Maximizing the out-of-plane-permeability of preforms manufactured by dry fiber placement

Oliver Rimmel*, David Becker and Peter Mitschang

Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Straße, Gebäude 58, 67663 Kaiserslautern, Germany

Abstract Dry fiber placement (DFP) is a technology which enables outstandingly high mechanical performance of composite parts as preform structures with load-related fiber orientations can be created with minimum of fiber crimp. Furthermore, DFP has high cost-saving potential due to minimum material wastage during production. Recently, the efficiency has been further improved using an online binder application system, allowing the direct usage of untreated rovings instead of pre-designed rovings with binder applied by the manufacturer. Nevertheless, the poor impregnation behavior of DFP-preforms during liquid composite molding processing methods remains a main challenge. Encouraging an out-of-plane impregnation, e.g. by using a vacuum-assisted or compression resin transfer molding process, reduces the flow length within the preform and is a first step toward reducing cycle times. However, further improvements are required in order to apply DFP-preforming methods in serial production. Within this study influences on the out-of-plane permeability of DFP-preforms were investigated. The considered parameters were related to the material (e.g. binder amount) as well as the layup process and subsequent process steps.

Keywords Dry fiber placement, Permeability, K3, Binder particles, Preforming

Introduction

Weight reductions of up to 75% compared to steel parts can be achieved with fiber-reinforced plastic composites, but this is commonly associated with tremendously higher part costs. To increase the industrial usage of composites it is crucial to achieve cost reductions, especially for the manufacturing processes. For larger volume production of high-performance composite parts, liquid composite molding (LCM) processes such as resin transfer molding (RTM) have experienced an increase in demand due to the possibility of automation. For these processes, near-net shape preforms made of dry fibers have to be produced prior to impregnation with 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 (up to 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). DFP allows the manufacturing of a near-net shape preform directly out of a roving within a single process step. In this method, several rovings are placed on a surface and can be oriented according to the designed load paths. However, this process, requires a method for layer fixation. 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 afterward a consolidation roll compacts the rovings, joins them with the already laid preform, and cools down the binder leading to solidification and fixation. By applying multiple tracks and layers of
rovin gs onto the tool, a complex preform with adapted fiber and mass distribution according to the relevant load paths can be produced. Besides the virtually zero-waste preform manufacturing, material savings can also be achieved by enabling completely new designs with this technique. For example, a direct integration of load introduction elements, core materials or functional elements is possible.

Binder rovings are already commercially available, but these semi-finished products are by far more expensive than the raw rovings. Also, the variety of commercially available fiber-binder combinations and the amount of binder is strongly limited. For this purpose, an online binder application system which allows the direct processing of standard rovings during a layup process with the online application of binder material in the nip point was developed during a research project at the IVW.²

Figure 1 shows a schematic illustration of the online binder application process and the layup head used during the layup process. As a consequence, the materials used for the production of a preform can be freely chosen and adjusted to material, process, and application requirements.

While the material efficiency of DFP-preforms is very advantageous, there is one severe drawback: the deficient impregnation behavior compared to woven or non-crimp fabrics. For example, the permeability in out-of-plane direction is in the range of 1E-15 m²–5E-14 m², typically 1–2 orders of magnitude lower than for conventional textile materials such as woven fabrics or non-crimp fabrics. The differences result from the DFP-structure, which does not show meso-flow channels (in between the rovings), neither in-plane nor out-of-plane (see Fig. 2). Meso-flow channels play an important role for resin distribution as their permeability is decades higher than the

Figure 1 Schematic illustration of the DFP process (left), fiber placement head during DFP process (right)

Figure 2 Fiber architecture modeled with Geodict® (top), micrograph of DFP-Preform (bottom, left), woven fabric (bottom, middle) and biaxial non-crimp fabric (bottom, right), all with 56% fiber volume content
permeability of micro-flow channels (i.e. within the rovings, between single fibers). As a result, this means that the impregnation step is significantly prolonged compared to when using conventional textile materials. Hence, DFP-preforms can only be impregnated using resin systems with reduced reactivity. This contradicts the demand for faster process cycles and the use of fast curing resin systems. Also, the use of high injection pressures (e.g. up to 150 bar for high pressure RTM) leads to a hydrodynamic compaction during resin flow and therefore to a further reduction of permeability. In addition, the danger of preform deformation is present and the use of higher pressure requires more expensive facilities.

