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In-plane permeability changes of plain weave glass fabric induced by tufting

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The presence of the tufts has direct influence on the permeability of textile preforms. In this paper, new insights are presented into the mechanisms responsible for changes to the in-plane permeability of tufted preforms according to three different tufting patterns relative to flow direction with a constant tufting distance. The saturated permeabilities are measured based on the rectilinear flow in a tool constituted by a steel base, a transparent PMMA top, and steel supports. Beforehand, the permeability measurements of textile preform composed of eight layers of plain weave glass fabric without tufting are conducted at three different cavity heights. The results show that the in-plane permeability values for the tufted preforms are lower than the permeability values of the preform without tufting. The paper reveals the significant influence of the tufting patterns on the permeability values for three different fibre volume fractions.

Keywords: preform; three-dimensional reinforcement; permeability; liquid composite moulding

1. Introduction

The tufting is a popular method of localized Through-Thickness Reinforcement (TTR) for dry preforms. As the use of TTR is rising, stitching methods have become high priority research fields. Conventional stitching (e.g. two interlocking threads) was proven to be very effective for damage resistance. In its present form, however, it requires high capital cost due to the complexity of sewing machine, and also access to both sides of the preform being reinforced to the interlock threads. More recently, a number of stitching technologies have been exploited, such as one-side stitching methods, which need access only to a single side of the preform.

The simplest version of the one-side stitching methods is tufting, and it is particularly designed for the dry preform of Liquid Composite Moulding (LCM) [1]. The insertion of tufts into the assembly of textile preforms results in enhanced mechanical properties of laminated structures (e.g. the impact or delamination behaviour) [2]. The reader is referred to Gnaba *et al.* [3] for a detailed analysis of the literature on the tufted three-

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dimensional structures and their influence on the mechanical properties of composites. Owing to easy process ability, handling, and draping by building up a complex net shape preform geometries [4], it also reduces the Liquid Composite Moulding (LCM) cycle times [5]. This therefore helps materialize an increase in the use of composites.

The influence of tufting process and tufting yarn on the mechanical characteristics of laminates has been widely addressed [6–11]. It is also common sense that the presence of additional solid phases in a preform alters the composite manufacturing processes [12–14]. For instance, the goal in LCM processes where a fibrous preform is compacted to a desired thickness is to have the resin fill all the empty spaces between and within fibre tows completely in the shortest time. Crucially, the calculation of the pressure field (and consequently the flow front positions at each instant) is highly dependent on the quality of the permeability inputs, which are provided for the mould filling simulations [15]. The insertion of additional yarns, via a single needle, through the thickness direction of a reinforcement stack increases the local fibre volume fraction [16,17], and hence, raises the possibility of showing local perturbations of the spatial geometry to textile permeability. Successful adoption of tufting as a through-the-thickness methodology for real-life composite component manufacturing necessarily requires the development of comprehensive knowledge about any implication that the presence of tufts might have on the resin injection stage.

2. Previous works and objectives

The vast majority of studies on the permeability of preform with through-thickness reinforcement focus on conventional stitching of non-crimp fabrics (NCFs). These studies revealed significant influences of the stitching yarn on the permeability of NCFs. The in-plane permeability components of stitched preform are very sensitive to mesoscale variability due to the gap variation (inter-yarn channels), confirming that the size of an inter-yarn channel will vary significantly along a yarn path, due to the periodic presence of the stitch [18,19]. Chiu and Cheng [20] showed lower in-plane permeability in the warp direction (0°) of multi-layer multi-directional warp knit (MMWK) preform stitched by Kevlar fibres, K_1 , with the existence of stitches than that without stitching. Meanwhile, the existence of stitches had little or no effect on the in-plane permeability in the weft direction (90°), K_2 of the same preform. The reason for no effect on K_2 was explained by the flow direction relative to the stitching patterns. The stitches hinder the fluid from flowing toward the 0° direction, and hence the fluids tend to flow along the stitching direction (90°). A similar conclusion was reached by Riber and Mitschang [14] for seven and ten layers of a glass twill weave textile stitched by a polyester core spun yarn. On the other hand, the transverse permeability of the stitched preform increases as compared to that without stitches [21,22]. When comparing the microstructure of the stitched and unstitched preforms, the flow channels created by the stitching allow the liquid easily pass through [23].

