INFLUENCE OF TEXTILE ARCHITECTURE BY PROCESSING CARBON FIBER BASED NON-CRIMP FABRICS IN AUTOMOTIVE SERIAL APPLICATION USING HIGH-PRESSURE-RTM

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Abstract

The industrial application of CFRP in automotive mass production using automated RTM-processes requires the monitoring of key materials parameters to ensure robust processes. The key parameters are the permeability, the compaction behavior and draping behavior of the carbon fiber based non-crimp fabrics (CF-NCF). All of these factors can be influenced by the textile architecture. The aim of this study was to characterize CF-NCF of identical textile design (type of carbon fiber utilized, areal weight, etc.) but different stitching style (Tricot and Pillar) in terms of their injection capacity. A methodology of CF-NCF qualification was generated, starting from laboratory and technical center scale, and progressing to high volume industrial application. The method indicated that textile permeability (especially in the transverse direction) is one of the key parameters for successful impregnation, even in thin shells typical of automotive constructions.

1. Introduction

With the introduction of BMW i, the BMW Group has clearly demonstrated the industrial application of CFRP in automotive mass production. A sustainable mobility solution has been achieved based on the "LifeDrive" architecture, which consists of an aluminum chassis and a CFRP passenger cell. This construction concept results in a significant weight reduction. The CFRP “Life module” is mainly fabricated using a complex, automated, high-pressure RTM process.
The automated processing of dry textile semi-finished products (mainly carbon fiber non-crimped fabrics (CF-NCF)) in conjunction with the use of high-pressure injection with a fast-curing epoxy matrix, enables cycle times for individual components of significantly less than ten minutes. This represents the baseline for the production rate of components required at an industrial scale.
For the further development of CFRP in an industrial environment, it is necessary to continue to meet the existing challenges the material faces. This includes cost, production, technology, reliability and environmental sustainability. A main issue in this context is ensuring robust manufacturing processes. This includes all areas of the value chain. In addition to the primary production process, all sub-

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processes must be capable and controlled along the entire process chain. Semi-finished products in particular (e.g. textiles, stacks and preforms) require high levels of process control. The understanding of the so-called "Cause and Effect relationships" of the materials used, and their interaction with the manufacturing processes, is highly important [1-3].
The identification of the significant control variables along with the removal of sources of interference will be required to effectively manage the correlation between material and relevant product properties. This work will provide the basis for process optimization, definition of the processing window, and finally the establishment of tolerances and specifications to ensure consistent component quality and cost-effective production processes.
For the automated high pressure RTM-process (HP-RTM), the main material parameters are the permeability, compaction and draping behavior of the NCF used. All of these factors can be influenced by the textile architecture, as already shown in various previous studies [4-7].
However, the presented analyses are limited to laboratory scale, pilot applications or simulative investigations. The transfer of the knowledge gained in these examinations to a large-scale industrial application relevant process such as HP-RTM (up to 100 bar) is now achievable. That enables a continuous description of the textile properties along an industrialized process chain, e.g. BMW project i.

2. Objective and Approach

Referring to the industrialized process chain of BMW project i and following Darcy’s law, the most relevant parameter for injectability is the permeability of the NCF used. Permeability can be influenced by several parameters along the process chain, ranging from product parameters such as the type of carbon fiber used, textile areal weight, stitching yarn, stitching pattern, binder system used; process parameters such as manufacturing temperatures, or even the geometric shape of the finished component [4-10].
In the experiments introduced in this study, two identical CF-NCF are examined with regard to their injection capacity. The two fabrics are identical in terms of the aforementioned textile parameters to avoid interferences from processing conditions, but differ in stitching pattern (Pillar/Franse).
Starting from the analysis of the global textile structure utilizing optical measurement methods, the corresponding permeability of these materials in the in-plane and transverse directions is measured using a simple and fast device. Based on these results, the influence of these properties on a medium-pressure RTM (MP-RTM) injection is shown for flat parts.

