INFLUENCE OF THE PRODUCTION PARAMETERS ON THE TRANSVERSAL PERMEABILITY OF PREFORMS PRODUCED WITH AUTOMATED FIBRE PLACEMENT

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Abstract

Automated Fibre Placement has been established for serial production of complex CFRP parts within the last years. While most applications are using conventional prepreg and autoclave production chains the potential of dry bindered materials is turning into focus. Following the preforming process, usually one of the numerous liquid composite moulding technologies with transversal impregnation direction is used. A challenge still is the reproducible and reliable impregnation of the compact and undulation free preforms. The dominating parameter for this process is the transversal permeability. Within the presented work, several production parameters of the AFP production process such as the compaction force and binder activation temperature have been investigated and their influence on the transversal permeability was tested. Moreover, the effect of the distribution of gaps within the preform, known as staggering, was analysed.

1. Introduction

The economic aspect and the lightweight potential are two of the major points for a successful use of CFRP in serial production. The Automated Fibre Placement (AFP) technology is providing benefits to both aspects. The additive manufacturing of carbon tows reduces material scrap to a minimum compared to the conventional use of woven or non-crimp fabrics (NCF). With the material cost in most cases, being between 50% and 75% of the total cost [1-3] the economic benefit is most likely to be seen. Since the AFP process provides the technology to place the carbon exactly according to the load path the fibre material is most effectively used resulting in further economical and lightweight benefits. Especially for large complex structures the combination of the AFP technology with liquid composite moulding (LCM) processes such as the Vacuum Assisted Resin Infusion (VARI), Vacuum Assisted Process (VAP), Compression Resin Transfer Moulding (C-RTM), Wet Compression Moulding (WCM), Resin Film Infusion (RFI) is becoming an attractive alternative to the prepreg-autoclave process [4-7]. With the material suppliers doing fast process in developing dry bindered carbon tows [8-10] and the proof of several research institutes and AFP machine suppliers to provide reproducible and reliable high quality preforms with the AFP technology [11], the impregnation process is coming into focus [12-15]. Arising from the good alignment without significant undulation or gaps within the carbon fibres the permeability of the preform is comparatively low and the impregnation can be challenging [16]. In the presented work, different approaches to optimize the permeability of preforms made from dry bindered tows using the AFP technology have been investigated.

2. Methods

For the presented work, a commercial available AFP machine by Coriolis Composites SAS was used (see. Figure 1). The transversal permeability of the preforms was tested using an enhanced transversal saturated test method developed by Fraunhofer IGCV. Both methods are presented hereafter in more detail.

2.1. AFP technology

The Automated Fibre Placement (AFP) technology is characterized by several key aspects. In general, the AFP machines run with tows cut or spread to a precise width of 1/8” to 1,5”. Either single or multiple (up to 32) tows are placed at the same time according to a predefined layup courses. Each tow can be fed and cut individually along the layup course. The overall scrap of fibre material is therefore reduced to a minimum and near net shape production is possible. Using portal machines with numerous axes or standard industrial robots the layup course can be three-dimensional. Hence the fibres can be placed according to the load path in the most efficient way. To keep the materials at the tooling, heat is applied to the material (and the substrate) and a roller is compacting the material to the tool surface or the previously placed substrate layers (Figure 2). The AFP technology is capable to process dry bindered materials as well as thermoplastic or thermoset prepregs with slightly different machine configurations (usually adaptions of the energy application method).
Besides the choice of the material, several machine parameters can be modified to approach the challenges of the preforming process. For thermoplastic and thermoset prepregs some literature dealing with these aspects can be found in [17-19]. One major challenge that needs to be addressed when using the AFP technology with dry bindered materials to produce preforms is the subsequent process of the resin infusion.

Figure 1. Automated Fibre Placement Equipment

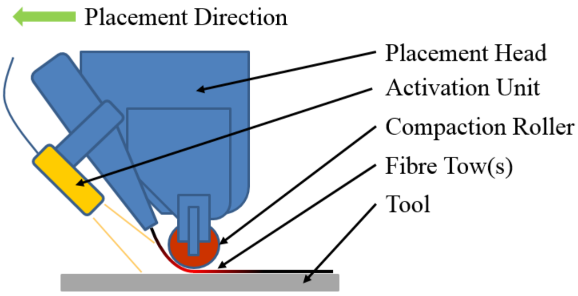

Figure 2. Schematic drawing of Placement Head

2.2. Permeability testing

Based on the anisotropic behaviour of fibre textiles, its permeability is given by a second order tensor. By a suitable rotation of the axis, only the major components on the diagonal are different to zero. K_{11} and K_{22} represent the parameters of the inplane permeability and K_{33} the offplane permeability value, also known as transversal permeability. The known test procedures to experimentally gain these values group into methods for inplane and transversal permeability testing. An overview is presented in [20] and for inplane methods [21,22] is showing an international benchmark of the widespread methods used.