A shift from two interlocking threads towards tufting is likely to pose additional challenges to the impregnation process. The block of tufts can cause localised air entrapment during in-plane impregnation of the preform whereas they may enhance through-thickness resin flow due to the formation of flow channels by tufting loops. There have been very few experiments reporting permeability results of tufted preform. Rimmel *et al* [24–]. observed that tufting of preforms fabricated by dry fibre placement led to an increase in out-of-plane permeability. However, their work did not cover the relevance of the tufting

pattern nor the questions about the influence of tufting on in-plane permeability. There has been a study designed by Song [23] to address the influence of the tufting distance and density on the in-plane permeability of tufted five-harness satin woven carbon fabric, where tufting is normal to the surface of the reinforcement. The observation followed a similar trend noted by the permeability results of stitched preform: a reduction in in-plane permeability, K_I , corresponding to the tufting distance of 5 mm. His results strengthened the understanding that the density and direction of the tufting thread relative to flow direction can affect permeability values. However, the author did not specify how the tufting pattern relative to flow direction would change the magnitude of permeability components.

This work aims to study the influence of the tufting pattern on the flow behaviour of the injection fluid, where we assess the in-plane permeability of tufted preform against thoroughly characterised in-plane permeability of plain-weave glass fibre preform without tufting. In particular, the difference between the classical two-sided stitched preforms and the one-sided tufted preform is investigated in terms of the influence of stitching or tufting pattern on the in-plane permeability. The permeability measurements of preforms with and without tufting are conducted at three cavity heights (1.1, 1.0, and 0.9 mm), corresponding to fibre volume fractions (V_f) of 46, 50, and 56 % without counting tufting fractions, correspondingly.

3. Materials and experimental methods

As part of the development of tufted preform and in order to make a comparison study, the experiments were carried out at two stages: (1) permeability measurements of textile preform composed of eight layers of a plain weave glass fabric without tufting, 2) permeability measurements of a stack of two identical preforms, in which each preform composed of four layers of the plain weave glass fabric was tufted through-thickness with 67 Tex or 1000 carbon filaments. The tufting thread was supplied by Schappe techniques Company.

3.1. Textile

A plain weave glass fabric with an areal weight of 160 g/m² from HEXCEL (Figure 1) was used for the in-plane permeability measurements. The textile is a balanced fabric with the linear density of 68 Tex with 11.8 yarns per cm in the warp direction and 10.7 picks per cm in the weft direction.

3.2. Tufting

An overall of three tufting patterns relative to the flow direction with the same tuft distance (Figure 2) were applied to four layers of the plain weave glass fabric. The four layers of the fabric were sewn with the carbon. In Figure 2, the tufting step, S , represents the distance between two points of insertion of the needle. The distance between rows of tufts is represented by the distance D . For all tufted preforms, the tufting step (S) and the distance (D) were fixed as 10 mm. The tufting was made with the needle with a diameter of 2 mm. The pressure applied on the needle during the tufting process was 2.5 bar.



Figure 1. A plain weave glass fabric.

3.3. *Experimental set-up*

A photo of the experimental set-up is shown in Figure 3. The in-plane permeability components, K_1 , K_2 , were obtained by visually observing the flow front in a rectilinear flow experiment. The tool used for these measurements consisted of a steel base mould ($800 \times 270 \times 40 \text{ mm}^3$) with a transparent PMMA top tool. The transparent top mould helps us to understand how the tufting patterns can potentially influence the flow patterns. A dry preform ($110 \times 250 \text{ mm}^2$) was placed on the steel block and within metallic spacers. The spacers controlled the fibre volume fraction. In order to meet the acceptable limit of the mould deflection, i.e. 2% of the nominal thickness of the mould [26], four 50 mm thick steel supports were placed on the top of the PMMA block and compressed towards the spacers by eight bolts. The area around the inlet was kept empty to ensure a uniform liquid pressure on the sample boundary.

3.4. *Permeability measurements by rectilinear flow experiments*

All the permeability measurements were carried out on preforms with eight layers. We employed three cavity heights of 1.1, 1.0, and 0.9 mm, corresponding to the fibre volume fractions of 46%, 50%, and 56% without counting the tufting fraction for the case of tufted preforms, respectively. In order to take into account statistical variance of the results, for each of the three cavity heights with or without tufting, experiments were repeated three times. For the saturated permeability measurements, the mineral oil was injected into the compacted preform under constant injection pressure of 1 bar. The fluid viscosity determined using a BROOKFIELD DV1 viscometer at five different temperatures are plotted against temperature in Figure 4.

