INVESTIGATION INTO THE VARIABILITY OF CARBON FIBER NON-CRIMP FABRICS AND ITS INFLUENCE ON THE RTM-PROCESS

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Abstract

The introduction of low cost carbon fiber non-crimp fabrics (NCF) in high volume carbon fiber reinforced plastics (CFRP) production is associated with increased levels of variability in textile properties with relevance to liquid composite molding processes. The aim of this study is to verify the validity of a non-destructive measurement concept to quantify unidirectional NCF and stack properties, and provide direct correlations of variability to performance in the high pressure resin transfer molding (HP-RTM) process. An experimental study is conducted in which the local flow channel width of unidirectional NCF plies and local thickness of stack layups is measured. The semi-finished products are further processed to HP-RTM short shot parts, and the local flow front shape is analyzed. Results validate that the combined evaluation of local flow channel width and thickness variation directly correlate to measured flow front progression in HP-RTM parts. The measured variability corresponds with deviations of local fiber volume fraction and porosity, which can cause part defects in adverse combinations. Therefore, the measurement concept will be refined to allow enhanced non-destructive quantification of textile variability. The provision of these capabilities will contribute to the development of robust RTM injection concepts, as well as preforming and injection simulation tools.

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1. Introduction

As part of Project i, BMW builds passenger compartments made of carbon fiber reinforced plastics (CFRP) in high volume production. One of the semi-finished products within the process chain are textile layups made of carbon fiber single plies. These so-called “stacks” are processed to form preforms, and subsequently RTM parts (as summarized in Fig. 1).

Figure 1. HP-RTM process chain from single plies to parts

The knowledge and understanding of the influence of single ply and stack properties on the subsequent process steps is of high relevance. The overall objective is the use of low cost carbon fiber fabrics, in order to implement economic production of CFRP components on an industrial scale. The key challenge is the high variability within such textiles. In addition, common measurement methods are often slow and destructive, and do not allow direct correlations between textile properties and the HP-RTM process to be made. In this paper, we focus on the following aspects to help design future high volume manufacturing processes:

- Approaches to quantify relevant local textile (single ply and stack) properties to RTM filling.
- An experimental study with a non-destructive and rapid measurement concept that allows direct correlation of textile variability of stacks made up of unidirectional carbon fiber non-crimp fabric (UD-NCF) plies to local flow front progression and defects in 2D RTM parts.

2. Relevant textile properties to RTM

2.1. Textile construction of UD-NCF

The textile construction of non-crimp fabrics is characterized by the number of fiber bundles within a certain width and their orientation. UD-NCFs consist of one or several fiber layers in one direction [1]. Textile structure is further influenced by the areal weight as described in ISO 3374 and the applied stitching pattern, e.g. pillar, tricot, or cord stitch according to ISO 4921. In addition, binder materials can be applied to allow automated preforming [2]. The width between two fiber bundles is in parts of literature called flow channel. When several UD-NCF plies are stacked, several types of nesting can be observed depending on the layup sequence. Nesting can be reduced via multiple methods e.g. tricot stitching, or weft insertion perpendicular or diagonal to the CF fiber bundle orientation [3].

2.2. Variability of textile properties

Variability can be understood in the sense of deviations of properties in the carbon fiber product for various reasons, including raw material variation and process parameter variation [4]. Textile properties that affect permeability and compaction behavior include the areal weight and the architecture of a particular NCF. The areal weight is directly proportional to the fiber volume fraction [5]. Local deviations of areal weight, density, textile construction or certain local textile defects (e.g. gaps) lead to local variability in fiber volume fraction for the case of constant cavity thicknesses, as in common RTM tools. In manufacturing processes, variability can additionally be caused by improper cutting of fiber plies, misplacement of preforms in the RTM tool or uneven compression of preforms [6]. Nesting also affects the fiber volume fraction due to different packing densities of the fiber bundles [5].

