Full Characterization of a Stitched Twill Weave Textile by Unsaturated 2-D and 3-D Permeability Measurements

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SUMMARY
In this paper the influence of stitching seams on the 2-D and 3-D permeability are presented. The 2-D measurements are conducted with lineal capacitive sensors; the 3-D measurements are conducted by ultrasound time-of-flight technique. The paper will reveal the significant influence of the stitching seam distance on the permeability values K1 and K2. The difficulties of the 3-D permeability measurement of stitched textiles are described.

Keywords: permeability, 2-D and 3-D permeability measurement, Resin Transfer Molding (RTM), stitching

INTRODUCTION
Textile preforming is stitching, cutting, and assembling of reinforcement textiles to enhance mechanical properties or optimize the RTM-tool loading. Preforming reduces manual work and therefore cuts liquid composite molding (LCM)-cycle times and costs [1, 2]. The influence of the stitching process [3, 4] and the stitching yarn on the mechanical characteristics [5, 6] of laminates are widely examined. Only relatively few research work is published concerning the processability of stitched preforms [7, 8]. The influence of 5 different stitching seam distances on the permeability is described in this paper. Beforehand a pre-evaluation of the textile without any stitching has been conducted. The study revealed the influence of the fiber volume fraction on the anisotropy.

MATERIALS & METHODS
Glass fiber twill weave textile
The preforms consist of seven and ten layers of a glass fiber twill weave textile (390 g/m²) from Schloesser & Cramer (art. no. 3106) equipped with a finish for epoxy resin (K 506). The textile is built-up anisotropic: the linear density in weft direction is 272 tex with 6.7 yarns (picks) per cm, the linear density in warp direction is 68 tex x 5 t0 (multiple wound yarn) with 6.0 yarns (picks) per cm. The measurements regarding the influence of the stitching seams on the permeability are conducted at two cavity heights.
2-D Permeability measurement cell
The permeability measurement cell consists of 8 capacitive linear sensors integrated in stellar arrangement around a central injection port in a matched metal tool [9]. The thickness of the aluminum tool is 160 mm on each side to guarantee a deflection-free measurement. Direct conclusions can be drawn from the output signal of the sensors to the position of the flow front as there is a linear relationship between the (by injection-fluid) covered sensor area and the measured capacity values [9, 10]. The flow front values taken over a length of 185 mm (1 sensor) in 8 directions are averaged and an ellipse is calculated on top of these data. The permeability algorithm is based on the one developed by Douglas et al. and Adams et al. [11, 12]. The operation and data acquisition is executed with LabView®.

3-D Permeability measurement cell
The permeability measurement cell consists of a lower ultrasound sender and an upper ultrasound receiver (Figure 1). The reinforcement textile layers are placed in between. On top of these layers is a PMMA disc to monitor the arrival. The injection fluid used is oil. The measurement is based on the fact that the velocity of the ultrasound is faster guided through oil than through air. The higher the flow front height, the shorter the time of flight of the ultrasound signal. An average K1 and K2 value is determined by the mass of the injected oil. The calculation is based on the one by Weitzenböck [13]. The cavity height is 8 mm. Due to restrictions in the transmission of the ultrasonic signal and influencing errors of the inlet geometry only this height can be realized.

Figure 1. 3-D permeability measurement cell positioned on a scale accurate to 0.1 g
Pre-evaluation of textiles without stitching

The goal of the pre-evaluation of the plain textile (without stitching) was to determine: the fiber volume fraction-permeability-dependency, the influence of the cavity height on the permeability, and a possible influence of the fiber volume fraction on the anisotropy of the glass fiber textile without stitching. These results are shown in Figure 2 and 3, both Figures are based on the same data. In Figure 2 the K1 and K2 values for 4 different cavity heights are plotted versus the fiber volume fraction. As expected, there is a linear dependency of the fiber volume fraction on the permeability, when the permeability is plotted logarithmically, the typical Kozeny-Carman relationship. The permeability values, K1 and K2, are about the same for all four cavity heights over the evaluated fiber volume fraction range (Fig. 2).

![Figure 2. Permeability data K1 (upper lines), K2 (middle lines) and K3 (lowest line) plotted against the fiber volume fraction. K1 and K2 results are measured at 4 cavity heights each (1.95 mm, 2.97 mm, 3.95 mm, 6.00 mm)](image)

The anisotropy, the relation of K2 divided by K1, changes over the fiber volume fraction. This can be seen as the slopes of K1 and K2 are not parallel. The flow front changes its shape with increasing fiber volume fraction.

K3 is lower by a factor of 10 in comparison to the in plane permeability K2. This is in agreement with the literature results of woven textiles. The permeability in through the thickness direction, K3, cannot be measured for fiber volume fractions below 50 %. For the glass fiber twill weave textile used the compaction pressure for fiber volume fractions below 50 % is too low for a reproducible ultrasound signal.