In the saturated version of permeability measurements, the preform was first completely saturated with the fluid and then pressure differences between the inlet and outlet (Figure 3) were measured by using pressure transducers. A balance with an accuracy of 0.001 g was placed at the mould exit to record the liquid mass. The balance was zeroed at the onset of injection and it continuously measured the mass of the liquid. Mass flow rate

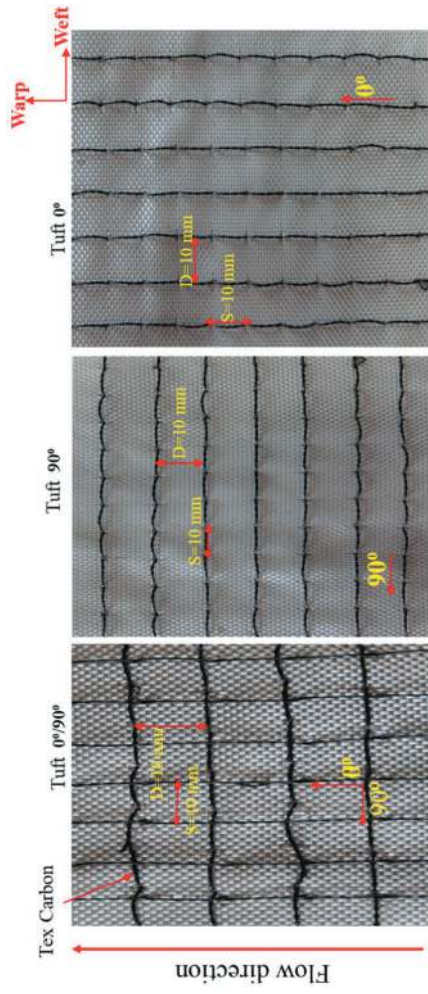


Figure 2. Tufted four layers of the fabric with a $2 \times 1 \times 1 \text{ K} \times 67 \text{ Tex}$ carbon thread: 0° and 90° are the tufting directions relative to the flow direction.

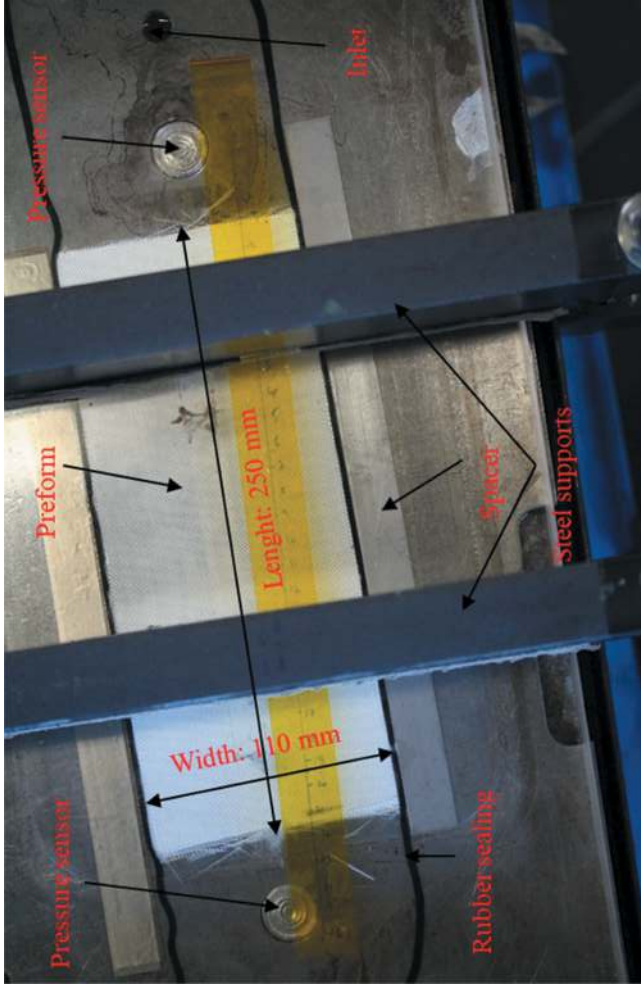


Figure 3. The in-plane permeability measurement set-up.

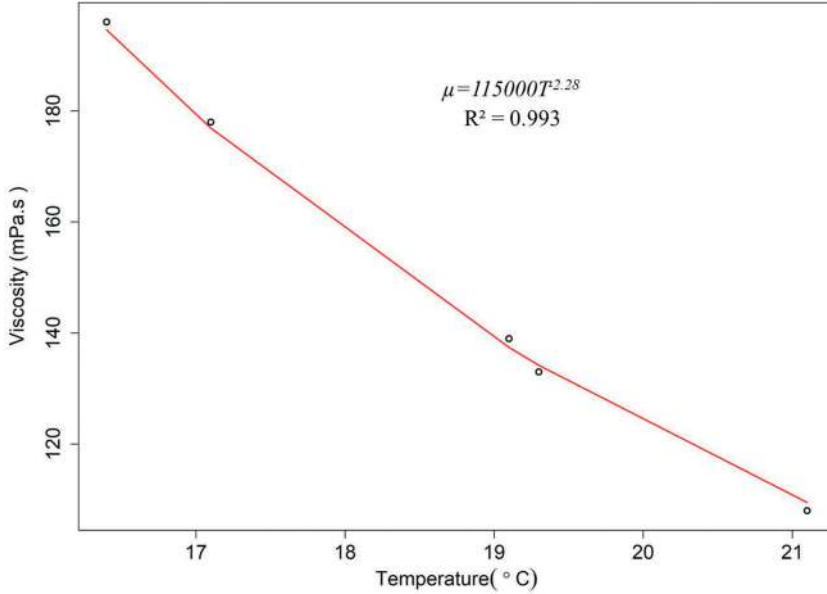


Figure 4. Testing fluid viscosity (μ) versus temperature (T).