Porosity is calculated based on fiber volume fraction. It is defined as the proportion of the cavity, which is filled with resin during impregnation, if the laminate is void freed. Zones of high porosity have a low flow resistance. This can lead to the so called “race tracking” effect, i.e. the flow front progression is altered. This is particularly true for edge zones, if the reinforcing fibers do not completely fill the cavity and therefore small gaps at tool edges are formed. [7, 8]

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2.2. Compaction, Permeability

Carbon fiber semi finished products are repeatedly compressed in manufacturing processes. In particular, during preforming or in RTM tools, there is a compaction of the textile structure to the micro level [5]. Distinction has to be made between compression in the fiber direction and transverse compaction. The latter always occurs in the HP-RTM process chain (Fig. 1), even if there is no draping in the preforming step.

The increase in force during the compaction of flat textile structures (as when closing a preform or RTM tool) is highly nonlinear. The semi-finished fiber is elastically deformed with additional plastic share. In addition, the deformation is time- and speed-dependent. If the target thickness is reached, a reduction in compression force can be observed, since the fibers are subject to frictional sliding at the micro level. The compaction behavior of semi-finished fiber products can thus be summarized as viscoelastic. In the literature, compaction behavior is therefore described with different mechanical models. [9]

Permeability describes the resistance to fluid flow through a porous medium. One way to describe the impregnation behavior of semi-finished fiber products provides the flow law of Darcy. It is a simplification of the general vectorial form of the Navier-Stokes equations. It describes the velocity of a fluid in a saturated porous medium depending on the applied pressure gradient, the viscosity of the fluid and the permeability of the porous medium. [7, 6]

Permeability can be estimated computationally with different methods. A detailed summary can be found in a work of SHARMA AND SIGINER [10]. It should be noted that the permeability is dominated by capillary forces in the rovings at low injection pressures. Due to the pressure levels in the HP-RTM process it is assumed that resin flow in the textile flow channels is dominant [11].

3. Non-destructive measurement methods for textile variability

Various established methods for the measurement of compaction response and permeability exist. However, permeability and compaction testing usually require the cutting of samples, and/or the use of liquids, leading to destructive measurements. Therefore, no direct correlation is possible to a subsequent RTM process, utilizing the same material for characterization and production.

Established methods for variability characterization of CFRP parts include computer tomography [12]. Concepts for quality control of carbon fiber products range from simple camera solutions up to inline integration of machine vision systems for quality inspection [13]. A patent describes a vacuum assisted measurement method for waviness of textile single fabric plies [14]. This method is adapted within this study for the measurement of stack layups made of multiple textiles and subsequent local stack thickness characterization. Another non-destructive measurement method is eddy current testing, which can be applied to CFRP parts as well as semi-finished products. A review by HEUER ET AL demonstrates the strong potential for in-depth measurements of fiber-orientation and textile imperfections [15].

4. Materials

4.1. Non-crimp fabrics

Three different types of single layered UD-NCF plies (with respect to the carbon fibers) made of 50k heavy tows were utilized in this study. All ply types are reinforced with full glass fiber weft insertions perpendicular to the carbon fiber direction to minimize nesting effects. The knitting yarn is made of polyester. Binder powder is sintered to the top side of all plies to allow preforming/ hot pressing of the stacks. The used single ply types can be differentiated by their total areal weight (Type A: 180 g/m^2, Type B: 335 g/m^2, Type C: 645 g/m^2).

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4.2. Stack layups

The single plies were combined together into unidirectional stacks. Therefore, the carbon fibers of all layers are oriented in the injection direction. This is conducive to the applied line injection gate and outlet, and allows the visual determination of flow fronts across all layers. Furthermore, all methodologies can initially be validated with these simplified layups. The number of layers depends on the grammage of the single ply types, as all stacks were designed with a total areal weight of at least 1800 g/m^2. This is equivalent to a target total fiber volume fraction of at least 0,43. The layups are symmetrical with regard to the binder-side, as the layers are turned over as depicted in Figure 2.

