AN EXPERIMENTAL STUDY ON THE INFLUENCE OF FLOW CHANNEL INDUCED FIBRE UNDULATION.

Kracke, C.[1]; Staudt, B.[1]; Bickerton S.[2]; Mitschang, P.[3]

[1]BMW Group, Ohmstraße 2 84030 Landshut, Germany
Christoph.Kracke@bmw.de
Bernhard.Staudt@bmw.de
[2]Centre for Advanced Composite Materials, University of Auckland, Private bag 92019
1142 Auckland, New Zealand
S.Bickerton@auckland.ac.nz
[3]Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Str., Gebäude 58
67663 Kaiserslautern, Germany
Peter.Mitschang@ivw.uni-kl.de

Keywords: Effects of manufacturing effects, Resin transfer moulding, flow channels

Abstract

Resin Transfer Moulding (RTM) is one of the key manufacturing technologies for automotive carbon fibre reinforced plastic composite parts. Flow channels in the tool assist the resin distribution, since they decrease the longest distance the fluid has to flow through the preform and temporarily increase the flow front length. Hence, a well-designed system of flow channels can help to strongly reduce cycle times. Yet, the flow channels can also affect the mechanical properties. In this study the effects of flow channels on the mechanical part properties are investigated in a series of RTM plate manufacturing experiments. An influence of the flow channel cross section has been observed. The orientation of the fibres relative to the flow channel influences the movement of fibres into the flow channel. The experiments have shown that close to the injection point fibre undulation is worse than at the end of the flow channel. The observed fibre undulations correlate to a reduction of mechanical properties. The results help to reduce the influence of flow channels on mechanical performance of parts due to optimized flow channel attributes.

1. Introduction

To increase process stability and reduce the injection pressure needed to fill the mould, typical automotive Resin Transfer Moulding (RTM) tools not only have an injection point but also a resin distribution pattern consisting of flow channels integrated into the tool. Although flow channels across the part surface do not affect the permeability of the preform, they reduce the longest distance the fluid has to flow through the preform. Furthermore they temporarily increase the flow front length, since they act like an extended injection gate. In [1] different injection gate forms have been investigated, with the result that the length of the flow channel is particularly important. An influence of the flow channel cross section shape on the injection time has not been proven. While [2] and [3] show different approaches to optimize the layout of the flow channel distribution system, the cross section shape is not optimized. In [4] optimal cross section shapes for heated flow channels in injection moulds are discussed. In this work the optimal solution is a full circular channel shape. Since this requires exact shaping of both tool halves, a compromise solution, a one sided parabolic shape, is shown. In this work the focus is on industrial HP RTM processes. Therefore apart from the process requirements, the impact on the part properties, especially the part weight and mechanical performance, has to be considered.

Excerpt from ISBN 978-3-00-053387-7

2. Flow channel cross section and classification

This study focuses on the flow channels (FC) on the tool surface. The flow channels have the task to transport the fluid through the cavity and spread it into the preform. The flow through the flow channel can be described with the Hagen-Poiseuille equation. The estimated Reynolds number is below 1. Assuming the following values, fluid density ρ: 1kg/m^3, viscosity µ: 0,1Pa s, FC diameter d: 6mm and mass stream M: 25 gr/s. The increase in weight due to additional flow channels is a negative side effect, assuming the flow channels have no other purpose. The increase in weight is directly related to the cross sectional area of the flow channel. To compare different cross section shapes to each other and to the permeability of the fabric, an equivalent permeability K_{FC} is calculated with the Hagen Poiseuille equation (Eq. 1). The radius of the flow channel is r, the perimeter is P and the length of the flow channel is l_{FC}. For all non-circular cross-section shapes, the radius can be described using the hydraulic radius (ratio of the flow channel cross-section area and wetted perimeter). In (Eq. 1) the Hagen-Poiseuille is equated to the equation from Darcy's law. This leads to an equivalent permeability in (Eq. 2). The validity of an equivalent permeability has been shown in [5].

$$Q = -A \frac{r^2}{8\,\mu\, L} \Delta P \;\; = - \frac{K\, A}{x_f\, \mu}\, \Delta P \tag{1}$$

$$K_{FC} = \frac{r^2}{8} \tag{2}$$

Dividing the FC equivalent permeability by the corresponding cross-sectional area leads to a dimensionless factor (parallel to the pipe friction factor). While a circular cross section is not possible, since the fabric would divide the cross-section into two semi-circles, the parabolic cross-section is the next best cross-section shape. A different optimization goal (for example a limited height of the flow channel) may lead to a different optimal cross-section shape.