was calculated using the acquired liquid mass and time data. Additionally, the density of oil (875 kg/m^3) was used for calculating the volumetric flow rate (Q). The saturated permeability components, $K_{\delta=1,2}$ were then calculated from one-dimensional version of Darcy's law:

$$\frac{Q}{A} = \frac{K_{\delta=1,2} \Delta P}{\mu L} \quad (1)$$

where Q is the volumetric flow rate, A is the cross-sectional area of the porous medium, μ is the dynamic viscosity of the liquid, and ΔP is the pressure difference over the distance L .

4. Results and discussion

4.1. Permeability evaluation of textiles without tufting

The aim of the evaluation was to determine the dependency of permeability on fibre volume fraction and a possible influence of fibre volume fraction on the permeability scatter. In Figure 5, the in-plane permeability components are plotted versus the fibre volume fraction. The values of K_1 and K_2 are approximately equal, particularly for the small cavity height. In fact, for the low fibre volume fraction, the larger difference of permeability between K_1 and K_2 may be due to more possible arrangements for fibres in a yarn.

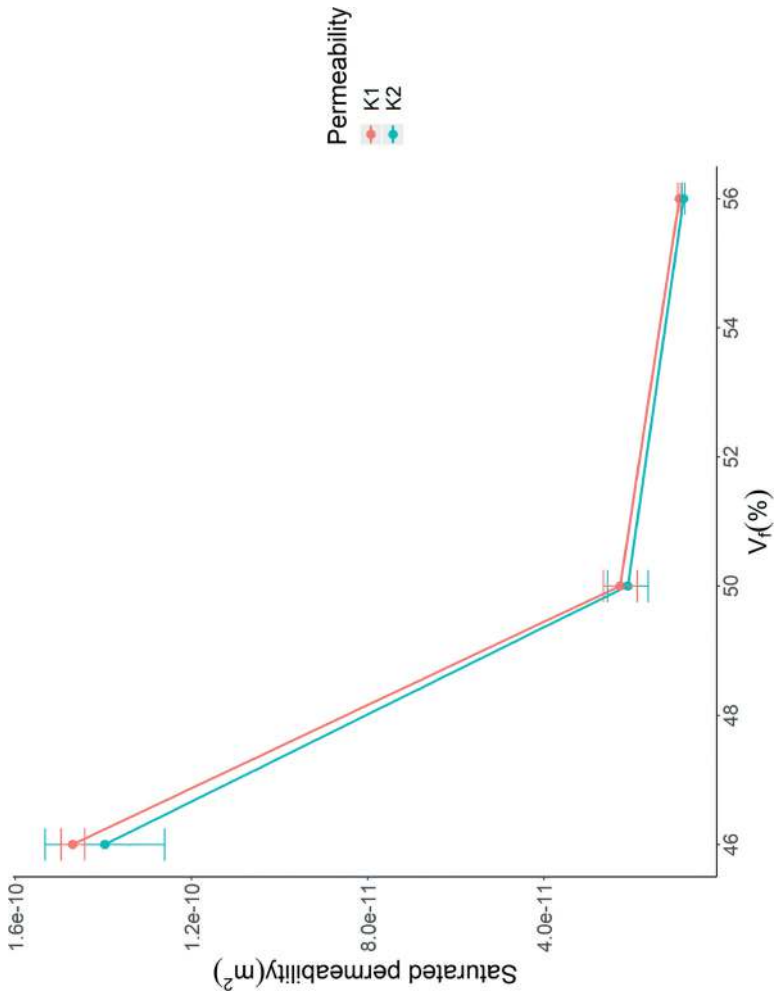


Figure 5. Saturated permeability data $K1$ (red line) and $K2$ (blue line) at three different fibre volume fractions for the preform without tufting.

4.1. Permeability evaluation of textiles with tufting

A comparative bar graph is used to compare the permeability of the preform with and without tufting. Figure 6 shows the permeability values for the tufted preforms are lower than for the preforms without tufting, at three fibre volume fractions of 46, 50 and 56%.