The pre-evaluations results can be summarized as followed:

- K1 and K2 are independent of the cavity height.
- The anisotropy, K2/K1, is a function of the fiber volume fraction. Anisotropy values therefore should be only compared with the same fiber volume fractions.
• K3 is lower than the K2 permeability by a factor of 10.

In Figure 3 the impregnated area per unit of time, which can be titled global permeability as well, is plotted versus the fiber volume fraction. The decrease over the fiber volume fraction is typical and fulfills Kozeny-Carman equation. Additionally, the decreasing anisotropy is displayed on the right with drawn ellipses.

\[ y = 83172e^{-0.1681x} \]

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Fiber Volume Fraction

0,59

Anisotropy:

0,53

0,48

0,43

0,38

Figure 3. Impregnated area per unit of time plotted versus the fiber volume fraction. On the right the shape of the flow front, the anisotropy (K2/K1), is displayed

**Stitching Process**

An overall of eight stitching patterns have been applied to ten and seven twill weave layers with a modified double lock stitch (see Table 1).

<table>
<thead>
<tr>
<th>Version no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stitching pattern [°]</td>
<td>without</td>
<td>-45°</td>
<td>-45°</td>
<td>-45°</td>
<td>-45°</td>
<td>-45°</td>
<td>+/-45°</td>
<td>+/-45°</td>
<td>+/-45°</td>
</tr>
<tr>
<td>Seam distance [mm]</td>
<td>stitching</td>
<td>7.5</td>
<td>10</td>
<td>12.5</td>
<td>15</td>
<td>20</td>
<td>7.5</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

Ten layers have been measured at a cavity height of 3 mm resulting in a Vf of 51.5 %. Seven layers have been measured at a cavity height of 2 mm resulting in a Vf of 54.9 %. The stitching patterns applied can be seen in Figure 5. The stitching yarn tension was set to 45 cN for the needle thread and to 110 cN for the bobbin thread. With these tensions no resin rich areas are created in the area of the stitching hole. This has been revealed by cut polished images (Fig. 4).

Figure 4. Cut polished images showing the stitching yarn inside the laminate (height: 3mm); left: high stitching seam tension (resin rich areas are emphasized); right: low stitching seam tension
RESULTS  

Stitching pattern $+45^\circ$  

In the following $K_1$ is displaying the first main axis (longer axis) of the flow front ellipse and $K_2$ the second main axis of the ellipse as shown in Figure 5. $\alpha$ is displaying the anisotropy, i.e. the relation $K_2/K_1$, $\beta$, is displaying the angle of orientation of the ellipse against the textile warp direction. In the following diagrams the permeability measurement results ($K_1$ and $K_2$) are displayed for each stitching seam distance. The following Figure presents the influence of the $+45^\circ$-stitching pattern on the orientation of the flow front ellipse (Figure 6).

Figure 6. Orientation angle plotted against the stitching seam distance of the $+45^\circ$ stitching pattern for 51.5 % Vf and 54.9 %Vf

The influence of the stitching seam distance on the orientation angle of the flow front ellipse is pronounced. As for the $K_1$ and $K_2$ values, the orientation angle is more
affected at the lower fiber volume fraction. The orientation of the flow front ellipse for the textile without stitching is in the direction of the weft yarn, at 0°. With a decreasing stitching seam distance the reorientation of the flow front ellipse towards the direction of the stitching seam increases. The main axis of the flow front turns into the direction of the stitching seam (45°). This is resulting in a more isotropic flow front as the short flow front \(K_2\) stays constant. At a fiber volume fraction of 51.5 % the maximum stitching-influenced orientation is 33° (at a stitching seam distance of 7.5 mm). At the same stitching seam distance but at a fiber volume fraction of 54.9 % the stitching-influenced orientation is 20°. The orientation of the stitching seam has been 45° as shown in Figure 5.

**Stitching pattern +/- 45° (stitching grid)**

The flow front shape becomes more circular as the seam distances are getting smaller. If the stitching grid is applied with a seam distance of only 7.5 mm the flow front is almost circular.

![Graph](image)

**Figure 7.** Anisotropy plotted versus the stitching seam distance of the +/- 45° stitching pattern for a \(V_f\) of 51.5 % and 54.9 %

**Limitations of measuring stitched textiles with ultrasound**

It was not possible to measure stitched samples with the current set-up. As described above the flow front height is measured by the time-of-flight method by ultrasound. Knowledge of how much fluid has flown in the in-plane direction is drawn by the measurement of the injected volume and necessary for the follow up calculation. The formula

\[
r_{2D,3D} = \sqrt{\frac{3 M_{el}}{2\pi \rho \phi z_f}}
\]

describes the average propagation in \(xy\)-plane. The coordinate \(r_{2D,3-D}\) can be determined with the flow front height \(z_f\) and the injected mass \(M_{el}\). This formula is only valid for an ellipsoidal flow front shape. Even though the stitching tension has been at the lower limit, race tracking has been observed during the measurement (Figure 8). This has been confirmed by resin injections with polyester resin. Polyester resin has been chosen as the gel time can be adjusted quite exact.
DISCUSSION