For the K_{33} parameter, the first international benchmark was performed in 2017 and the results will be published in 2018. The values presented in this work were generated using an enhanced saturated testing method for transversal permeability developed by the Fraunhofer IGCV [23] avoiding systematic issues that have been identified in previous experiments [24].

2.3. Current theories of permeability influencing factors

Based on the law of Hagen-Poiseuille the pressure drop within a tube is proportional to the mean diameter of the tube. This approach can be transferred to fibre textiles. The mean length between filaments or respectively the Fibre Volume Fraction (V_f) is proportional to the permeability value. It thus is obvious that a higher compaction and thus lower V_f of the preform is resulting in lower permeability values.

Another influencing factor dealing with dry textiles occurs when binder is used. The intended purpose for the use of binder is to fix the position of the placed tows at the tool surface or the previously placed material. This is achieved by applying energy just prior the tows are placed. Resulting from that, the binder softens and after the tows are pressed onto the substrate material solidifies again binding the newly placed tow to the surface or the substrate.

The influence of the binder on the permeability is believed to depend on the binder mass content and the activation temperature. In [25] an increasing permeability was detected for low mass content resulting from an interspace caused by the binder between the plies of the preform. However an increasing amount of binder congests the flow channels result in decreasing permeability. Results from [26] are not showing a uniform trend for binder mass and transversal permeability but a significant influence of the binder particle size was found.

3. Material

For the production of the AFP preforms carbon tows with a low-grade areal weight were used. On both sides, a binder was applied with an additional areal weight of 5-7%. The binder was able to be activated multiple times.

As test fluid for the permeability experiments a commercially available sunflower oil was used. The temperature dependent viscosity was within a range of 61-64mPa·s (temperature at test lab between 20-22°C).

3.1. Testmatrix

In order to identify the influence of several design and machine parameters on the permeability and therefore generate the knowhow to optimize the process regarding a more effective and reliable impregnation a set of standard parameters was defined. The reference layup was chosen to be a 16 plies symmetric stacking with biaxial orientation [0/90]4Sym. The preforms were placed with an eight-tow head using a programmed gap of 0,5mm between the courses. In addition, a staggering sequence was applied to avoid the 0,5mm intercourse gaps of plies with the same direction to stack directly on top of each other. The reference staggering sequence was configuration I (compare Figure 3). The activation temperature was measured by an infrared camera (emissivity of 0,95 was set constant throughout the whole test campaign). A suitable activation temperature was defined (note that due to the interaction of the laser and the hot surfaces of the material with the facing objects an absolute value for the surface temperature is not stated). The compaction force was set to 100N and the layup speed was programmed to be constant 0,4m/s which was identical to the feeding and cutting speed providing a preform produced with uniform parameters.

To show the influence of the several parameters a variation according to Table 1 was done and the transversal permeability of the produced preforms was determined.

Table 1. Testmatrix with parameter variation

Specimen Type	*Stacking sequence*	*Staggering sequence*	*Activation Temperature*	*Compaction force*	*Layup speed*	*Gapwidth*	*Gap amount*
	-	-	°C	N	m/s²	mm	gap after x-th tow
Reference	[0/90]4Sym	Config I	**T_ref**	100	0,4	0,5	8
T_low	[0/90]4Sym	Config I	**0,9 · T_ref**	100			
T_high	[0/90]4Sym	Config I	**1,3 · T_ref**	100			
F_med	[0/90]4Sym	Config I	T_ref	**400**			
F_high	[0/90]4Sym	Config I	T_ref	**800**			
Stag_CII	[0/90]4Sym	**Config II**	T_ref	100			
Stag_CIII	[0/90]4Sym	**Config III**	T_ref	100			

