MAXIMIZING THE OUT-OF-PLANE PERMEABILITY OF PREFORMS MANUFACTURED BY DRY FIBER PLACEMENT

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Abstract

By providing a load-related fiber orientation at a minimum of fiber crimp, the Dry Fiber Placement (DFP) allows outstanding high mechanical performance of composite parts. Furthermore, DFP bears a high cost-saving potential because of little scrap production. Within an ongoing research project the efficiency was further improved by an online-bindering system, allowing the direct usage of untreated rovings instead of expensive pre-bindered rovings. Nevertheless, the deficient impregnation behavior of DFP-preforms during Liquid Composite Molding (LCM) remains a main challenge. Applying an out-of-plane impregnation, e.g. by using a SCRIMP or Compression Resin Transfer Molding (RTM) process, reduces the flow length within the preform and is a first step to reach acceptable cycle times. However, further improvement is required in order to apply DFP-preforms in large-batch production.
Within this study influences on the out-of-plane permeability were investigated. The considered parameters were related to the material (e.g. binder amount) as well as the layup process and subsequent process steps.

1. Introduction

Weight reductions of up to 75 % compared to steel parts can be achieved with fiber reinforced plastic composites (FRPC). Yet, this commonly also involves tremendously higher part costs. To increase the industrial usage of composites it is crucial to achieve cost reductions, especially for the manufacturing processes [1]. For high volume production of high performance composite parts, Liquid Composite Molding (LCM) processes such as Resin Transfer Molding (RTM) experience an increasing demand. For these processes, near-net shape preforms made of dry fibers have to be produced prior to the impregnation with the resin. Currently, most parts are manufactured using conventional semi-finished textile products such as woven fabrics or non-crimp-fabrics (NCF). Due to their areal shape, the fabrics lead to a high amount of scrap (10 - 50%) and also load related fiber orientations within the preforms are difficult to implement. One possibility to overcome these drawbacks is the use of direct preforming technologies such as Dry Fiber Placement (DFP). Within these processes, several rovings are placed on a surface and can be oriented according to the designed load paths. As the used fiber material does not possess a sufficient cohesion between the layers, a method for layer fixation has to be used. One possible solution is the application of powdery binder material (thermoplastic or thermoset) to the rovings. During the layup process the binder is melted and a subsequent consolidation roll leads to solidification and joining of the roving with the already layed preform.

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Binder rovings are commercially available, but these semi-finished products are expensive and the variety of fiber-binder combinations and the amount of binder is strongly limited. For this purpose, an online bindering system was developed during a research project which allows the direct processing of standard dry rovings in a layup process with the online-application of binder material in the nip point. Figure 1 shows a schematic illustration of the online bindering process and the layup head during the layup process. In consequence, the used materials for the production of a preform can freely be chosen and adjusted to the requirements.

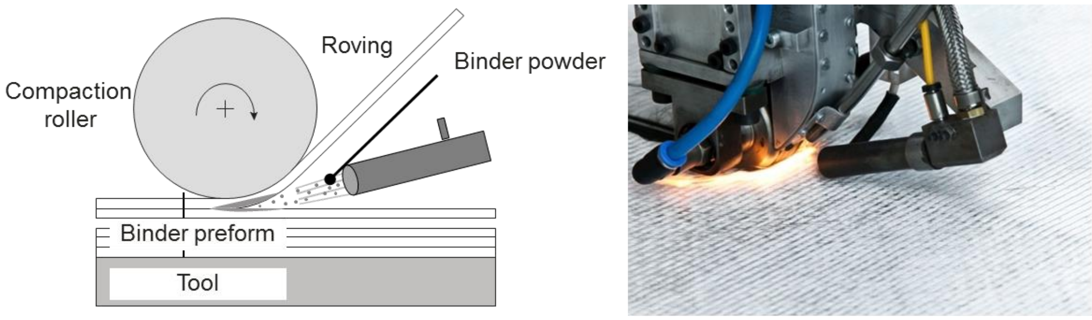

Figure 1. schematic illustration of the DFP-process (left), Tape laying head during DFP process (right)