For a seam distance of 7.5 mm the global permeability (sqrt (K1xK2)) is reduced by 33 % by the insertion of the stitching yarn in comparison to the unstitched fabric. This can not be explained with the increasing Vf due to the diagonal stitching seam. The increase in Vf is only 0.8 %, 0.24 % respectively for a stitching seam distance of 20 mm. The stitching seams can be regarded as obstacles that are hard to cross and redirect the injection fluid. A similar conclusion has been made by Chiu and Cheng [14], they stated, the stitching zone will act as a wall where the fluid has difficulty penetrating through. Talvensaari [8] applied the same +/-45° stitching pattern to a preform, but her study revealed an increase of the global permeability with a lower stitching seam distance (i.e. higher stitching density). This disagreement is most likely due to the fact, that the needle thread tension of the stitching machine was set 5 times as high as in this study. At a high stitching thread tension flow paths are created. The influence of the stitching seams for both patterns has been lower at the higher fiber volume fraction. This is in agreement with Hu, Liu, and Chao [7]. They performed numerical simulations with a unit cell with a straight column constituting the stitching yarn. This study revealed that the effect of the stitches increases at an increased permeability, i.e. at a lower fiber volume fraction. The linear relationship that has been investigated by [7] could in this study only be confirmed for the diagonal stitching pattern. For both stitching pattern, +45° and +/-45°, the preforms show more isotropic behavior with decreasing seam distances, i.e. with an increasing stitching density. This finding agrees with [14] even though Chiu and Cheng worked with NCF fabric and the stitching seam direction was 90°. This behavior is more pronounced for the grid pattern than for the diagonal pattern. Even though the direction of K2 is changing by up to 32° the permeability value K2 stays constant for the diagonal and grid stitching pattern over all seam distances. The K2-value in [14] was not influenced by different stitching seam distances as well. The average standard deviation in our study has been 12 % for the measurements at the fiber volume fraction of 51.5 % and a little lower for the higher Vf of 54.9 %.
CONCLUSION

The resin flow in LCM processes is highly affected by stitching seams. The ellipse orientation as well as the shape is influenced even at low stitching thread contents (e.g. diagonal stitching pattern; seam distance of 20 mm). The lower the stitching seam distance the more the global permeability is reduced and, if the stitching seams are not running in the K1-direction, the higher the anisotropy. Using only one stitching direction (+45°) the ellipse orientation is mainly affected. The closer the parallel stitching lines are the stronger the influence on the twisting of the ellipse’s longer axis towards the stitching direction. By using an orthotropic stitching (+/-45°) a circular flow is achieved at close seam distances. The ellipse orientation angle changes are more pronounced at the lower \( V_f \) (51.5 %). The effects of stitching on permeability are summarized in Table 2.

Table 2. Overview of the effects of stitching on 2-D permeability

<table>
<thead>
<tr>
<th>Stitching Pattern; ( V_f )</th>
<th>Global permeability (( \sqrt{K_1 \times K_2} ))</th>
<th>Anisotropy</th>
<th>Orientation angle</th>
<th>K1</th>
<th>K2</th>
</tr>
</thead>
<tbody>
<tr>
<td>+45°; 51.5 %</td>
<td>lower than the unstitched reference textile; no influence of the seam distance observed</td>
<td>increases with decreasing distance between seams</td>
<td>flow front ellipse is redirected from 0° (no stitching) up to 32° at a stitching seam distance of 7.5 mm</td>
<td>decreases with decreasing distance between seams</td>
<td>no effect observed</td>
</tr>
<tr>
<td>+45°; 54.9 %</td>
<td>basically lower than the unstitched reference textile; influence of seam distance undetermined</td>
<td>increases with decreasing distance between seams</td>
<td>flow front ellipse is redirected from 0° (no stitching) up to 24° at a stitching seam distance of 7.5 mm</td>
<td>decreases with decreasing distance between seams</td>
<td>no effect observed</td>
</tr>
<tr>
<td>+/-45°; 51.5 %</td>
<td>tendency to increase with decreasing distance between seams</td>
<td>increases with decreasing distance between seams</td>
<td>no effect observed</td>
<td>decreases with decreasing distance between seams</td>
<td>no effect observed</td>
</tr>
<tr>
<td>+/-45°; 54.9 %</td>
<td>tendency to increase with decreasing distance between seams</td>
<td>increases with decreasing distance between seams</td>
<td>no effect observed</td>
<td>decreases with increasing distance between seams</td>
<td>decreases with decreasing distance between seams</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

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References