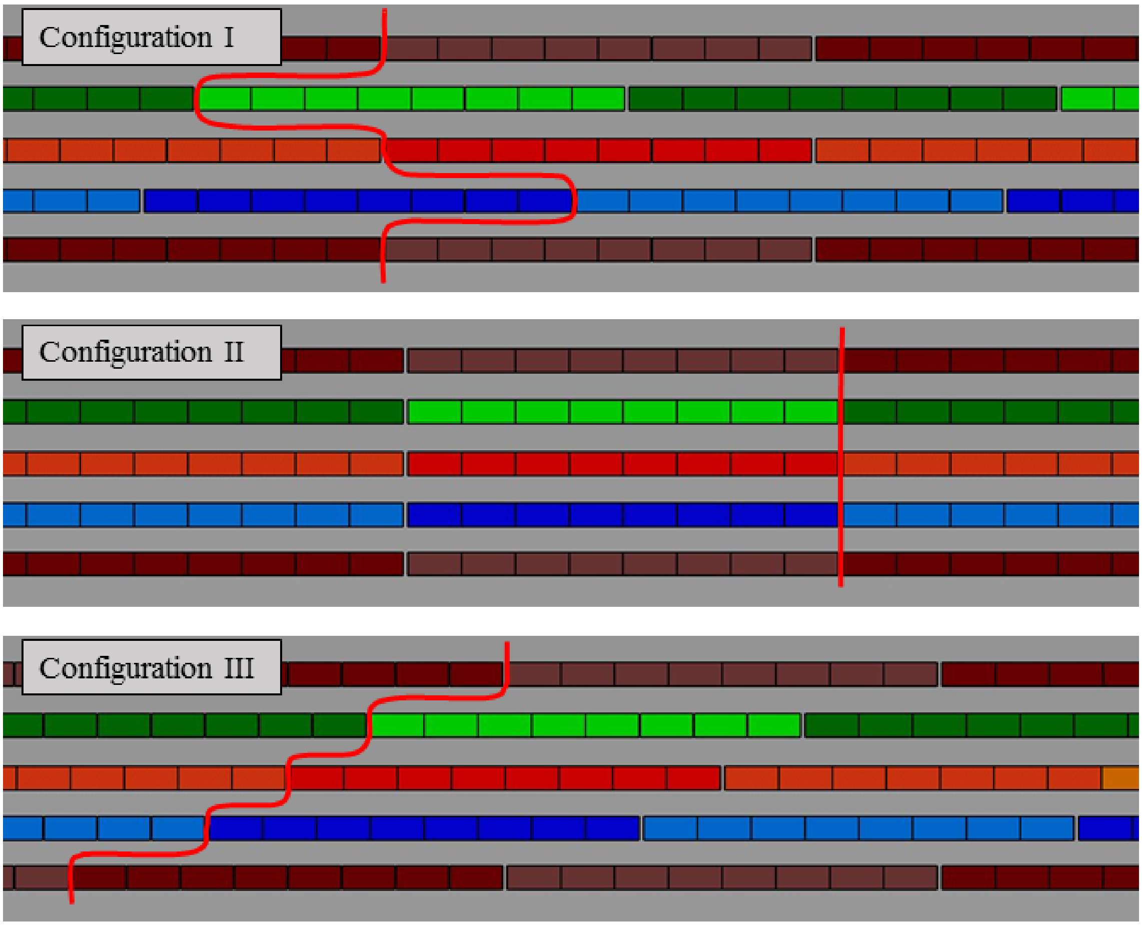

Figure 3. Staggering configurations with shortest flow path (only plies with same orientation are visualized)

4. Conduct of Experiment

For the experimental permeability tests, samples have been cut with a diameter of 199mm from the produced preforms. The mass (Kern & Sohn GmbH PLS 8000-2A balance) and the thickness (according to DIN EN ISO 5084) of each sample was determined prior to the permeability test. A minimum number of three specimen was tested for each parameter variation and the arithmetic average for the transversal permeability was calculated.

During the test the permeability equipment was installed in a conventional universal testing machine (Hegewald & Peschke Inspect 250kN). Tests with Fibre Volume Fraction of $V_f = 52\%$, 55% and 57%

have been carried out. The cavity height was therefore adapted to the preliminary calculated values using the testing machine and a stiffness correction with respect to the compaction force was included in the closed loop control of the machine.