While the material efficiency of DFP-preforms is very advantageous, there is one severe drawback: the deficient impregnation behavior. The flow of a liquid through a porous media, such as textile fibers, can be described by Darcy's law for the saturated state [2]. Following this law in a one-dimensional case, the permeability K can be calculated by referring the product of volumetric flow q, the fluid viscosity η and the flow length Δx to the perfused cross section A and the pressure drop Δp.

$$K = -\frac{q \cdot \eta \cdot \Delta x}{A \cdot \Delta p} \tag{1}$$

Correspondingly, in the context of RTM processes the permeability describes the conductance of a preform for the resin flow. The permeability of DFP-preforms is relatively low, which results from the preform structure. Compared to conventional textile products such as woven fabrics, the applied fibers tend to form a very homogeneous packing as can be seen in (Figure 2, left). On the other side, the roving undulation in woven fabrics leads to macro flow channels (Figure 2, right). These flow channels are highly relevant for an efficient distribution of the resin material between the textile layers during infusion processes. The micro-flow channels between the filaments within the single yarns are by far less permeable. As macro flow channels are not present in preforms manufactured by dry fiber placement, the entire impregnation process of the preform has to be achieved by micro impregnation. For this reason, the impregnation time of DFP-preforms is orders of magnitude higher than for conventional preforms. Previous research work for increasing the permeability was limited to introduction of gaps between the rovings during layup [3], [4]. However, the resulting reduction of fiber volume content contradicts the demand of high fiber volume contents for high performance parts.

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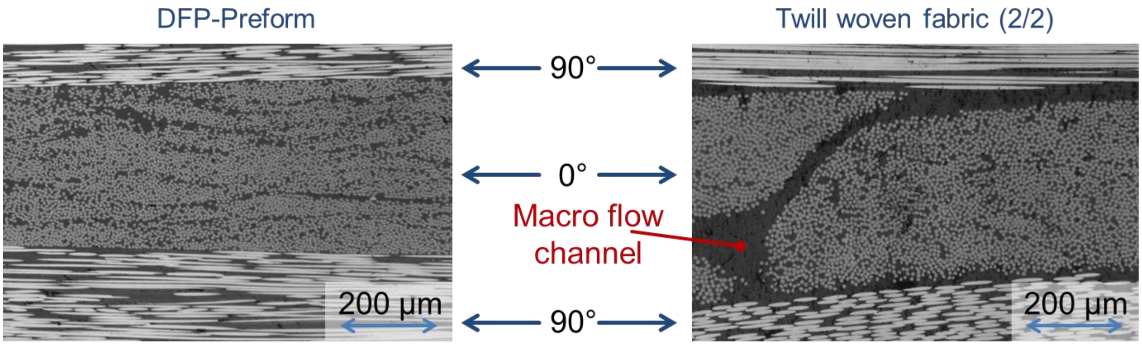

Figure 2. At a comparable fiber volume content (58%), the microscopic cross-sections of woven fabrics (right) reveal macro-flow channels while DFP-preforms (left) are highly dense (both materials 0°/90° lay-up)

The target of the presented study was to investigate different possibilities to increase the permeability of DFP-preforms. Due to the high aspect ratio of most FRPC components (large surface, small thickness), processes which provide out-of-plane impregnation, such as Compression RTM, could be suitable for DFP-preform impregnation. Hence, the out-of-plane permeability is of particular interest.
To investigate possibilities to increase the out-of-plane permeability DFP-preforms were manufactured and measured with an apparatus which allows the measurement of the saturated out-of-plane permeability at different pressure drops while also monitoring hydrodynamic compaction [5]. Several strategies for the maximization of the out-of-plane permeability were tested, e.g. variation of binder amount, binder particle size, optimized layup sequence of rovings, and textile manufacturing methods like tufting.
As expected the manufactured DFP-preforms showed a very low out-of-plane permeability in the range of 1E-15 to 5E-14 m² at fiber volume contents between 51 % and 56 %. Higher injection pressures cause hydrodynamic deformation and further reduce the out-of-plane permeability.