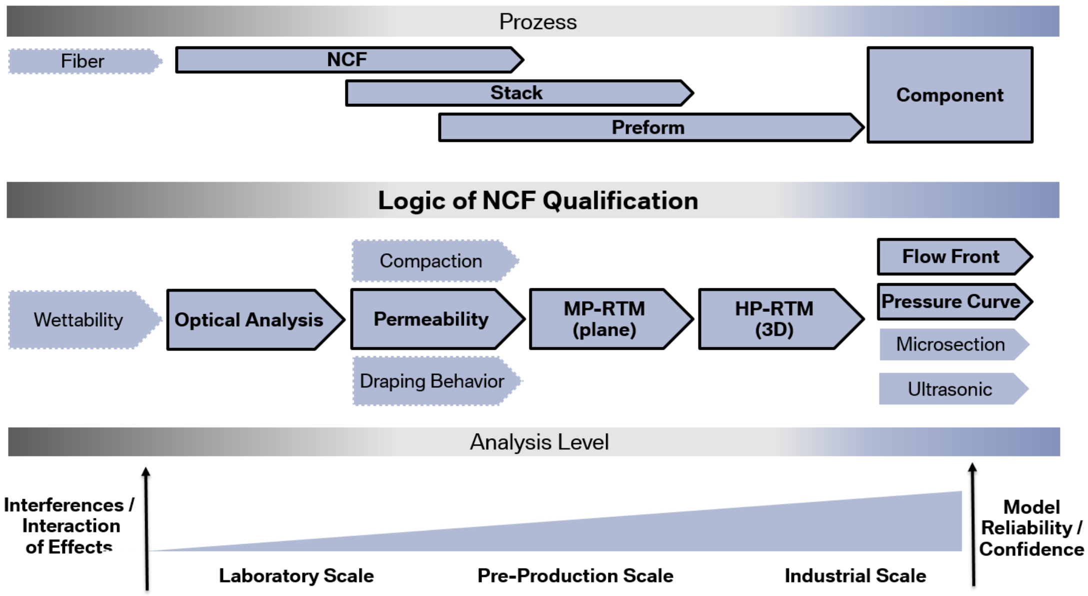

Figure 1. Logic of CF-NCF-Qualification.

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In order to meet the specified objectives of the study, the obtained results are verified in an industrial HP-RTM process by analyzing the produced parts and the corresponding pressure curves. The correlation between the measured permeability of raw textiles, industrially produced stacks and preforms, to mold filling behavior demonstrates the relevance of this measurement in a production environment. From this experimental program an examination procedure linked to the single process steps of RTM-part manufacturing can be created.
Figure 1 outlines the single stages of the planned investigations (black outlined icons) in the context of the individual process and the respective levels of analysis. It also highlights the challenges associated with using laboratory scale methods and serial conditions to verify textile behavior, particularly with concern to reliability and the expected level of interference.

3. Experimental Equipment

Based on the presented examination procedure (Figure 1) the methods used are described below.

3.1. Textile Scanning

A large flatbed scanner (size DIN A0) was used as the basis for optical analysis of textile structure. The method of image recording utilized by scanning enabled single NCF layers to be analyzed in a defined state of compaction, prior to further processing. A MatLab® based algorithm for image processing was used to enable evaluation of the scanned structure in terms of flow channel width, inhomogeneity (e.g. fiber crossings), etc.

3.2. Permeability Measurement

The permeability rig allowed the determination of the saturated average in-plane permeability ($\sqrt{K_{12}}$) and through-thickness permeability K_3. Sample preparation was equivalent to typical production conditions. Individual plies (e.g. ten layers) were layered to form a stack, compressed by a hot press to a defined fiber volume fraction (V_f) to activate powder binder on the textile, then cooled under defined conditions. This procedure reflected the single process steps from fabric, to stack, to preform. Individual specimens with a diameter of 60 mm were punched out of the flat preforms and placed in the mold of the permeability rig. The test itself was undertaken with a Newtonian fluid, in this case distilled water, at a constant pressure of 0.1 bar once the sample was fully saturated. Each sample was tested at three different V_f: 0.47, 0.53, and 0.57. A minimum of ten samples per experimental run were tested. The through-thickness permeability was calculated based on Darcy's law, and the average in-plane permeability was discerned according to the chosen radial "center to end" flow, and was calculated from the equation presented in [8].