Processes, such as compression RTM (CRTM), provide an impregnation in through-thickness direction which can lead to major reductions in flow path length. This is due to the high aspect ratio, e.g. of typical automotive body parts, which have quite a large surface area but are rather thin. Hence, CRTM offers high potential for DFP-preforms, but the out-of-plane permeability is still so low that even with CRTM DFP-preforms can currently not be used for serial production. Therefore, concepts have to be identified, which offer the possibility to increase the out-of-plane permeability up to the level of conventional textiles.

For this reason, the aim of this research work is to evaluate different approaches in order to enhance the out-of-plane permeability of DFP-preforms. If this aim can be accomplished, the use of DFP for larger volume productions seems attainable, as the lower mass output per machine could be compensated by the parallel use of multiple layup systems for one LCM-tool.

### Theoretical background and state of the art

The flow of a liquid through a porous media, such as textile fibers, can be described by Darcy’s law for the saturated state. Following this law in a one-dimensional case, the permeability $K$ can be calculated by relating the product of volumetric flow $q$, the fluid viscosity $\eta$ and the flow length $\Delta x$ to the perfused cross section $A$ and the pressure drop $\Delta p$, as shown in Equation (1).

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

Correspondingly, in the context of RTM processes the permeability describes the conductance of a preform for the resin flow. To represent the three-dimensional diffusion, three characteristic values are needed: the highest and lowest in-plane permeability ($K_1$ and $K_2$) as well as out-of-plane permeability ($K_3$). In state-of-the-art RTM processes, impregnation is mainly achieved by in-plane flow. As the aspect ratio of most FRP parts is greater than 1:100, the parts show a large surface while having a relatively small thickness. Hence, newer approaches such as advanced or compression RTM provide an impregnation which is mainly directed in the out-of-plane direction. Due to the tremendous shortening of flow path lengths, shorter cycle times can be accomplished. All three permeability values ($K_1$, $K_2$, and $K_3$) are relevant for the use of DFP-preforms in LCM processes. Based on the theory of flow through porous media, several possibilities to increase the permeability of fiber structures can be derived:

- Available pore space for flow has the biggest influence. If this space is reduced by compaction (increased fiber volume content, fiber volume content [FVC]), a strong decrease in permeability is a direct consequence. One of the best-known equations to describe this effect is the Kozeny–Carman equation as shown in Equation (2):

$$q = \frac{\varepsilon \cdot \Delta p \cdot A \cdot d_p^2}{(1 - \varepsilon)^2 \cdot \eta \cdot \Delta L \cdot C} \tag{2}$$

where $d_p$ is the particle diameter, $\varepsilon$ is the porosity, $C$ is an empirical constant. Similar to Darcy’s law, the fluid viscosity $\eta$ and the flow length $\Delta L$ as well as the perfused cross section $A$ and the pressure drop $\Delta p$ are used for calculation of the volumetric flow. It describes a creeping flow but instead of a variable for permeability, it contains variables to describe pore space. Pore content is cubed in this equation. However, as increasing the pore content would lead to a decreased fiber volume content and a reduction of lightweight potential, the applicability of the parameter is strongly limited.

- Besides fiber volume content, the structure of the pore space also has a high influence on permeability. For woven and non-crimp fabrics, the architecture includes meso-(between rovings or textile layers) and micro-scaled flow spaces. Permeability inside micro-scaled flow spaces is several decades lower than in meso-scaled pore spaces. Hence, mainly meso-flow channels in flow direction, as introduced, for example, during stitch-bonding, have a large influence. If the porous structure is assumed as a solid block with capillary tubes in the flow direction (simple model of first order), the influence of stitch-bonding can be considered on a theoretical basis. The law of Hagen–Poiseuille allows the calculation of the resulting fluid flow inside a tube in dependency of the pressure drop:

$$q = \frac{\pi \cdot r^4 \cdot \Delta p}{8 \cdot \eta \cdot \Delta L} \tag{3}$$

where $r$ is the tube diameter, $\Delta L$ the flow length which corresponds to the tube length in this case. $Q, \Delta p$, and $\eta$ are defined as the volume flow, pressure drop, and viscosity, respectively. For this simple first-order model, this equation together with Darcy’s law can be resolved using $\Delta p$ and equated with one another; the permeability can subsequently be derived as $r^2/8$. This shows that for the same total surface area, a lower number of large flow channels show a higher permeability than a higher number of smaller flow channels. Hence, a non-crimp fabric shows a higher permeability compared to a DFP-preform at an equal fiber volume content. In the NCF the meso-flow channels induced by the sewing strongly increase permeability which more than compensates for the reduced permeability in the strongly compacted rovings. On the other hand, DFP-preforms, which only contain micro-scaled pore spaces, show tremendously lower permeability compared to textile semi-finished products.

- Besides total volume and distribution of flow channels, also their tortuosity (how much they are meandered) has a high relevance, as it reduces permeability. Scheidegger, for example, proposed a reduction of the calculated channel permeability by a tortuosity factor which can be calculated as the ratio of actual flow
channel length and thickness of the porous structure. Therefore, the strong tortuosity inside semi-finished products strongly reduces permeability. The advantage of stitch-bonding, e.g., in non-crimp fabrics is that the resin goes straight through the complete structure with a minimum of tortuosity. Furthermore, the theory of tortuosity explains why in-plane permeability, i.e., in the fiber direction, usually is one order of magnitude higher than the transverse permeability.

In conclusion, the permeability of fiber structures can be influenced if the above-mentioned factors are manipulated. During numerous research works, influences on the permeability of textile semi-finished products like woven or non-crimp fabrics have been examined. Especially, variations of textile architecture (stitch-bonding parameters for non-crimp fabrics) and weaving patterns as well as roving/fiber type for woven fabrics, preforming-related parameters like draping and shearing, and sewing and binder application can have a large impact on in-plane as well as out-of-plane permeability. Studies have shown that textiles with nearly identical mechanical properties can exhibit strongly varying permeability values up to the point where the injection time varies by a factor of 200.

Concerning the impregnation behavior of DFP-preforms, very few findings exist. The main focus of previous research works was to estimate the influence of layup-induced effects on later impregnation steps. Rudd et al. developed a theoretical model to predict the permeability depending on in-plane waviness. Still, they conducted their examinations at fiber volume contents of lower than 45%. The influence of roving shifting during layup has been considered by Belhaj et al. Besides a reference, at which all rovings (12 k) have been ideally placed next to each other without separation, they also investigated preforms with gaps or overlaps of 2 mm at each fifth roving. The permeability with the laps was about 30% lower than for the other layup patterns, which were all in a very close range. Still, only one in-plane direction was measured using water as the measurement fluid which has a viscosity more than a decade lower than for a typical resin system. Graupner et al. considered gaps between rovings as a method to enhance permeability instead of considering it as a defect. The number and width of roving distances were varied. Out-of-plane permeability was increased by two decades compared to a reference of (~1.5E-14 m²) by applying a gap of 4 mm after each four rovings. Still, the fiber volume content was reduced from 54.9 to 47.7%, resulting in the corresponding mechanical properties. Similar experiments conducted by Marquardt et al. have also shown that the position of gaps in the thickness direction of the preform largely influences their effect on overall permeability.

The method of creating roving gaps is partly complemented with highly permeable fleece layers between the roving layers to ensure complete impregnation. A systematic study considering the impregnation behavior of DFP-preforms and the possibilities to influence it currently does not exist.

### Materials and methods

#### Approach

From the possibilities reviewed in the previous section, the following approaches have been identified to have a potential influence on the out-of-plane permeability:

- Micro-flow spaces created by variation of binder content
- Micro-flow spaces created by variation of binder particle size
- Meso-flow spaces created by modification of layup sequence
- Meso-flow spaces created by adding a tufting step

To investigate the effect of these approaches on improving the out-of-plane permeability, corresponding samples were manufactured and measured via an out-of-plane permeability measurement system.

#### Materials

For this parameter study a carbon fiber from SGL (SGL Sigrafil 50 k C030, 3300 tex) was selected as binder roving reinforcement. The relevant material data is summarized in Table 1.

A bisphenol-A-based powder binder (XB 3366) from Huntsman Advanced Materials, Switzerland was used. The material data are shown in Table 2.