2. Materials and Methods

For the preform manufacturing, a 50K carbon fiber roving (SGL Sigrafil 50K C030, 3300 tex) and a bisphenol-A-based epoxy binder (Huntsman XB 3366) were used. Preforms of the size of 1000 x 1000 mm² were manufactured and afterwards fixation frames with the shape of the samples required for permeability measurement were applied (elliptical 120 x 160 mm²). Due to the frames the samples could be cut out of the preform without fringe-out or other damage of fibers.
The out-of-plane permeability measurements were performed with a system following a saturated principle [5]. The measurements were performed at a pressure drop of 1.0 bar. Rapeseed oil was used as measurement fluid since it has a viscosity of about 73 mPas at room temperature, which is in the range of typical resin systems at processing temperature.
Each measurement was repeated three times for statistical coverage. The following parameters were varied.

3. Study on the optimization of the out-of-plane permeability

3.1. Binder content

One possibility to increase the permeability is to vary the binder amount. Binder material is used for fixation of the rovings during manufacturing. However, the presence of binder particles can induce small flow channels and also bears the potential to reduce the permeability-lowering effect of hydrodynamic compaction during infusion by preventing nesting effects. Yet, the binder of course also reduces the pore space available for flow. During the conducted study, the binder content was varied between 4.07 % and 9.76 % (in weight) to examine the impact of this effect (Figure 3). A slight increase of permeability with higher binder contents has been observed, whereas also the standard deviation of the measured values strongly increased. The positive effect of binder particles was partially also counteracted by blockage of the resin flow for higher binder contents. The results show that positive and negative influences are strongly interlinked and a targeted permeability increase is

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highly difficult. Yet, they also show that binder amount should carefully be chosen in order to receive a reproducible material behavior during impregnation.

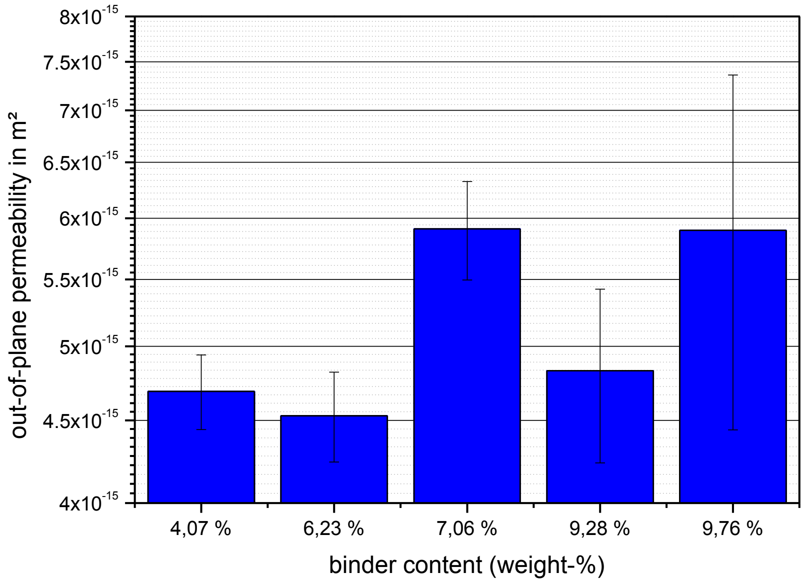

Figure 3. Out-of-plane-permeability of preforms at 52-55 vol.-% with different binder contents (weight-%)

3.2. Binder particle size

Besides the binder amount also the particle size can be varied. The used binder material was sieved to determine the composition of binder particle sizes in delivery condition. It was found that about 50 % of binder particles are in the range of 125 µm to 250 µm (declared as medium sized hereafter) and about 26 % are larger than 250 µm (coarse) (Figure 4). The diameter of the used carbon fibers is specified to 7 µm by the manufacturer.

The influence of binder particle sizes on out-of-plane permeability was determined using sieved binder powder. For the comparison binder materials with coarse and medium particles as well as manufacturer`s mixture were used.