3.3. Plane Injection (MP) and Real Part Injection (HP)

The MD-RTM experiments were conducted in a 300x700 mm flat plate mold with line gate injection. The mold was mounted on a press, manufactured by Joos (Germany) that provided clamping forces up to 1500 kN. The cavity height was variable from 1.8 mm up to 2.2 mm, which enabled fine control of the FVF. Resin impregnation was achieved using a two-component injection device, produced by Dekumed (Germany). Resin was injected at a constant flow rate, and the injection pressure was monitored up to 30 bar.
For the HP-RTM experiments an experimental production setup was used. It was composed of an existing preform mold and a matching RTM tool. Both tools were designed to be mounted within industrial production facilities. The HP-RTM process was able to achieve cavity pressures of up to 100 bar, with resin injection being provided by a three-component injection device, produced by Kraus Maffei (Germany). The required mold clamping forces were provided by a 3600 tonne press, manufactured by Schuller (Germany). The double curved RTM tool had a part size of 400x1300 mm, excluding clamping areas. It utilized a centric line gate and several sensor-controlled outlets.

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4. Experimental program

4.1. Materials

Two different unidirectional non-crimp fabrics, referred to as NCF 1 and NCF 2, were used for the laboratory and technology center experiments. NCF 1 and NCF 2 were characterized as having an identical stitching density, and a carbon fiber areal weight of 300 g/m^2. Two additional fabrics, referred to as NCF 3 and NCF 4 were utilized for the production scale HP-RTM experiments. In order to minimize the effect of fiber induced variations, all samples were made from an identical carbon fiber source (SGL ACF 50-01) and stitching yarn. The details of the fabrics are presented in Table 1. All fabrics were manufactured by SGL ACF (Germany). The resin system used for the injection experiments was epoxy resin XB3585, produced by Huntsman.

Table 1. Used CF-NCF.

Type	Carbon Fiber	CF-Areal weight (g/m²)	Orientation (°)	Stitching	Stitching density (stitch/inch)
NCF 1	50K ACF 50-01	300	0	Pillar	E 5
NCF 2	50K ACF 50-01	300	0	Tricot	E 5
NCF 3	50K ACF 50-01	300	+45	Tricot	E 3,5
NCF 4	50K ACF 50-01	300	-45	Tricot	E 3,5

4.2. Procedure

A series of experiments were performed in order to demonstrate the influence of textile architecture on filling behavior, and to confirm the competency of the proposed examination procedure. At the laboratory and pre-production scale, all of the materials used for the experiments were first tested using the textile scanning procedure. This determined the samples global textile structure, which provided precise data on the flow channel width. Using this information, four monolithic layups with known gap sizes were produced from each of the NCF 1 and NCF 2 fabric types and pressed to form a stack. The first sample for each of the two fabric types consisted of ten plies with alternating 0°/90° fiber orientations, and were used for permeability measurement. The following three samples for each fabric type consisted of six layers in the 0° direction, and were used for evaluation in MD-RTM.
For the production scale testing a second series of experiments were carried out. In order to be representative of real production conditions, a six layered stack with a fiber orientation of +45, -45, $0|_s$ was used. Two variants of this stack orientation, that utilized different fabrics, were analyzed. Stack type 1 had a fabric sequence of NCF 3, NCF 4, NCF $1|_s$, while stack type 2 had a fabric sequence of NCF 3, NCF 4, NCF $2|_s$. Samples were tested for permeability at both the stack and the preform phase, before being injected with resin in HP-RTM.

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5. Results and discussion

5.1 Laboratory and Pre-production Scale

Optical analysis of the scanned data from 30 textile samples was used to determine the average gap size of NCF 1 and 2, as shown in Figure 2. The results indicate that NCF 2 has a slightly lower flow channel width than NCF 1. The detection of roving undulation in NCF 2, shown in Figure 2, which utilizes tricot stitching, is noteworthy. The cause of this undulation is the thread guide 'constricting' single rovings during stitch formation. This undulation is not present in NCF 1.

