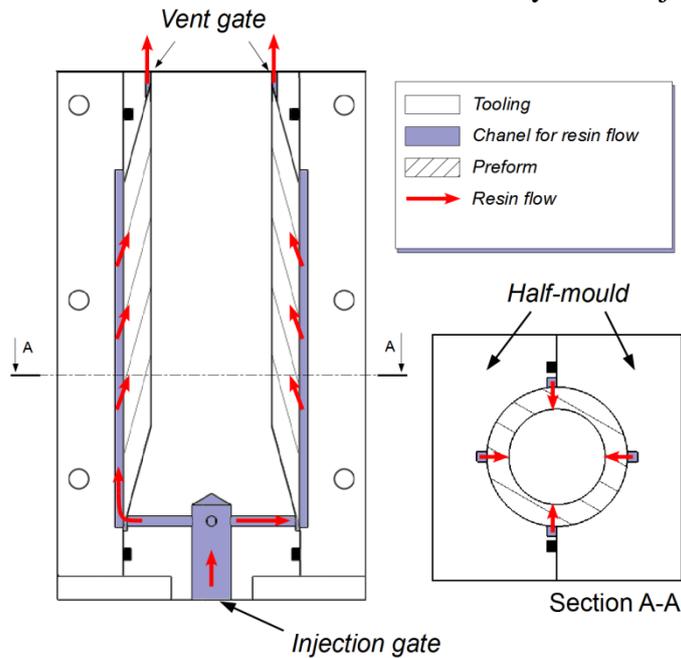


Figure 8: Radial injection mould with four preferential channels

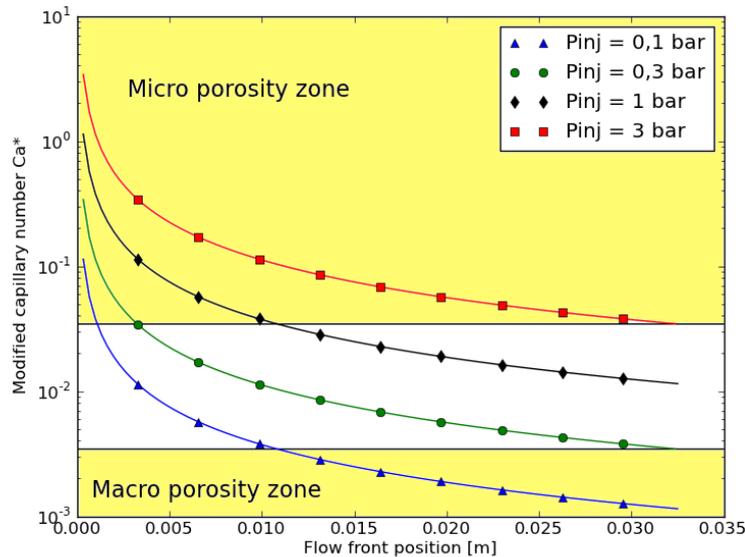


Figure 9: Simulation of the processing window based on the modified capillary number for the preferential four channel design mould



Figure 10: Cross section of a tube manufactured by radial injection moulding (4 preferential channel mould)

CONCLUSIONS

This work concerns the manufacturing of a composite tube from a 3D particular preform arrangement using RTM process. During the preforming step of the RTM process, a woven ribbon is laid down and stacked on a mandrel so that reinforcement plies form conical shapes with a defined angle. Preforming cannot be performed by using a classical braiding machine because of the specific and predefined orientation of the plies. Consequently, an innovative experimental preforming procedure has been developed. To avoid displacement of the plies, macro or micro void defects, the resin injection step requires to be optimized. Numerical and experimental approaches were used to optimise the design of a mould and the associated process parameters. The influence of the mould design, as well as the processing parameters such as the injection pressure or the imposed flow rate upon the number, the position and the size of possible defects have been evaluated.

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