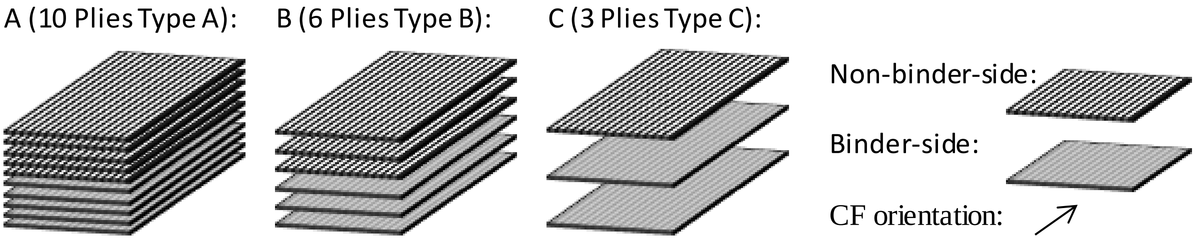

Figure 2. UD Stack layups (size 750 by 350 mm^2) for the experimental study.

5. Methods

The industrialized process chain for production of HP-RTM-Parts (Fig. 1) does exist at lab scale for material testing and qualification with smaller part sizes and experimental tools (Fig. 3). For this study the preforming step has been replaced by a hot-pressing step, in order to reduce the number of influential variables on the RTM filling behavior. Thus, stacks were not draped, instead being made available as stiff 2D preforms suited for the HP-RTM process. In order to analyze the local flow front shape during injection, preforms were only partially injected as short shots.

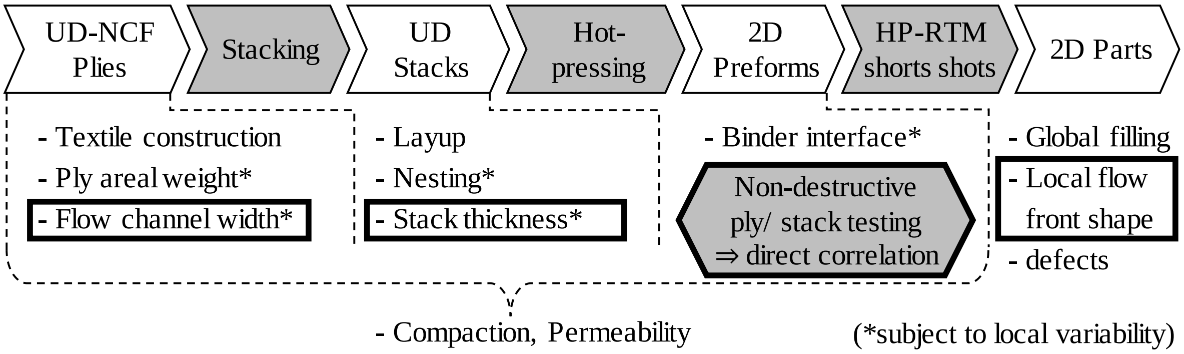

Figure 3. Utilized process chain with selected properties for non-destructive testing within this study.

Relevant single ply and stack properties that characterize injection behavior were selected based on the literature summarized above. This study focuses on measurement of local flow channel width of single plies and thickness measurements of UD stacks. Through the use of non-destructive testing, the characterized samples can be further processed through the RTM process. The aim of this study is to directly correlate the measured locally variable properties to the local flow front in short shot RTM parts. Furthermore, the non-destructive testing concept is to be verified for future studies.

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5.1. Experimental sequence

UD-NCF plies were cut from textile rolls (Fig. 4a), and the local flow channel width was measured. The variation of flow channel width was quantified and plies were sorted by flow channel variability (Fig. 4b). After stacking, the local stack thickness was optically measured (Fig. 4c). Then, the flow front shape of the RTM short shot parts was analyzed with regard to the measurement results (Fig. 4d). In total, 10 stacks and RTM parts were manufactured and tested (Table 1). Finally, microsections were taken from selected characteristical parts to validate the measurement results (Fig. 4e).

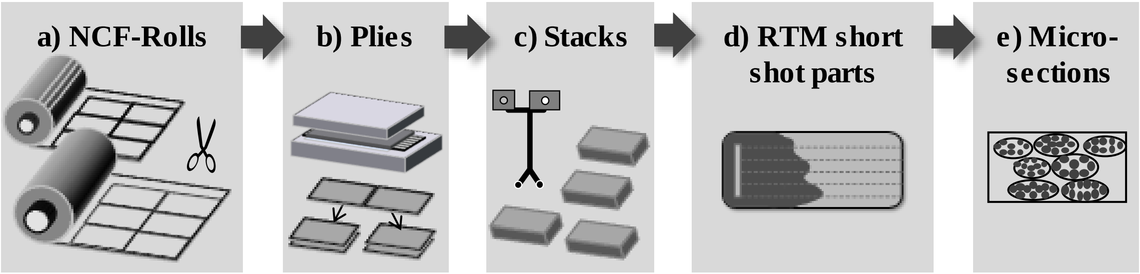

Figure 4. Sequence of experimental study.