The conduct of the experiment started with the compaction of the preform within the permeability equipment until the final cavity height was reached. Thereafter the preform was completely saturated using a pressurized tank holding a test fluid at 200mbar. When a homogenous fluid flow was detected the first data acquisition sequence was started with the same differential pressure. For 45s the mass of the recuperation buckets was logged along with the pressure difference and the temperature. Subsequently the differential pressure was increased to 400mbar and the next data acquisition sequence was started after a constant fluid flow had established. This procedure was repeated for 600mbar, 800mbar and 1bar respectively. Based on the logged data, the flow rate $\dot{Q}$ can be calculated. With the temperature values, the viscosity μ of the test fluid could be determined. Together with the pressure difference $\Delta\bar{p}$, the known preform area A and the cavity height l, the transversal permeability K_{33} was calculated according to $K_{33} = \dot{Q}\,\mu\,l/(A\,\Delta\bar{p})$.

5. Results

The results of the transversal permeability tests conducted with preforms produced using different machine parameters are presented in Figure 4 to Figure 6. All samples were tested using a cavity height resulting in a V_f of 55%.

While only a small effect can be registered reducing the activation temperature to 0,9·T_ref (K_{33} = +4%), increasing the temperature to 1,3·T_ref is reducing the K_{33} value by -24%. For an increased compaction force a trend to lower transversal permeability values can be found (K_{33} = -3% for 400N and -10% for 800N).

In addition to the variation of the machine parameters, the influence of the staggering configuration was investigated. With all gaps aligned on top of each other regarding plies with the same fibre orientation, Configuration II was expected to show significantly higher values for K_{33}. This assumption was confirmed by the test results (K_{33} = +72%). On the contrary, Configuration III with its more complex staggering method is resulting in 4% smaller values.

For the reference preform, a correlation of the transversal permeability and the V_f was conducted. The results are presented in Figure 7.

In Figure 8 the results of the thickness measurement are shown. Since all samples for the V_f variation were cut from the same preform the occurring scatter for V_f = 52%, 55% and 57% show the deviation within a single preform. For increasing activation temperatures, the thickness significantly is reduced. The same trend is found for increasing compaction forces while the staggering configuration not seems to influence the thickness of the preforms.