#### Experimental setup

Preforms of the size 1000 × 1000 mm² were manufactured via DFP with a layup speed of 10 m/min. For all measurements except the later described changed layup, a layup sequence of (0/90°)⁴ was chosen to achieve an overall thickness of ~1.8 mm at 50% FVC. Subsequently, fixation frames with the shape of the samples required for the permeability measurement were applied (elliptical in shape 120 × 160 mm², Fig. 3). Due to the frames the samples could be cut out of the preform without fringe-out or other types of damage to the fibers.

Out-of-plane permeability values were determined following the saturated measurement principle as visualized in Fig. 4. The measurements were performed at a pressure drop of 1.0 bar. Rapeseed oil was used as a 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.

#### Test plan

An overview of all conducted tests is shown in Table 3. The modified parameter is highlighted in orange. The binder content is calculated as the added weight referring to the weight of the untreated roving. The particle size has been varied from the reference mixture as delivered by the manufacturer, see Section Binder particle size for further details. For the modification of layup sequence and after treatment, see Sections Modification of layup sequence and Insertion of flow channels by tufting, respectively.

| Fiber type | Number of filaments | Yarn count (tex) | Density (g/cm³) | Diameter (μm) | Sizing | Fiber sizing degree (%) | Tensile strength (GPa) | Young's modulus (GPa) | Failure strain at break (%) |
|------------|---------------------|-----------------|-----------------|--------------|--------|------------------------|----------------------|------------------------|---------------------------|
| Sigrafil C30 Basic modulus | 50 k | 3300 | 1.80 | 7 | Epoxy | 1.0 | 4.0 | 240 | 1.7 |
particles was partially also counteracted by blockage of the resin flow for higher binder content. The results show that positive and negative influences are strongly interlinked and a targeted permeability increase is very difficult. Yet, the results also show that the binder amount should be carefully chosen in order to achieve a reproducible material behavior during impregnation. Furthermore, high binder content could also lead to unwanted effects influencing the mechanical properties of the finished part. One further issue is the increasing range of variation with higher binder content as the variation coefficient increases from 5.31% for a binder content of 4.07% up to 24.75% for a binder content of 9.76%.

Binder particle size

Besides the amount of binder its particle size can be varied as well. The binder material used was sieved to determine the composition particle sizes of the binder powder in delivery condition. It was found that about 50% of the binder particles fall in the range of 125–250 μm (defined as medium-sized hereafter) and about 26% are larger than 250 μm (coarse) (Fig. 6). The diameter the carbon fibers used is 7 μm.

---

**Table 2** Material data Huntsman XB 3366

| Epoxy index | Hydroxyl value | Density at 25 °C | Flash point |
|-------------|----------------|------------------|-------------|
| Eq/kg       | Eq/kg          | g/cm³            | °C          |
| 0.34 – 0.42 | 3.1            | 1.17–1.19        | ≥215        |

---

**Results**

**Binder content**

One possibility to increase the permeability is to vary the amount of binder. Binder material is used for fixation of the rovings during manufacturing. However, the presence of binder particles can induce small flow channels and also has 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 amount of binder compared to the weight of the roving in delivery condition was varied between 4.07 and 9.76% (by weight) to examine the impact of this parameter (Fig. 5). A slight increase in permeability with higher binder content has been observed. The positive effect of having more binder particles was partially also counteracted by blockage of the resin flow for higher binder content. The results show that positive and negative influences are strongly interlinked and a targeted permeability increase is very difficult. Yet, the results also show that the binder amount should be carefully chosen in order to achieve a reproducible material behavior during impregnation. Furthermore, high binder content could also lead to unwanted effects influencing the mechanical properties of the finished part. One further issue is the increasing range of variation with higher binder content as the variation coefficient increases from 5.31% for a binder content of 4.07% up to 24.75% for a binder content of 9.76%.

**Binder particle size**

Besides the amount of binder its particle size can be varied as well. The binder material used was sieved to determine the composition particle sizes of the binder powder in delivery condition. It was found that about 50% of the binder particles fall in the range of 125–250 μm (defined as medium-sized hereafter) and about 26% are larger than 250 μm (coarse) (Fig. 6). The diameter the carbon fibers used is 7 μm.
The influence of binder particle sizes on the out-of-plane permeability was determined using the sieved binder powder. For the comparison, binder materials with coarse and medium-sized particles as well as the manufacturer’s mixture were used. A processing of the smaller sized particles was not possible due to limitations of the binder application system. All measurements were conducted using a binder content of ≈7 wt.-%.