It is noticeable that the in-plane permeability of tufted preform is lower than that of untufted preform regardless of the relative direction between the flow direction and the tufting direction, whereas it has been reported in the literature [14,20–22], the in-plane permeability in the stitching direction of stitched preform is the same as or slightly greater than that of unstitched preform. During the classical two-sided stitching process, both the needle and the stitching thread pass through the preform and exit completely to the other side of fabric while applying normal pressure, which compresses locally the preform. Then, the stitching thread returns to the initial side of fabric when the needle retreats. As a result, the stitching thread ties the yarns firmly, which are locally compressed and a flow channel is created along the stitching thread. The stitching process can have two competing effects on the permeability of a preform. The stitching thread may increase the permeability by locally compressing the yarns to create a flow channel. Meanwhile, it may decrease the permeability by occupying the volume of the inter-yarn flow channel and blocking the resin flow. In the case of the two-sided stitching, these two competing effects are offset or the influence from the creation of a flow channel by local compression of yarns to the change of permeability is slightly greater than that from the reduction of the inter-yarn channel size. It should be noted, however, that only the permeability in the stitching direction is increased or conserved whereas that in the other direction is decreased by the stitching thread which blocks the resin flow in the inter-yarn channel.

Conversely, during the one-sided tufting process, the needle does not go through the preform completely, even if the preform is compressed. When the needle retreats, the friction between the tufting thread and the fibres in the fabric makes some part of tufting thread remain at the other side of preform while making a loop [1]. As a result, the preform is loosely tied by the tufting thread and the compressed yarns are relaxed partially or completely to return to the initial state. Hence, because there is little influence from tufting threads on the shape and size of yarns, the permeability is governed by the volume of tufting threads, which block the resin flow.

As Figure 6 reveals, however, it is also evident that tufting pattern may influence the magnitude of permeability of tufted preform. The effects of tufting pattern decreases as the fibre volume fraction increases. At the fibre volume fraction of 46%, the permeability of tufted preform with tufting direction of 0° (parallel to flow direction) is reduced by 35% compared to the permeability of the preform without tufting. This reduction in permeability of tufted preform is more pronounced for the grid tufting pattern ($0^\circ/90^\circ$). The tufting pattern in flow direction (Tuft 0°) yielded higher permeability values than the tufting pattern perpendicular to flow direction (Tuft 90°) and the grid tufting pattern (Tuft $0^\circ/90^\circ$). Interestingly, when fibre volume fraction increases, there is a small difference between permeability values of different tufting patterns. As fibre volume fraction increases, further decreasing of the inter-yarn channels is limited by the presence of the tufting thread and thus there is a slight further decrease of permeability for higher fibre volume fraction. Therefore, the difference in permeability of different tufting patterns will decrease with increasing fibre volume fraction.

The reason for the change in permeability values with tufting pattern can be explained by the change in flow direction according to the tufting pattern. In the first