5.2. Measurement of flow channel width

A flatbed scanner, enhanced with a light unit was used for scanning of individual plies. To ensure a reproducible compaction and measurement of flow channel width, the NCF plies were placed below a glass plate. After scanning the local flow channel width was analyzed with an image-processing algorithm. Variability of flow channel width could be determined based on 225 local measurement values for each NCF ply by calculating the coefficient of variation.

5.3. Measurement of local stack thickness

Structured light scanning was used for measuring the local stack thickness (Fig. 5). The position of the camera was made independent of its position relative to the surface plate through the use of an initial reference scan and reference marks. The stack surface was compacted by pulling vacuum under a bag to obtain a flat stack compression, as found in the subsequent manufacturing process steps of hot-pressing and HP-RTM.

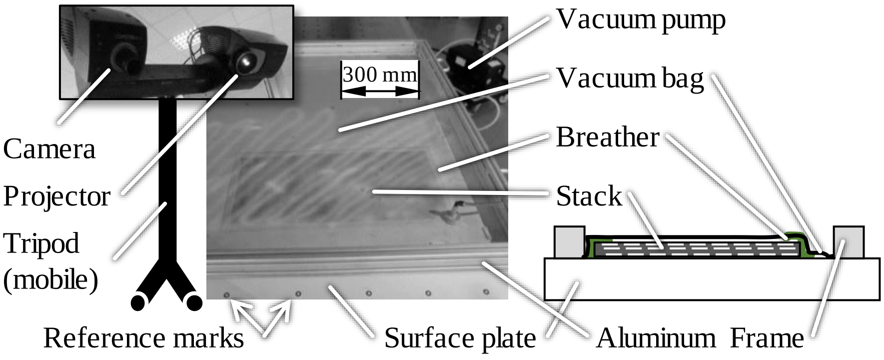

Figure 5. Experimental setup for measurement of thickness variation in stacks.

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5.4. High Pressure RTM short shot part manufacturing

All stacks were hot-pressed to form stiff 2D preforms before they were processed into partly filled RTM parts with a size of 700 by 300 mm^2. The utilized RTM tool uses a line injection gate and vent. It was mounted in a press that allows a closing pressure of 200 bar at the set cavity thickness of 2,3 mm. An epoxy resin system was injected at a rate of 11 g/s. The short shots were realized by stopping the injection process at a pressure of 15 bar.

6. Results and discussion

The total flow channel pattern of all stack layups (Table 1) was calculated by averaging the local flow channel width of each single ply. The results were visualized (as for layup A-4 in Fig. 6a) along with the corresponding local stack thickness (as in Fig. 6b) and the resulting flow front shape of the lower side of the part (as in Fig. 6c). Example areas of high local stack flow channel width and large stack thickness are labeled exemplarily.