Similar to the effects described in Section Binder content, 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 size, a lower number of binder particles is introduced and thus the positive effect of lowering the hydrodynamic compaction can be reduced for very large sizes. This is also observed in the conducted measurements (Fig. 7). The as manufactured 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. However, the achieved increase in permeability is insignificant when compared to the permeability of textile semi-finished materials. For this reason, an optimization of binder particle size is reasonable, but is not the decisive step to achieve an acceptable impregnation behavior of DFP-preforms. Furthermore, the increased permeability for differing binder particle sizes also inherited an increasing variation coefficient from 4.03% for the reference mixture up to 24.75% for medium-sized particles.

**Modification of layup sequence**

One reason for the missing macro-flow channels in DFP-preforms is the parallel layup paths 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 soft undulation. In this study, two different layup strategies were compared. First, the reference layup with eight layers alternating at 0° and 90°, where the rovings are placed directly next to one another. Second, a layup with 2x8 layers alternating at 0° and 90° layers, respectively, where the rovings are placed with a gap of one roving apart (Fig. 8, left). This leads to the same total areal weight and fiber volume content, as the rovings are slightly undulated after compaction. In total, the produced preform provides intended undulation (Fig. 8, middle) in which the fibers are still mostly stretched, while flow channels are introduced into the material. It is known from woven fabrics that such undulation can improve permeability since they cause gaps between the rovings. Yet, compared to a real woven
advanced manufacturing: polymer & composites science

The influence of this effect was also tested for the preform manufactured by DFP in this study. To investigate the effects of the flow channels introduced by tufting, the preform sample was sewed using a lockstitch and the lower yarn was removed afterward – this corresponds to the structure of a tufting process. The used thread was an Amann Saba C50 with a stitch distance of 3 mm. In total, 1070 stitches were applied in a rectangular pattern with a pattern width of 10 mm. The result can be seen in Fig. 11. As it can be observed in the surface microscopy image, the fibers are contracted to bundles and gaps within the preform emerge. These gaps build flow channels in the out-of-plane direction as well as in the in-plane direction. This effect is also shown in the microscopy image of the plate after injection via a VARI process (Fig. 9) and in a µCT-scan (Fig. 10).

In a µCT-Scan, it can be seen that the flow channels inserted have the shape of a converging lens as the fibers are redirected around the stitching point (Fig. 10). The tension applied to the rovings by the sewing yarn leads to a local reduction of fiber volume content to achieve the stitching channels. As the constancy of the total fiber amount can be assumed, a local increase in fiber volume content next to these channels will be the consequence. In total, the fiber volume content of the preform will not be significantly changed and will therefore not lead to a decrease in mechanical properties. However, the deviation of the fibers leads to a certain degree of disorientation which could also affect mechanical properties and can act as crack-initiating zones. Furthermore, it can be seen in the micro-section (Fig. 9) that large pores emerge in the resin-rich zones. These can either be caused by a curing reaction which is too quick leading to exothermal effects or by the inclusion of air.

In total, the conducted tufting-like process led to an increase of out-of-plane permeability by a factor of about 30 compared to the reference preform (Fig. 11, right). Hence, tufting is the most effective option to increase the permeability. Yet, it of course represents an additional process step. Furthermore, this result cannot be achieved by sewing and removing the thread as the fiber structure tends to close the gaps immediately after removal of the thread. For this reason, the thread has to remain inside the part. Compared to other methods which also inferred a strongly increasing range of variation with higher permeabilities, the variation coefficient only increased from 4.03% for the untufted preform to 7.20% for the tufted preform.

When considering the production of near-net shape preforms, it has to be taken into account that the tufting step is only applicable for nearly flat preforms. To produce three-dimensional preforms, a flat layup with a consecutive forming step would be needed. However, this step could be inhibited by the increased bending stiffness of the preform caused by a sewing or tufting step.