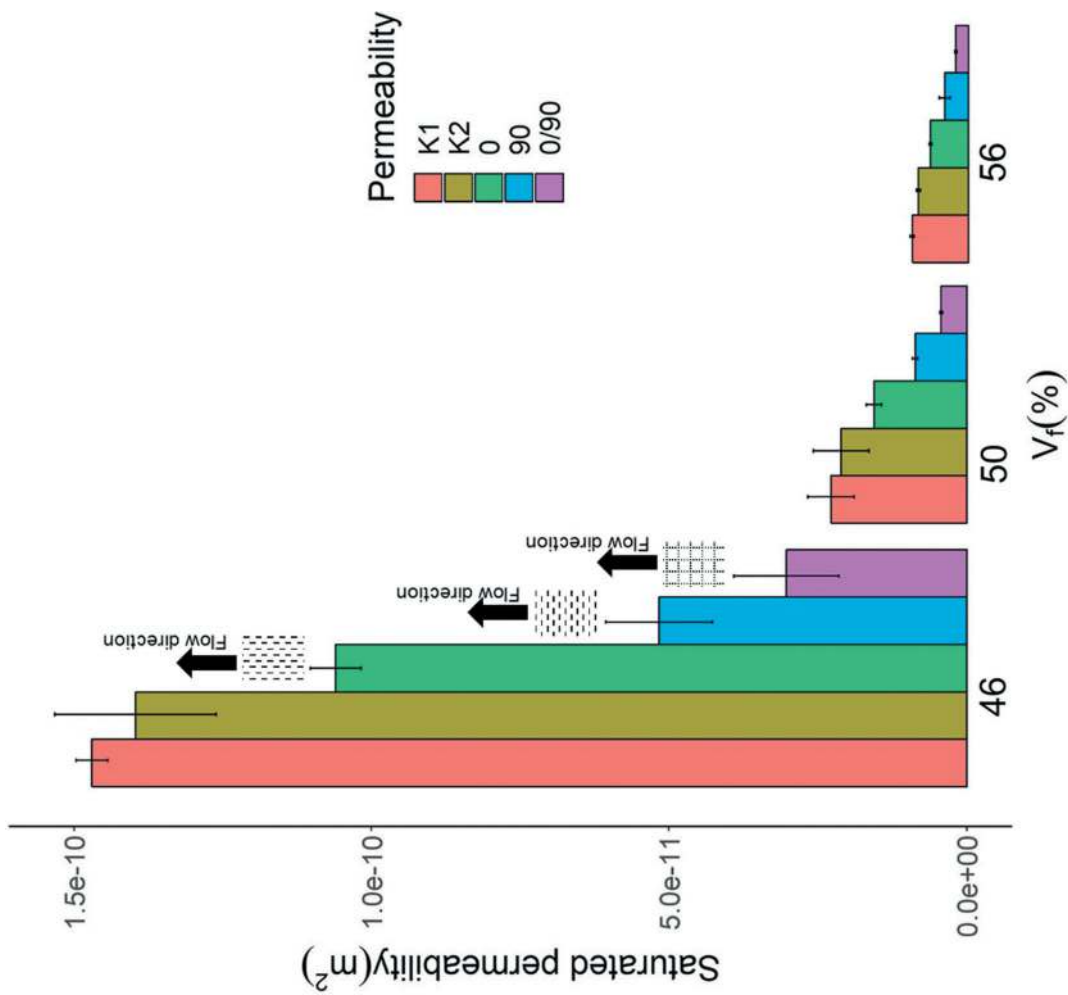


Figure 6. A comparative bar graph of saturated permeability against three different fibre volume fractions for both preforms with and without tufting.

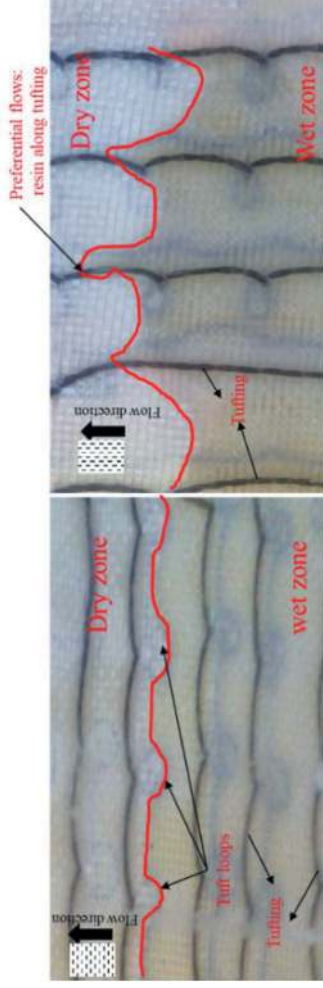


Figure 7. Flow patterns relative to tufting directions: flow direction perpendicular to tufting pattern 90° (left) and flow direction parallel to tufting pattern 0° (right). The experiments were carried out at the fibre volume fraction of 46% with the fluid viscosity of 143 mPa·s.