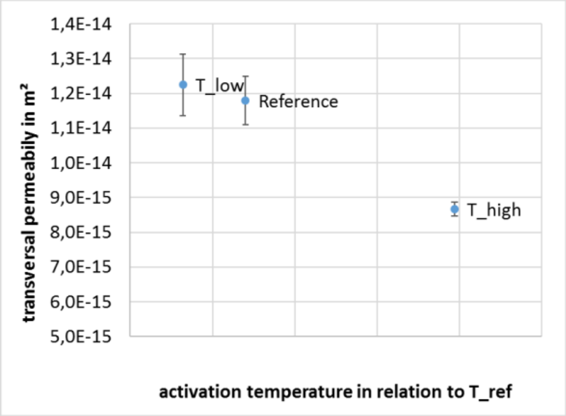

Figure 4. Transversal Permeability results depending on activation temperature

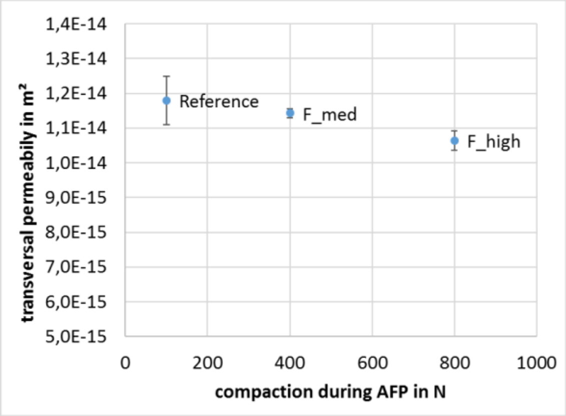

Figure 5. Transversal Permeability results depending on compaction force

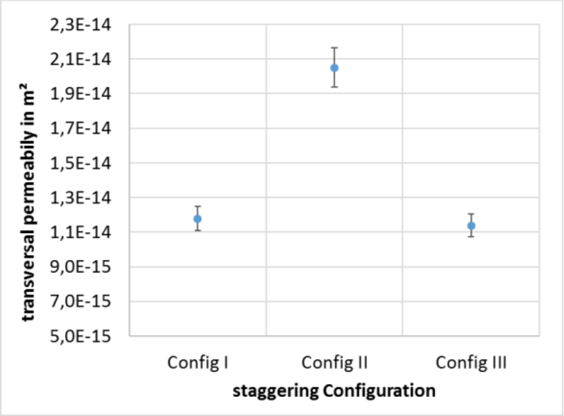

Figure 6. Transversal Permeability results depending on staggering configuration

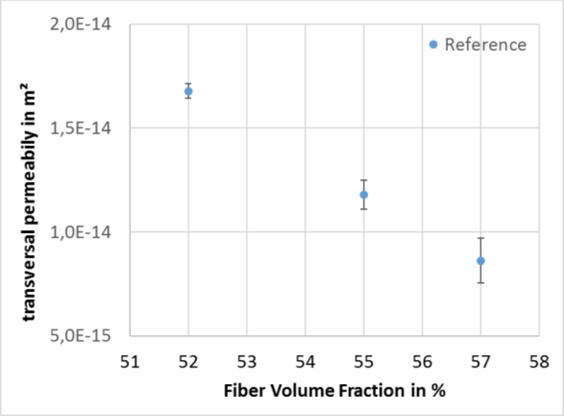

Figure 7. Transversal Permeability results depending on Fiber Volume Fraction

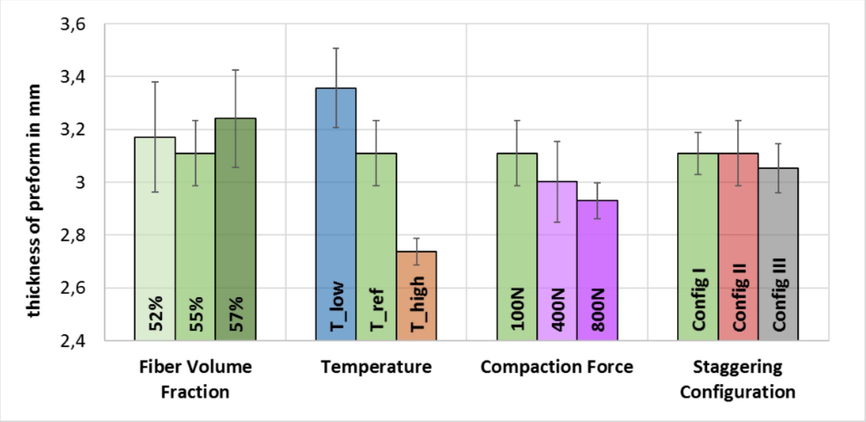

Figure 8. Thickness of samples prior to transversal permeability testing

6. Discussion

The expected correlation of the transversal permeability value K_{33} and the V_f, as found in numerous publications, was approved in the presented work (compare Figure 7). Increasing the V_f results in decreasing porosity and consequently the available space for the fluid to flow through the preform is as well reduced yielding a lower transversal permeability.

Since the binder fixes the tows at the moment when the compaction force is applied a higher compaction force results in a more compact preform (compare Figure 8) and therefore in a lower permeability.

A more compact preform is the reason for the correlation of the activation temperature and the transversal permeability value as well. The increased activation temperatures results in lower binder viscosities and the binder that is mostly at the surface of the tows distributes throughout the cross-section of the tows, fixing the inner filaments as well. In contrary lower temperatures lead only to fixation of the filaments close to the surface and the material can bulk after the compaction roller has passed leaving a less compacted preform (see results of thickness measurements).

The expected increased K_{33} value for the staggering configuration II could be shown in the experimental data. However the improved transversal permeability results from a reduced flow path length and it is expected that only areas in the vicinity of the aligned gaps are impregnated. Possible dry spots could therefore result in reduced mechanical properties of a laminate produced with this staggering configuration. On the other hand a more complex staggering method as investigated in configuration III is not showing considerable influence on the K_{33} value.

Whether the presence of binder in general has a permeability increasing effect could not be validated in the presented work since tows without binder cannot be processed with the AFP machine.
The results of the presented work are showing a general correlation of thickness reducing parameters such as activation temperature or compaction force. Consequently, the transversal permeability is reduced. It is found that for the transversal permeability both, the V_f at which the preform is impregnated as well as the process parameters of the AFP process are relevant. With a sufficient knowledge of the influencing parameters the transversal permeability of the preforms can be optimised leading to a more stable, homogenous and reliable impregnation.

7. Conclusion

Using dry bindered tows to produce preforms with the AFP technology is showing high potential for large complex structures. For a commercial use, especially the challenges about a reliable matrix impregnation need to be faced. Resulting from the precise alignments of the tows nearly without imperfections or undulations low transversal permeability values occur. The impact of this effect is even more significant when high activation temperatures and/or high compaction forces are used during the placement process. It is therefore essential to gain sufficient knowhow about the process window of the dry bindered material and the correlation of the process parameters and the permeability. With the proper choice of parameters, the permeability can be optimized for the impregnation.

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