Summary

The conducted study shows the potential of varying several parameters for the increase of out-of-plane permeability of preforms produced by DFP. In conclusion, it has been shown, that all the examined approaches enhance the out-of-plane permeability of the DFP-preforms although the magnitude of the effect varies. In detail the tests have shown the following:

Insertion of flow channels by tufting

Besides woven fabrics, non-crimp fabrics also show a good impregnation behavior. As they do not possess macro-flow channels introduced by the weaving of separated yarns, the relatively high permeability can be attributed to the fiber-free regions in thickness direction around which the stitching points have created the resulting flow channels. The influence of this effect was also tested for the preform.
Figure 9  Micro-section (fibers in ± 45°) of a tufted preform after VARI-injection. Sewing yarn shown in the middle, the black areas emerge in the resin-rich zones.

Figure 10  µCT-scan of injected DFP-preform: Horizontal cut of one layer with yarn and gaps in layer caused by yarn (left), depiction of cutting plane (right)
well as its applicability to curved geometries will have to be
furthermore, the variation of process parameters in the tufting
or modification of layup sequence.

- Tufting of DFF-preforms showed the highest effectivity
  with a permeability increase of more than a factor of 30,
  although this represents an additional step required for
  an efficient LCM process.

To apply the aforementioned methods to enhance permeability
for future processes, further research work is necessary.
For example, the influence of the applied measures on the
mechanical properties has to be examined, especially when
tufting or modification of layup sequence. Furthermore, the variation of process parameters in the tufting
step which shows the greatest enhancement potential as well as its applicability to curved geometries will have to be studied.

Funding
The research project was financially supported by the Stiftung Rheinland-Pfalz für Innovation within the project “Entwicklung eines Online-Beindung- und Ablegeverfahrens zur automatisierten Herstellung lastoptimierter Preforms”.

Disclosure statement
No potential conflict of interest was reported by the authors.