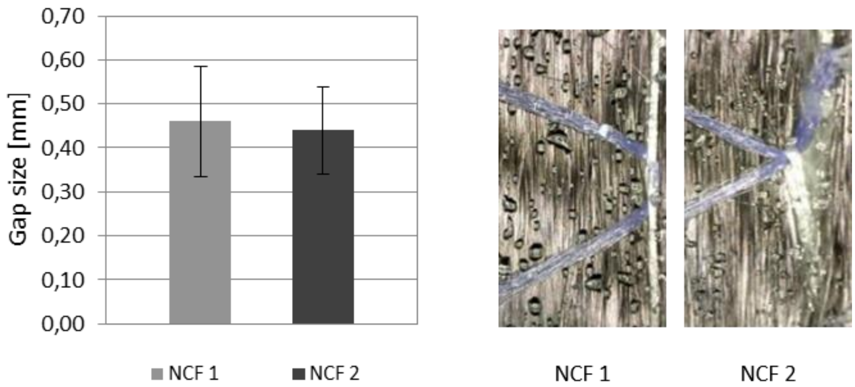

Figure 2. Measured Gap sizes (left) and microscopy of roving-undulation due to stitching (right) of NCF 1 and NCF 2.

The corresponding results of the permeability tests undertaken on the NCF 1 and 2 samples are shown in Figure 3. The results shown were from the tests undertaken at a V_f of 0.53.

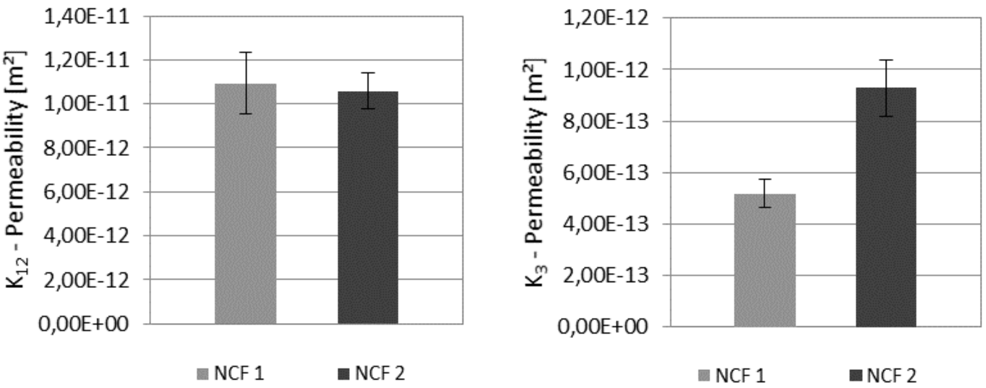

Figure 3. Permeability $\sqrt{K_{12}}$ and K_3 of NCF 1 and NCF 2 (ten layers, 0°/90°|$_5$ stacking sequence).

The data indicates that, while both fabric types have comparable permeability in the in-plane direction, NCF 2 has a higher through-thickness permeability than NCF 1 by up to 40%. The explanation for this difference was the undulation of the CF-rovings in NCF 2, uncovered during optical analysis of the fabrics. The Tricot stitching utilized in NCF 2 opens the textile structure of the fabric, which subsequently forms flow paths along the fiber direction. These paths result in an increase in transverse permeability.

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To confirm this hypothesis, plane injection experiments utilizing MD-RTM were carried out following the permeability tests. Six-layer structures with known gap sizes were injected at a V_f of 0.51, with a total of three repeats. The impregnation process was terminated once the internal cavity pressure reached 15 bar to allow the analysis of the resin flow front after injection. Figure 4 describes the results of the plane injection experiments, detailing both the total mass of resin injected and the flow front difference (FFD) for both fabric types. FFD is calculated from the difference between the detected flow front progression on the plate upper surface, as compared to the bottom. The value is given in percentage form. Taking into consideration the standard deviation of the results, there was no notable difference in the total mass of resin injected into each fabric type. However, there was a significant difference in FFD between the fabric types. Despite the wide range of deviation between samples, the FFD of NCF 1 (18%) exceeds NCF 2 (7%) considerably.