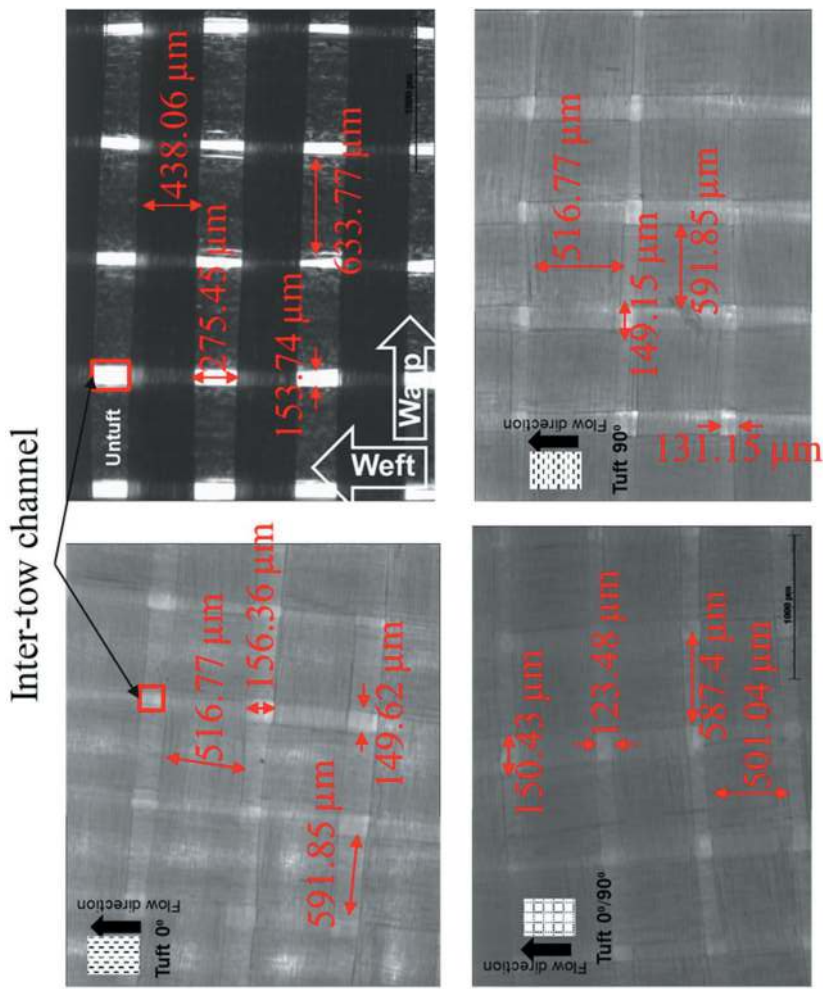


Figure 8. Microscopic surface images of preforms with different tufting patterns.

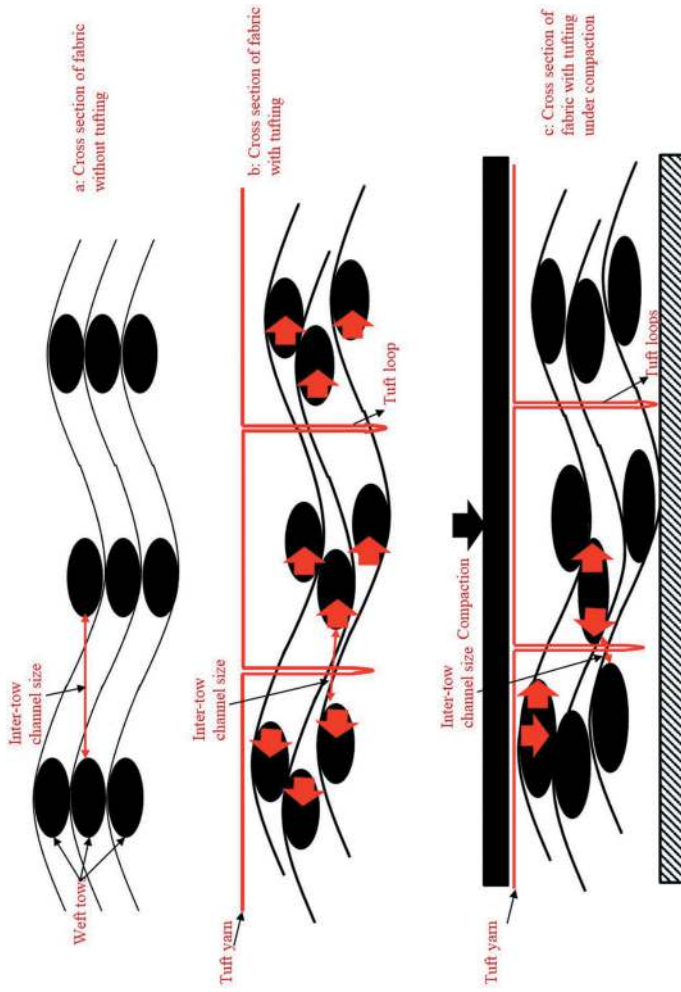


Figure 9. Schematic illustration of main deformation mechanisms of a fabric with tufting. (a) cross section of fabric without tufting, (b) arrows indicate that the tufts push fibre yarns, (c) arrows indicate that yarn become elliptical with a higher aspect ratio under compaction.

stage, the tufting can be considered as barriers, which are hard to cross and redirect the fluid flow. The tufting pattern (90°) perpendicular to the flow direction will act as a wall where the fluid has difficulty in penetrating outward. This block of tufts causes the fluid near the tufting zone to flow toward the 90° direction (Figure 7 left). On the other hand, as shown in Figure 7 right, the tufting pattern parallel to fluid flow causes preferential flows occurring near the tufting zone, and hence an increase of permeability. In the case of the grid tufting pattern, the tufting density seems to govern the permeability. The volume of flow channels for the fluid to flow is directly related to the tufting density. The permeability of the preform with the grid tufting pattern is therefore lower than that of the two other tufting patterns.