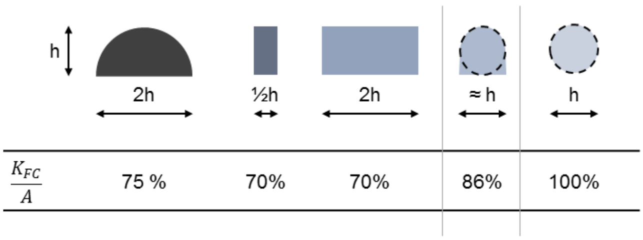

Figure 1. Comparison of different flow channel cross sections.

In the next step, with analogue to natural distribution patterns, a classification of the flow channels is possible. In regard to transport systems, two main optimization goals are important. First a sufficient supply of fluid is needed. In this case the FC, has to transport enough fluid to supply all subsequent routes with enough fluid. The next goal is to spread the fluid as efficiently as possible over the surface. The secondary flow channels do not need to have a large cross-section area. However, the position and course of the distribution channels is critical. This is very similar to the veins of a leaf. To sum up the general distribution pattern, the fluid comes from the injection point to the supply channels. The large supply channels provide the smaller distribution channels with sufficient fluid. In the next iteration, the fabric itself has a distribution system, consisting of the flow channels within the textile materials due to the stitching [6].

Excerpt from ISBN 978-3-00-053387-7

The previous explanations state that flow channels have a very positive influence on resin injection. Yet, they can also disturb the fibre structure: When looking at polished micrograph cross-sections of flow channels, an undulation of the reinforcing fibres can be observed. In Fig. 3 a typical undulation of the fibres within the flow channel is shown. All cross-sections in this work have the following in common, the undulation of the fibres is due to an increasing cross-sectional area of the rovings. The height of the roving in Fig. 2 is doubled compared to other rovings. This also leads to an undulation of load carrying layers, which might lead to decreased mechanical properties due to the induction of a three dimensional stress field [7].

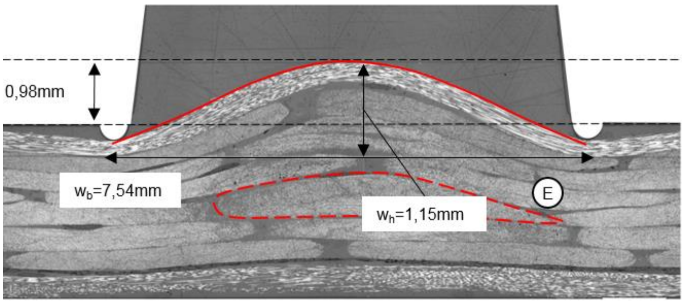

Figure 2. Example of fibre inwash into a flow channel cross sections.

3. Material and Methods

Based on initial observations, six parameters have been chosen for a series of RTM plate manufacturing experiments; FC cross-section area, (supply FC / distribution FCs), relative layup orientation to the FC orientation, clamping of the fibres next to the FC edges, position along the FC length, preform cut parallel to FC at the sides of the preform and the injection rate.

The main focus of the experiment is to show the influence of the FC cross-section area / shape in regard to the textile, and therefore these parameters are chosen for a full factorial design. In Fig. 3 the three FC cross-section shapes for the experiment are shown. One large supply channel, the same supply channel shape with a clamping line and five distribution channels parallel to each other have been chosen.