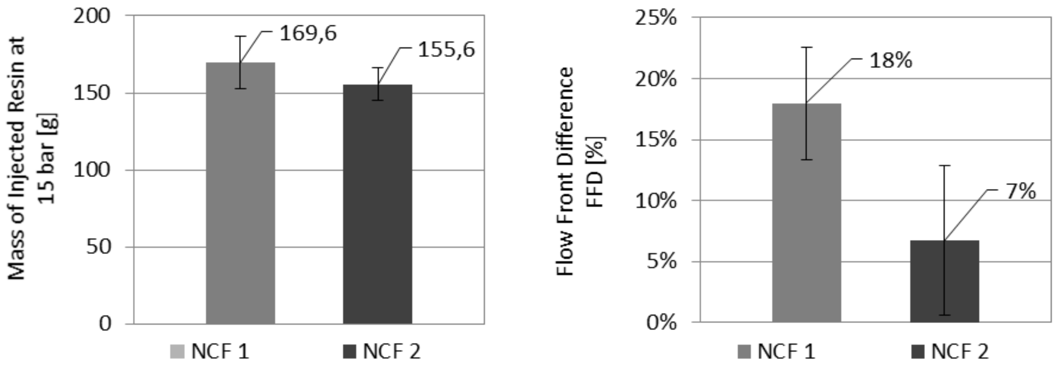

Figure 4: MD-RTM-Injection: mass of injected resin at 15 bar (left) and flow front difference (right).

The difference in FFD between NCF 1 and 2 can be attributed to the difference in through-thickness permeability of the fabrics. For NCF 2 the resin spreads homogeneously in the in-plane and transverse directions towards the gate, whereas for NCF 1 the lower through-thickness permeability impedes the flow in the transverse direction, resulting in a lag in the flow front on the bottom face.

5.2. Industrial Level

Prior to HP-RTM each textile sample was tested for permeability in the through-thickness direction at both the stack and preform stage. Figure 5 presents the results obtained for Stack 1, Stack 2 and the corresponding Preform 1 and Preform 2.

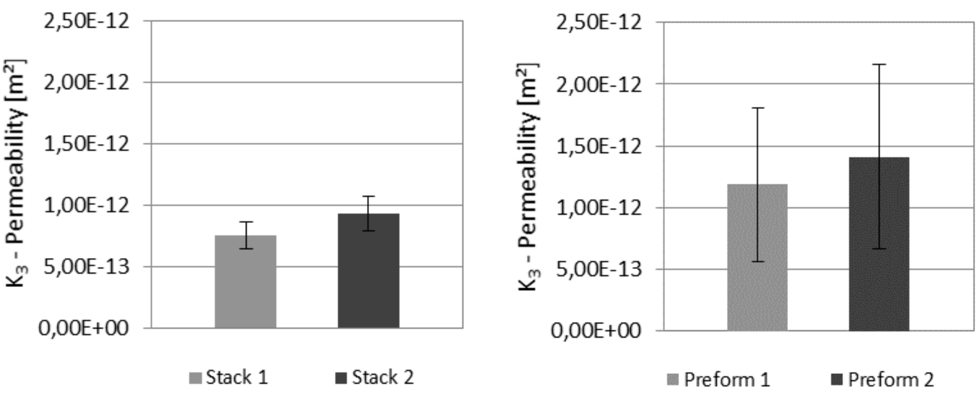

Figure 5. Permeability K_3: Stack 1 and Stack 2 (left) / Preform 1 and Preform 2 (right).

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There is noticeable difference in permeability between the layup types studied at both the stack and preform stage, reflecting the results of the previous laboratory and preproduction scale tests. Again NCF 2 shows a higher permeability in the transverse direction than the comparable NCF 1 setup. The difference is less distinctive than in the previous tests, due to only two of the six layers being varied between samples types. Additionally, there was an increase in the variation of the results, particularly in the preform tests. This is due to the deformation that occurs while processing a stack into a preform, activating local shearing and draping responses in the material, which lead to macro- and microscopic variation of the carbon fiber-roving orientation. As a result of this, the textile structure and effectively V_f vary locally, causing the large variability in the measured permeability.