References
1. R. Lässig, M. Eisenhut, A. Mathias, R. T. Schulte, P. Peters, T. Kühmann and T. Waldmann: “Serienproduktion von hochfesten Faserverbundbauteilen - Perspektiven für den deutschen Maschinen- und Anlagenbau (Serial production of high strength fiber composite parts – perspectives for german plant construction and engineering)”, 2012, München/Munich, Roland Berger Strategy Consultants.
2. P. B. Nedanov and S. G. Advani: ‘Numerical computation of the fiber preform permeability tensor by the homogenization method’, Polym. Compos., 2002, 23, 758–770.
3. R. Zirn: Anforderungen an die Pressentechnik bei Der Produktion Von CFK-Karosserieelementen, Leichtbau-Technologien Im Automobilbau, (W. Siebenpfeiffer) (Requirements on press technology for the production of crfp vehicle body parts, lightweight technologies in automotive engineering), 2014, Wiesbaden, Springer Fachmedien.
4. R. Chaudhari, M. Pick, G. Geiger, O. Schmidt, P. Elsner and F. Henning: ‘Compression RTM – A new process for manufacturing high volume continuous fiber reinforced composites’, in 5th International CFK-Vallley Stade Convention, 2011, Stade.
5. H. Darcy: Les Fontaines Publiques de la Ville de Dijon [The public fountains of the city of Dijon], Libraire des Corps Imperiaux des Ponts et Chaussées et des Mines, 1856, Paris, Victor Dalmont.
6. P. Bhat, J. Merotte, P. Simacek and S. G. Advani: ‘Process analysis of compression resin transfer molding’, Compos. Part A, 2009, 40, 431–441.
7. J. Kozeny: ‘Über Die Kapillare Leitung Des Wassers Im Boden [About the capillary conduction of water in soil]’, Wien. Akad. Wiss., 1927, 136.
8. P.C. Carman: ‘Flow of gases through porous media’, 1956, London, Butterworths.
9. K. M. Pillai and S. G. Advani: Numerical and analytical study to estimate the effect of two length scales upon the permeability of a fibrous porous medium, Transp. Porous Media, 1995, 21, (1), 1–17.
10. C. Binétruy, B. Hilaire and J. Pabiot: “The interactions between flows occurring inside and outside fabric tows during rtm”, Compos. Sci. Technol., 1997, 57, 587–596.
11. J. Poiseille: ‘Le Mouvement Des Liquides Dans Les Tubes De Petits Diamètres [The movement of liquids in tubes of small diameters]’, 1844, Paris, Imprimerie Royale.
12. A. Scheidegger: ‘Physics of flow through porous media’, 1963, Toronto, University of Toronto.
13. M. Arnold: ‘Einfluss Verschiedener Angusszusaten Auf Den Harzinjektionsprozess Und Dessen Simulativen Abbildung: Influence of different sprue scenarios on the resin injection process and its simulative description’ in ‘IWV Schriftenreihe Band 110’, 2014, Kaiserslautern, IWV GmbH.
14. S. Draper, A. Pagot, A. Vaurin and P. Henrat: ‘Influence of the stitching density on the transverse permeability of non-crimped new concept (NC2) multiaxial reinforcements: measurements and predictions’, Compos. Sci. Technol., 2002, 62, 1979–1991.
15. V. Antonucci, M. Esposito, M. Ricciardi, M. Raffone, M. Zarelli and M. Giordano: ‘Permeability characterization of stitched carbon fiber preforms by fiber optic sensors’, Express Polym. Lett., 2011, 5, (12), 1075–1084.
16. R. S. Parnas, K. M. Flynn and M. E. Dal-Favero: ‘A permeability database for composites manufacturing’, Polym. Compos., 1997, 18, 623–633.
17. T. S. Lundstrom: ‘The permeability of non-crimp stitched fabrics’, Compos. Part A, 2000, 31, 1345–1353.
18. M. Louis and U. Huber: ‘Investigation of shearing effects on the permeability of woven fabrics and implementation into LCM simulation’, Compos. Sci. Technol., 2003, 63, 2081–2088.
19. A. Endruweit and P. Ermanni: ‘The in-plane permeability of sheared textiles. Experimental observations and a predictive conversion model’, Compos. Part A, 2004, 35, 439–451.
20. P. Smith, C. Rudd and A. Long: ‘The effect of shear deformation on the processing and mechanical properties of aligned reinforcements’, Compos. Sci. Technol., 1997, 57, 327–344.
21. E. Heardman, C. Lekakou and M. G. Bader: ‘In-plane permeability of sheared fabrics’, Compos. Part A, 2001, 32, 933–940.
22. C. Demaría, E. Ruiz and F. Trochu: ‘In-plane anisotropic permeability characterization of deformed woven fabrics by unidirectional injection. Part I: Experimental results’, Polym. Compos., 2007, 28, 797–811.
23. M. Arnold, M. Caujati and P. Mitschang: Influence of the shearing of textiles on the in-plane permeability’, in ICCM19, 2013, Montreal, International Committee on Composite Materials.
24. H. Talvensaari, E. Ladstätter and W. Billinger: ‘Permeability of stitched preform packages’, Compos. Struct., 2005, 71, 371–377.
25. G. Rimmel et al. Maximizing the out-of-plane-permeability
32. M. Arnold, G. Rieber and P. Mitschang: ‘Permeabilität als Schlüsselparameter für kurze Zykluszeiten [Permeability as key factor for short cycle times], Kunststoffe, 2012, 3, 45–48.

31. C. Rudd, M. Turner, A. Long and V. Middleton: ‘Tow placement studies for liquid composite moulding,’ Compos. Part A, 1999, 30, 1105–1121.

30. M. Belhaj, M. Deleglise, S. Comas-Cardona, H. Demouveau, C. Binetruy, C. Duval and P. Figueiredo: ‘Dry fiber automated placement of carbon fibrous preforms,’ Compos. Part B, 2013, 50, 107–111.

29. C.-H. Shih and L. J. Lee: ‘Tackification of textile fiber preforms in resin transfer molding,’ J. Compos. Mater., 2001, 35, 1954–1981.

28. G. Estrada, C. Vieux-Pernon and S. G. Advani: ‘Experimental Characterization of the Influence of Tackifier Material on Preform Permeability,’ J. Compos. Mater., 2002, 36, 2297–2310.

27. R. Umer, S. Rao, J. Zhou, Z. Guan and W. Cantwell: ‘The low velocity impact response of nano modified composites manufactured using automated dry fibre placement,’ Polym. Poly. Compos., 2016, 24, 233–240.

26. D. Becker and P. Mitschang: ‘Measurement system for online compaction monitoring of textile reaction to out-of-plane impregnation,’ Adv. Compos. Lett., 2014, 23, 32–36.