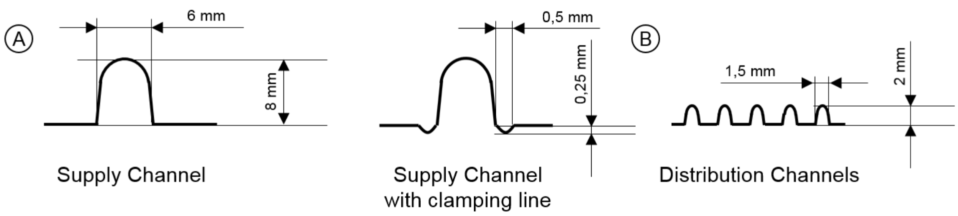

Figure 3: Classification of RTM-flow channel distribution systems.

For mould design it is important to know how fibre inwash evolves. While various hypotheses have been proposed, the influence parameters for fibre inwash are unknown. In the part factorial design more parameters are chosen for investigation (listed below), to screen for further influences on the creation of fibre inwash.

The layout of the manufactured plates is shown in Fig. 4. The experiment is devided into a full factorial design (parameters 1-3) and a part factorial design (1-6). The resulting fibre undulation in the manufactured test panels has been optically measured from images obtained from cross-sectioning, and the influence on the component properties has been evaluated with tensile tests orthogonal to the FC. In this work fibre undulation is defined as the ratio of the height w_h and the width w_b of the load carrying

Excerpt from ISBN 978-3-00-053387-7

90° layer. As defined in Fig. 2. The fibre inwash is defined as the total height of fibres in the flow channel and is not connected to any specific layer.

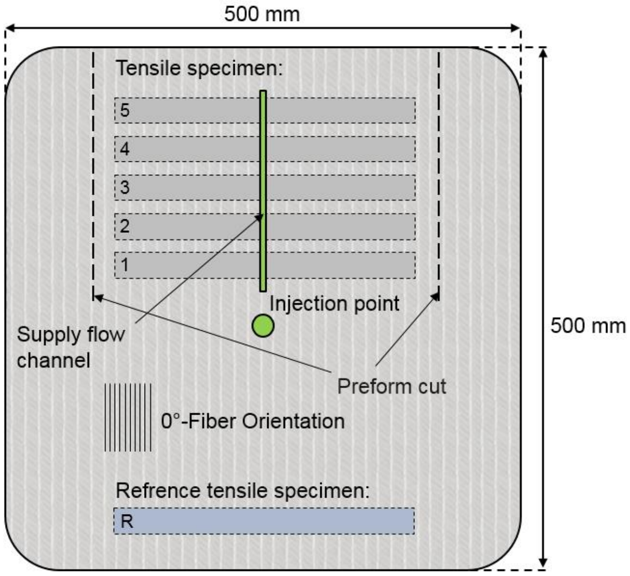

Figure 4. Schematic of experimental RTM platen layout

The FC configuration is distinguished by supply channels, and the five distribution channels. The dimensions of the flow channels are shown in Fig. 3. The five small flow channels are equally distributed along the free length for the tensile test [8]. The hypotheses for the cross-section area size is, that the fibre inwash into the FC is related to the cross-section area size and that the five small FC are therefore superior to the one single large supply channel.

The four applied preform layups have the same quasi isotropic set up, only the relative angle of the layup to the FC is varied. For all experiments a standard non-crimp carbon fibre fabric is used with an area weight of 2700g/m^2 and a fibre volume fraction of 50%. Since the layup is quasi isotropic, the tensile strength for all specimens should be the same. It is assumed that the fibre inwash might be related to the orientation of the fibres relative to the FC. Therefore, the layer adjacent to the FC varies with each stage. In particular, the load carrying 90° orientation layer has different positions for each layup. The definition of the 0° orientation is shown in Fig. 4. Following this argumentation, the second layup with the adjacent layer being parallel to the FC should be the worst case. Furthermore, Layup 3 and 4 should show the best results, with regards to reduced fibre undulation.

By consideration of the preform cut, and the clamping line (CL) at the FC edges, the possible influence of a fixation of the fibres is investigated. A micrograph of a supply channel with CL is seen in Fig. 3. The CL should fixate the fibres directly next to the FC and therefore help to reduce fibre inwash. Since a greater fibre inwash is expected for the supply channel, the clamping line is only realized for this shape. The CL geometry itself already leads to an undulation of the fibres, which already will lead to a decrease in mechanical performance. Therefore, a CL is not suitable for distribution channels. The applied preform cut should break the fixation of the fibres due to the clamping of the preform at the plate edges, which should lead to increased fibre inwash into the FC. The five specimen are evenly spaced along the FC (see Fig. 4).