To verify the effect of differences of permeability in the transverse direction, injection tests were carried out under industrial production conditions. Evaluation of the injection pressure during the injection phase indicated there were significant differences between samples with different permeabilities. Figure 6 presents representative mold cavity pressure curves obtained from the two different layup types. For each variant, the average injection pressure, along with the minimum and maximum values, are presented.

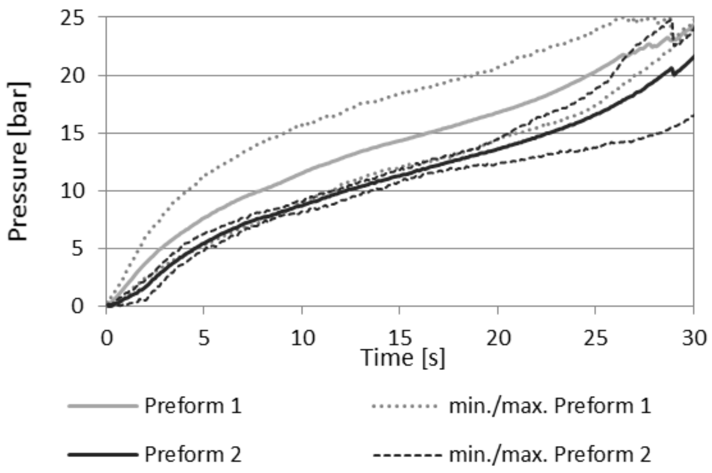

Figure 6. HP-RTM: Pressure curve of Preform 1 (based on NCF 1) and Preform 2 (based on NCF 2), six-layer setup (3,4,2|$_s$ and 3,4,1|$_s$).

The presented results highlight several important points. It can be noted that the average injection pressure curve for Preform 2 matches well the minimum injection pressure curve of Preform 1. By comparing both average pressure curves at 15 bar, with the tests being undertaken at a constant flowrate of 25 g/s, a difference of 155 g in the average injected mass of resin can be determined. This correlates to a 27% greater resin mass for Preform 2 over Preform 1. This result is confirmed by the visual evaluation of the filling behavior of components produced with a defined pressure cutoff at 25 bar cavity pressure. Visual inspection shows that the parts based on NCF 1 injected notably less resin by the time the pressure cutoff was reached. In these samples dry areas, superficial pores and a loss of clamping can be observed. Although these features are still present in NCF 2, they were far less prevalent.

6. Conclusion

This study demonstrated the correlation of CF-NCF textile properties measured at low, laboratory scale pressures, to results observed in pre-production and production level processes. The results of the laboratory scale, water based tests with pressures in the order of 0.1 bar, proved to be sufficiently

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precise and strongly correlated to textile behaviors in pre-production MP-RTM processes. In addition, the laboratory scale tests were also found to be able to indicate sample textile behavior in industrially relevant, three-dimensional HP-RTM applications.

Through the testing regime it was indicated that in-plane permeability alone is not sufficient to determine the filling behavior of thin CF-NCF samples. The results showed that filling behavior is influenced to a large extent by the transverse permeability of the sample. Samples which utilized tricot stitching were found to have a much higher injection capacity than those which utilized pillar stitching. This was due to the tricot stitch creating 'tight' rovings and subsequently increasing the area of flow paths in the through-thickness direction.

Of particular note was the large deviation of results in the tests. This indicates that industrial manufacturing processes for producing CFRP components must be robust enough to compensate for large variations in textile properties.

The confirmation that changes in the impregnation behavior of CF-NCF based semi-finished products can be detected at each stage of the production process highlights important regions for the development of industrial CFRP processes. The finding shows the strong benefit that a fast and easy permeability measurement method would have in an industrial application.

In the current state, permeability tests are time and cost intensive, prohibiting their use at a production scale. The development of non-destructive testing technologies will be required in order to affect actively monitored processes.

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