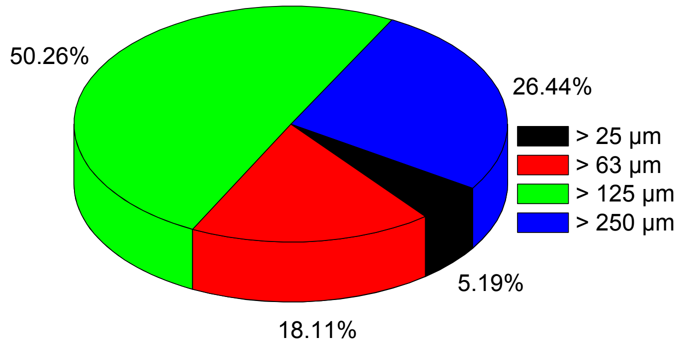

Figure 4. Composition of binder particle sizes in mixture

Similar to the effect discussed above, it is assumed that larger binder particles can contribute to a higher permeability by lowering hydrodynamic compaction. As the conducted measurements have been done using the same binder content with varying binder particle sizes, a lower number of binder particles is introduced and thus the effect can be reduced for very large sizes. This is also observed in the conducted measurements (Figure 5). The mixture of binder particle sizes shows the lowest permeability, coarse binder particles (large-sized) increase the permeability while medium sized particles show the highest permeability. Hence, it can be concluded that a variation of binder particle size is more effective than varying the binder amount and also shows better results concerning the reproducibility.

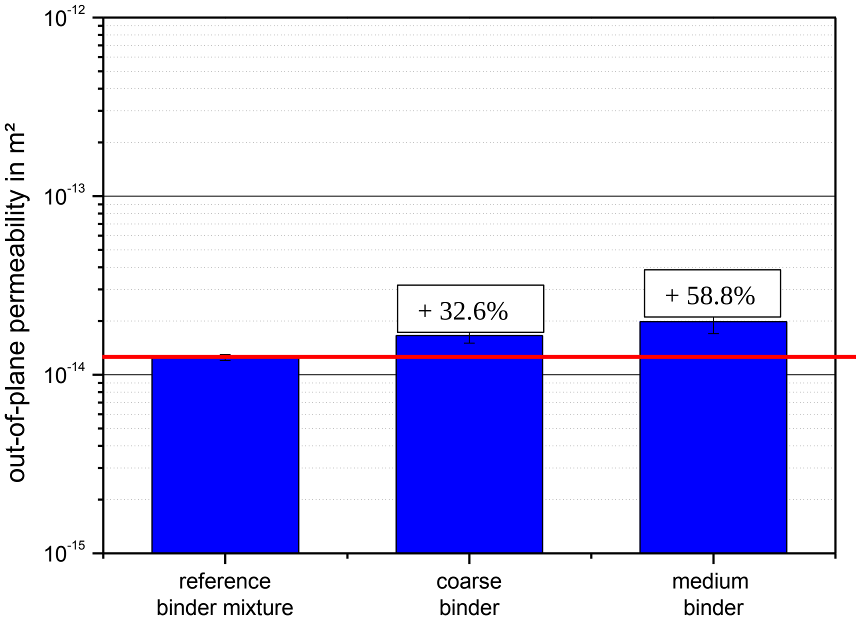

Figure 5. Comparison of out-of-plane permeability for different parameter variations

3.3. Modification of layup sequence

One reason for the missing of macro flow channels in DFP-preforms are the parallel layup paths for areal layup which lead to a very good fiber orientation without undulation. One possibility to enhance impregnation is modification of the layup sequence of the material in order to generate undulation. In this study, two different lay-ups were compared. First, the reference lay-up with 8 alternating 0° and 90° layers, whereat the rovings are placed directly next to each other. Second, a lay-up with 2x8 alternating 0° and 90° layers, whereas the rovings are placed with a gap of one roving (Figure 6, left). This leads to the same total areal weight and fiber volume content, wherein the rovings are slightly undulated. In total, the produced preform can be described as a "macro woven" textile (Figure 6, middle) in which the fibers are still mostly stretched while flow channels are introduced into the material. As a result, out-of-plane permeability was increased by factor 2.2 at equal fiber volume content (Figure 6, right).