The design of experiment is shown in Tab. 1. All stages of the design have been repeated three times, with three plates per each parameter set. Therefore, for each parameter set a convenient repetition of 15 specimens per stage has been chosen. During the experimentation a strong influence of the specimen

Excerpt from ISBN 978-3-00-053387-7

position was observed. For the design of experiments, this implies the addition of an additional parameter. Since the specimen position is varied in five stages, this resulted in a decreased number of repetitions per stage. For the screening series of experiments a part factorial design according to Plackett Burmann has been chosen. The same number of repetitions was used. Since the CL is not relevant for the distribution channels, experiments 2, 9 and 12 in the part factorial design have not been realized. Experiment 7 for the part factorial design is identical to experiment 2 of the full factorial design. A total of 60 RTM plates has been manufactured and 360 tensile specimens (including the reference specimens) have been tested and visualized via micrograph.

Table 1: Design of experiment, a) full factorial design and b) part factorial design.

Nr.	Layup Orientation	FC configuration
1	1 - (90/0/-45/+45)$_s$	⊓
2	2 - (0/90/+45/-45)$_s$	⊓
3	3 - (+45/-45/90/0)$_s$	⊓
4	4 - (-45/+45/0/90)$_s$	⊓
5	1 - (90/0/-45/+45)$_s$	∩
6	2 - (0/90/+45/-45)$_s$	∩
7	3 - (+45/-45/90/0)$_s$	∩
8	4 - (-45/+45/0/90)$_s$	∩
9	1 - (90/0/-45/+45)$_s$	∿∿∿∿∿
10	2 - (0/90/+45/-45)$_s$	∿∿∿∿∿
11	3 - (+45/-45/90/0)$_s$	∿∿∿∿∿
12	4 - (-45/+45/0/90)$_s$	∿∿∿∿∿

Nr.	Injection rate [gr/s]	FC configuration	FC CL	Layup orientation	Preform cut
1	50	∿∿∿∿∿	⊓	1 - (90/0/-45/+45)$_s$	1
2	50	∿∿∿∿∿	/	2 - (0/90/+45/-45)$_s$	-1
3	50	⊓	∩	1 - (90/0/-45/+45)$_s$	1
4	25	⊓	∩	1 - (90/0/-45/+45)$_s$	1
5	25	⊓	∩	2 - (0/90/+45/-45)$_s$	-1
6	50	⊓	⊓	2 - (0/90/+45/-45)$_s$	1
7	50	⊓	⊓	2 - (0/90/+45/-45)$_s$	-1
8	25	∿∿∿∿∿	⊓	2 - (0/90/+45/-45)$_s$	1
9	50	∿∿∿∿∿	/	1 - (90/0/-45/+45)$_s$	-1
10	25	∿∿∿∿∿	⊓	1 - (90/0/-45/+45)$_s$	-1
11	25	⊓	⊓	1 - (90/0/-45/+45)$_s$	-1
12	25	∿∿∿∿∿	/	2 - (0/90/+45/-45)$_s$	1

4. Results

Due to very different effect sizes and the unexpected influence of the specimen position, the influence parameters are clustered according to their impact. The cluster of results for different influence parameter combinations also help to counter the reduced number of repetitions. First, the results can be divided by the size of the FC cross-section area. The results show, that no undulation of a load carrying layer can be observed for any configuration in combination with the smaller distribution channels. For the larger supply channels almost always fibre undulations are observed. The next largest influence is the position of the specimen along the FC length. The largest fibre undulations are observed at specimen position 1. After specimen position, the results can be grouped for the different layup orientations. Layup orientation 1 and 2 exhibit the largest undulation as was hypothesized during the experimental design. Therefore, the remainder of this section is divided into four subsections according to the above explained effect groups.