In Figure 8 where the microscopic images of untufted and tufted preforms are shown, the size of inter-yarn gap of tufted preforms is smaller than that of the untufted preform. As aforementioned, the influence of the tufts on the change of shape and size of yarns may be relatively small. However, the tufts may alter the relative movement of yarns during the compaction stage of preforming in the mould. When compacting the tufted preform to a target fibre volume fraction, the tufts may push the fibre yarns to move and nest in such a way that it decreases the size of inter-yarn channels (Figure 8). Such a local nesting increases the fibre volume fraction in the vicinity of the tuft and changes the inter-yarn channel size, which decreases the permeability of tufted preform consequently. There are many possible ways of how adjacent layers will interlock because the peaks and valleys of the interfaces of the layers are not always going to fit exactly (maximum nesting).

The influence of tufting is significantly higher at low fibre volume fractions (46, and 50%). It is observed from Figure 6 that as fibre volume fraction increases the difference of permeability between preforms with and without tufting seems to decrease. This may be due to more possible arrangements for fibre yarns when the fibre volume fraction is low. The tufting yarn should be accommodated within the two dimensional fibre architecture of the preform without tufting (Figure 9a), and hence the local fibre volume fraction is increased (Figure 9b). The accommodation of the extra yarn in the fixed size cavity mould is likely to require excessive preform compaction, which may increase the local fibre volume fraction in the vicinity of the tuft (Figure 9c) [1]. Hence, the presence of tufts increases the required compaction pressure of the tufted preform to obtain the same thickness as the preform without tufting. The continuous fibres should rearrange themselves within the plies to accommodate the tuft threads and loops. As the fibre volume fraction increases, the fibre yarns will move closer together and will be constrained in their arrangement. Further increase in the fibre volume fraction packs the fibres together. This packing provides a less tortuous path for liquid flow. Thus, the difference in the values of permeability of preforms with tufting and without tufting decreases with increasing fibre volume fraction. Because these are dominant for the overall permeability behaviour, the reduction of permeability is greater for the grid tufting pattern where the tufting density is higher than tufting pattern 0° and tufting pattern 90° . Therefore, it can be concluded that the tufting density is the dominant factor in determining permeability components.

It follows from the aforementioned discussion that the presence of tufts in a textile preform is expected to influence the resin flow and impregnation. When the Resin Transfer Moulding (RTM) process is considered, given that the cavity height of the mould is fixed, various fabric layer interfaces should mesh with each other to accommodate surface tuft threads and loops and through the in-plane direction with the yarns

shifting by the tufts. The knowledge gained here has clearly shown that a correct evaluation of the local variations of fibre volume fraction becomes critical, particularly in the vicinity of the tufts. We plan to investigate this topic in future work. This will shed more light on which parameters in tufted preform production such as the reinforcing fibre content, in-plane fibre content, and anchorage of the tuft loops influence the resin impregnation process and help develop tighter controls on them to improve repeatability in the production process.

5. Conclusion

The influences of tufting on in-plane permeability of a plain weave glass fabric were studied. The in-plane permeability of untufted and tufted preforms was determined in rectilinear flow experiments at three different fibre volume fractions (46, 50 and 56%). The measurements regarding the influence of the tufting patterns on the permeability were also performed at the three different fibre volume fractions. A total of 45 experiments were transferred into the permeability values and the following features were observed:

- (1) The tufting reduces the permeability in comparison with the preform without tufting regardless of tufting pattern, whereas it has been reported in the literature that the classical two-sided stitching has little or no influence on the in-plane permeability in the stitching direction. It appears that the insertion of extra tuft threads through-the-thickness direction of the preform significantly influences fibre packing arrangements, yarn waviness, and yarn cross-section shapes.
- (2) It was shown that, as the fibre volume fraction increases, the reduction of permeability becomes more significant if compared with the preform without tufting. Tufting will increase the local fibre volume fraction, which reduces the permeability in that region. This will be more pronounced at higher fibre volume fraction where there is smaller space for the extra yarns to be accommodated within the textile preform in the fixed sized cavity mould. This will have a direct impact on the resin impregnation of the part.
- (3) It was also observed that the effect of tufting patterns increases at an increased permeability, i.e. at a lower fibre volume fraction. The grid tufting pattern resulted in the lowest permeability due to the larger number of tufts. When the fibre volume fraction was increased, however, it was found that the permeability values of different tufting patterns converged.
- (4) It is likely that tufts may decrease the in-plane permeability of any kind of textile weaving patterns as well as of the plain weave tested in this work, where the yarns are loosely tied by the tufting threads. Nevertheless, the influence of the tufting threads on the nesting behaviour, which is the other main factor to alter the permeability of preform, may depend on the weaving pattern. Hence, further investigation is still required to verify this speculation and this issue will be carefully addressed in the future work.

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Disclosure statement

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