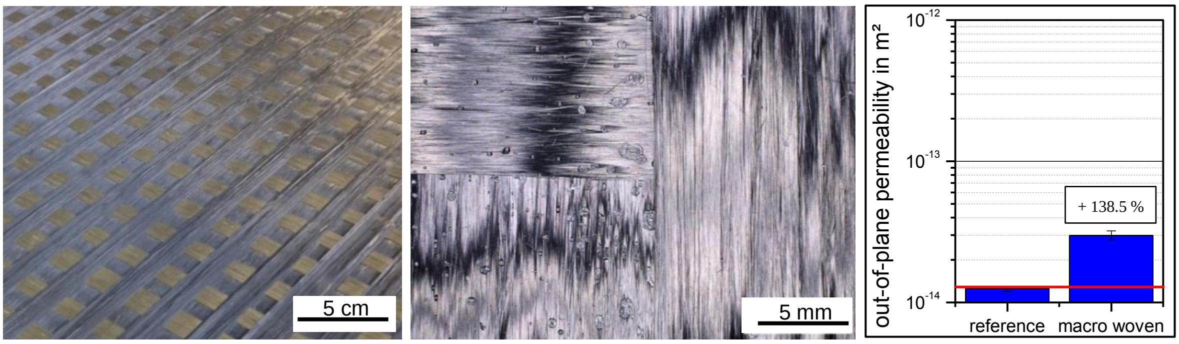

Figure 6. "macro woven" preform, photography (left), surface microscopy (middle) and comparison of permeability to reference (right)

3.4. Insertion of flow channels by tufting

Besides woven fabrics, also non-crimp-fabrics show a good impregnation behavior. As they do not possess macro flow channels inserted by weaving of separated yarns, the permeability is enabled by the fiber-free regions between the layers and the resulting flow channels [6]. The influence of this effect was also tested for the preform manufactured by Dry Fiber Placement in this study. To investigate the effects of the flow channels introduced by tufting, the preform sample has been sewed using lockstitch and the lower yarn afterwards was removed – this corresponds to the structure of a

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tufting process. The result can be seen in Figure 7. As it can be observed in surface microscopy, the fibers are contracted to bundles and flow channels emerge. In total, the conducted tufting-like process led to an out-of-plane permeability increased by factor 30 compared to the reference preform (Figure 7, right). Hence, tufting is the most effective option to increase the permeability. Yet, it of course represents an additional process step.

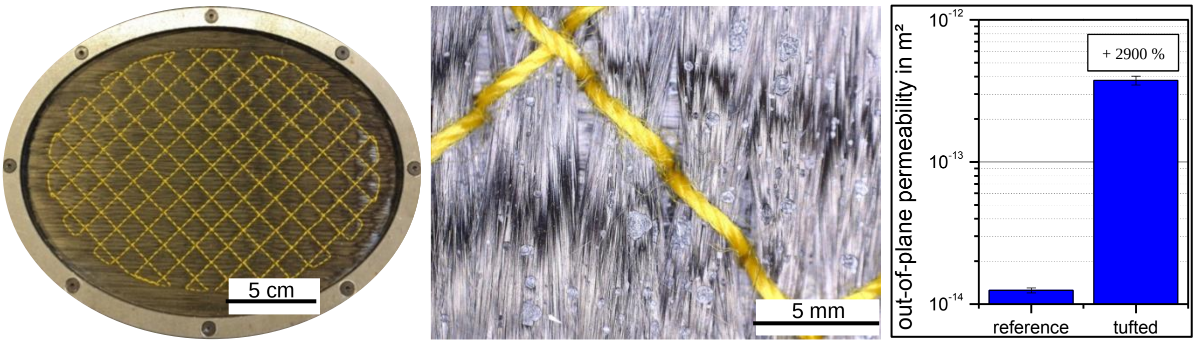

Figure 7. tufted specimen for permeability test (left), surface microscopy of tufted preform (middle) and comparison of permeability to reference (right)

4. Conclusions

The conducted study shows the potential of variation of different parameters for the increase of out-of-plane permeability of preforms produced by Dry Fiber Placement.

- Changing of the binder amount and binder particle size is easy to implement but has a relatively small impact on permeability. Optimizing the particle size is preferable in terms of effectivity and reproducibility.
- Modification of the lay-up sequence more than doubled the out-of-plane permeability by inducing undulation
- Tufting of DFP-preforms showed the highest effectivity with an permeability increase by a factor of more than 30, although this represents an additional step required for an efficient LCM process.

Acknowledgments

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