4.1. Influence flow channel cross-section area

The tensile strength data for each of the three FC configurations is summarized in Fig. 5. The error bars demonstrate the uncertainty, being plus/minus two standard variation. The small distribution channels exhibited no fibre inwash. Therefore, the tensile strength measured from all 90 specimens with the small FCs was not decreased. In contrast, the tensile strength is significantly reduced due to the fibre inwash into the supply flow channels. The tensile strength of specimens next to the injection point can be reduced by up to 70 %. This is shown with the red indicators in Fig. 6, which represent the lowest measured tensile strength for a single specimen. The determined reference strength (base 60 specimens) is 560,6 MPa, with a standard deviation of 50,5 MPa. The tensile strength can be related to the fibre inwash, in particular the undulation of the tensile load carrying layer. When no fibre inwash was observed, the tensile strength is not decreased. Due to the negligible influence of the distribution channels, only the two supply channel configurations are considered below.

Excerpt from ISBN 978-3-00-053387-7

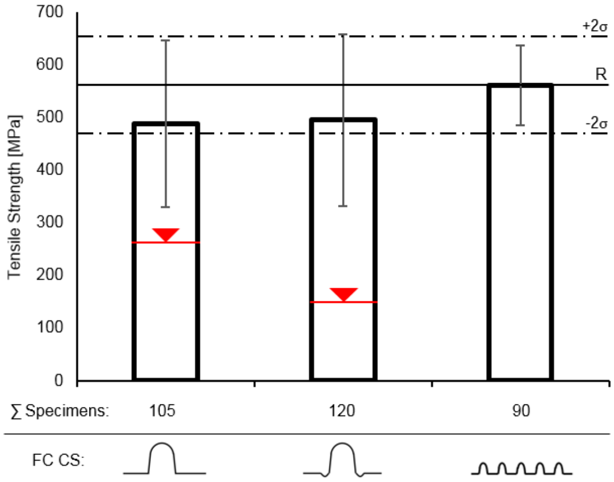

Figure 5: Fibre inwash along the supply channel for the different layups. The red indicators represent the lowest measured tensile strength for a single specimen next to the injection point.

4.2. Influence of specimen position

The maximum fibre undulation was typically observed at the position next to the injection point. While the specimens at the end of the FC suffered a significantly less fibre inwash.

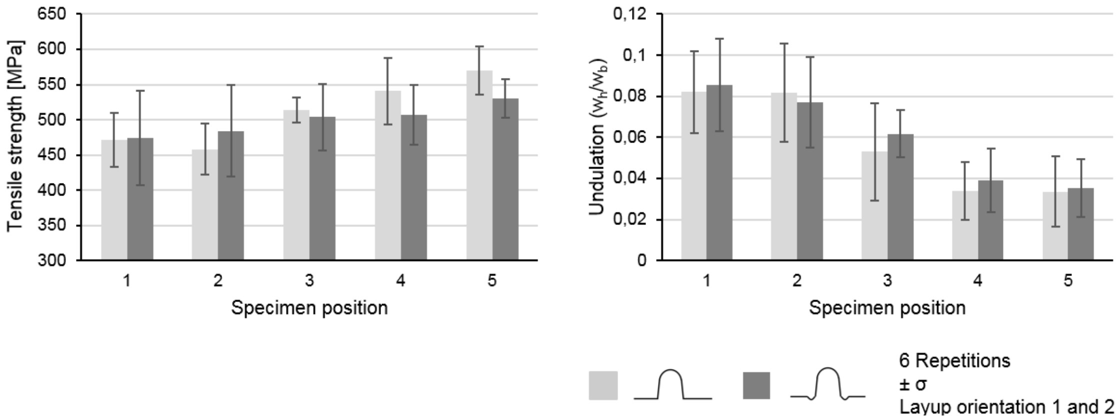

Figure 6: Influence of the specimen position for layup orientations 1 and 2, a) influence on tensile strength and b) influence on fibre undulation (wh/wb)

According to the decreasing magnitude of fibre undulation the tensile strength increases as demonstrated in Fig.6. In Fig. 6 the results for the tensile strength and fibre undulation for layup orientation 1 and 2 and the two supply channel configurations in the full factorial design are shown. The decreasing trend in the undulation is similar to reduction in undulation depicted in the parallel micrograph presented in Fig. 7.

The comparison against specimen position and layup is shown in Fig. 7. Above the different layups an example specimen with a micrograph parallel to the FC is shown. Both the parallel as well as the orthogonal micrograph cross-sections show a decreasing fibre inwash along the FC length.

Excerpt from ISBN 978-3-00-053387-7

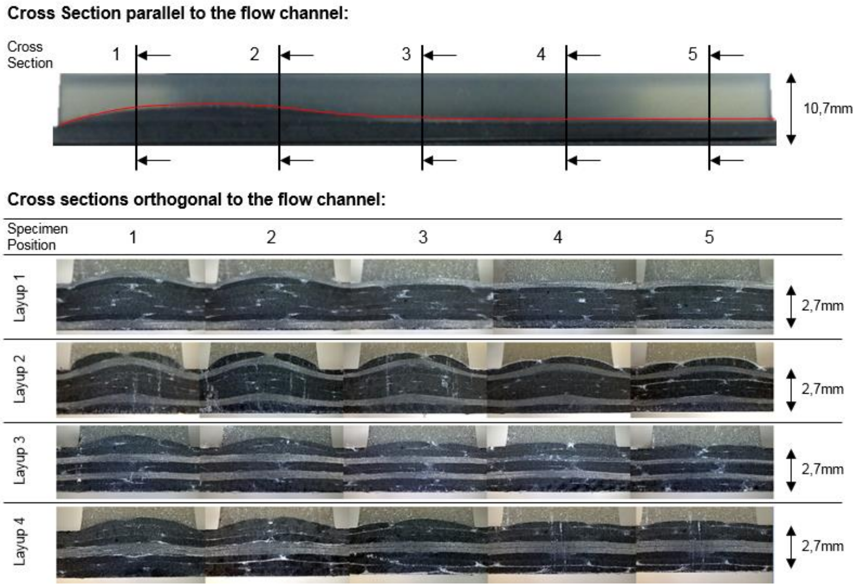

Figure 7: Micrograph visualisation of fibre inwash along the supply channel for the different layups.

4.3. Influence of lay up orientation

In Fig 8. the experimental results are displayed. The results are filtered for specimen position one in the full factorial design. The tensile strength for layup orientation 3 and 4 is larger then the tensile strength for 1 and 2. This proves the hypotheses, that layup 3 and 4 lead to the best results. It is assumed that this is due to the interface between the FC and the adjacent fibres, which is smaller for layups 3 and 4. This also explains why layup configurations 1 and 2 show the lowest tensile strengths. For those layups, the critical fibre orientations 90° (load carrying layer) and 0° (layer parallel to the FC) are adjacent to the flow channel.

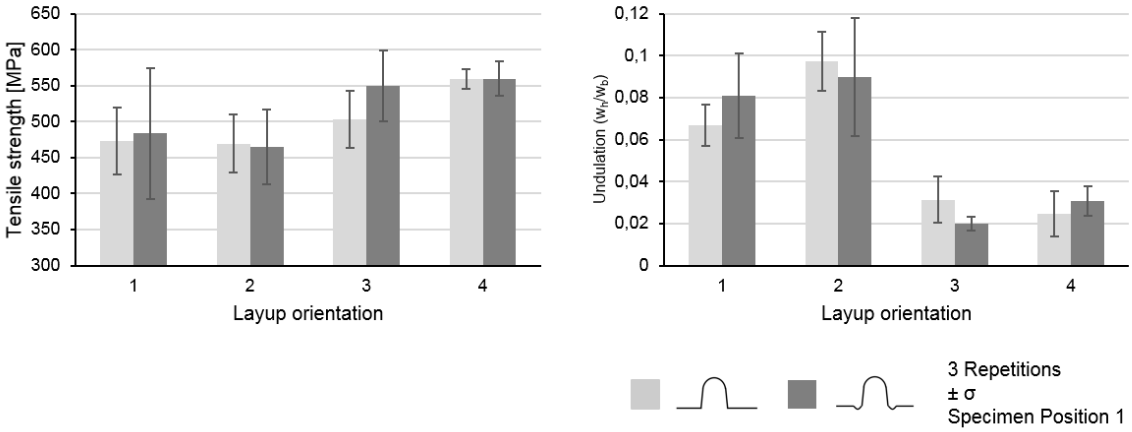

Figure 8: Influence of the layup orientation for specimen position 1, a) influence on tensile strength and b) influence on fibre undulation (wh/wb)

The size of the interface between the fibres and the flow channel is related to the orientation of the fibres relative to the flow channel. For an orthogonal orientation of the adjacent fibres to the flow channel, the overlapping length is equal to the flow channel width. This changes with differing layup angle. In the worst case scenario the fibre orientation is parallel to FC and the overlapping length is equal to the FC length.

Excerpt from ISBN 978-3-00-053387-7

4.4. Remaining influencial parameters

Even with the grouped results, for the injection rate, preform cut and CL no remarkable influence on the fibre inwash was observed. Although for the CL, a minor effect can be shown. The effect is less important compared to the main influence parameters of FC cross-sectional area, specimen position and layup orientation. In a direct comparison to a specimen with a specific layup orientation and position, the specimen with the CL always exhibits a decreased fibre inwash when compared to the specimen without an CL. However, the effective reduction of fibre inwash varies for each parameter set.

5. Summary and Conclusions

The presented flow channel cross-section shape is an optimal solution with regard to weight and permeability. A circular cross section is not possible because of the textile in the cavity, and therefore a parabolic shape is the next best solution. The presented calculation also shows, that for a different purpose and optimization goal a different shape might be better. One example is a limited height. Since the permeability is directly related to the cross-section area size, a larger cross-section area size may require a different shape. The presented RTM experiments have shown that the flow channel itself does not have a negative impact on the tensile strength of the part. Specimens with the distribution FC cross section reached one hundred percent of the reference tensile strength. However, for bigger cross section shapes significant fibre inwash may occur. This inwash of fibres into the flow channel leads to an undulation of possible load carrying fibres. The undulations leads to a three dimensional stress field in the area. Depending on the undulation the tensile strength is r**e**duced by up to 70%. The presented experiments show, that apart from the cross-sectional area, the position along the flow channel and the relative fibre orientation to the flow channel have an influence on the fibre inwash.

References

[1] M. Arnold. Einfluss verschiedener Angussszenarien auf den Harzinjektionsprozess und dessen simulative Abbildung: 111-115. *IVW Schriftenreihe Band 110, IVW GmbH, Kaiserslautern, Germany,*2014

[2] J. Kessels, A. S. Jonker, R. Akkerman. Optimising the flow pipe arrangement for resin infusion under flexible tooling. *Composites Part A: Applied science and manufacturing,* 11 April 2007

[3] N. Montés, F.Sánchez, N.C.Correia. A simplified computational treatment for Non-Isotropic Permeability Flow Models based on Flow Pattern Configuration Spaces. *Proceedings FPCM 10, Monte Verità, Ascona, Swiss,* 10-15 July, 2010

[4] G. Menges, W. Michaeli, P. Mohren. Spritzgießwerkzeuge: 121, *Carl Hanser Verlag, München* 2007

[5] S. Bickerton, S.G. Advani. Characterization and modeling of race-tracking in liquid composite molding processes, *Composites Science and Technology,* 59:2215-2229, 1999

[6] D. Becker. Transversales Imprägnierverhalten textiler Verstärkungsstrukturen für Faser-Kunststoff-Verbunde: 108. *IVW Schriftenreihe Band 108, IVW Gmbh, Kaiserslautern, Germany,* 2015

[7] A.P.J. Altmann. Matrix dominated effects of defects on the mechanical properties of wind turbine blades, *Dissertation, Lehrstuhl für Carbon Composites, Technische Universität München,* 98-105 04 May 2015

[8] DIN ISO 527-4:1997, Determination of tensile properties; Part 4: Test condidtions for isotropic and orthotropic fibre reinforced plastic composites (ISO 527-4:1997)

Excerpt from ISBN 978-3-00-053387-7