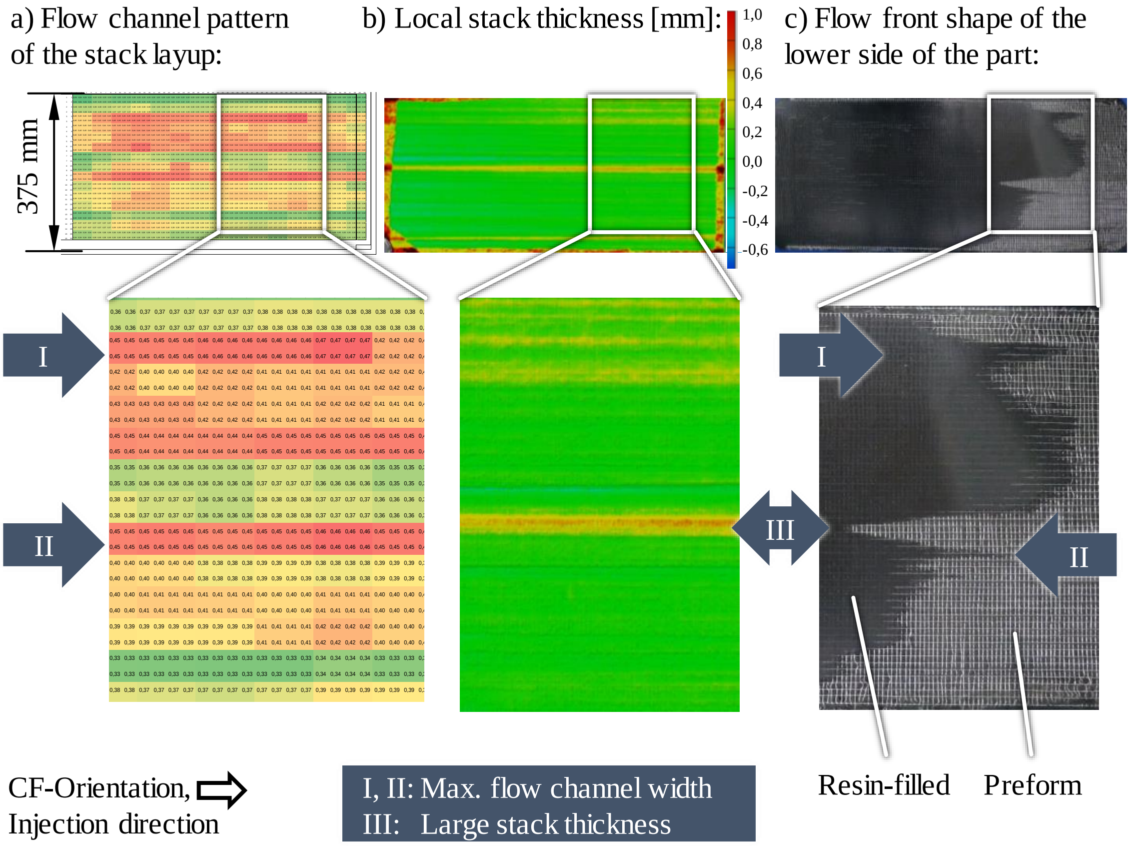

Figure 6. Comparison of stack flow channel pattern, local thickness and RTM part flow front shape of stack layup A-4 (high local variability in stack flow channel pattern and thickness).

It is evident that the local flow front shape correlates with both the flow channel pattern within a stack and local variations in stack thickness. In regions with locally higher flow channel width, the flow front can progress faster, whereas it lags behind in regions of high local thickness. If the span of adjacent flow channels is too high, race-tracking within the stacks is observed, which even led to a dry spot for layup B-3, which had very high variability in thickness in addition to high variability in flow

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channel width. In Table 1, the correlation of flow front shape to measured variability is evaluated qualitatively for all manufactured short shot parts. The correlation is moderate for all tested stack layups with both low flow channel and thickness variability. It is good for stacks with high or moderate thickness variability and very good if both flow channel and thickness variability are high. This fits the observation that local flow front deviations rise with higher textile variability.

Table 1. Qualitative evaluation of correlation of measured variability and flow front shape.

Stack Layup	*Variability*		*Correlation to flow front shape*	Stack Layup	*Variability*		*Correlation to flow front shape*
	flow channels	*local thickness*			*flow channels*	*local thickness*	
A-1	low	low	moderate	B-1	low	high	moderate
A-2	low	high	good	B-2	low	high	good
A-3	high	high	very good	B-3	high	very high	very good
A-4	high	high	very good	B-4	high	high	very good
C-1	low	low	moderate	C-2	high	moderate	good

Microsections of characteristic spots for flow front progression allow the validation of regions measured to be of high thickness. Regions of high thickness can either be caused by several thicker or thinner adjacent rovings (Fig. 7a), or one single heavy/ bulky roving (Fig. 7b). These imperfections have to be considered as possible resin-flow stoppers or the cause of local dry spots if their manifestation is too high. The most likely reason for the observed textile imperfections is the spreading process utilized in the production of the non-crimp fabrics out of the 50k heavy tows.

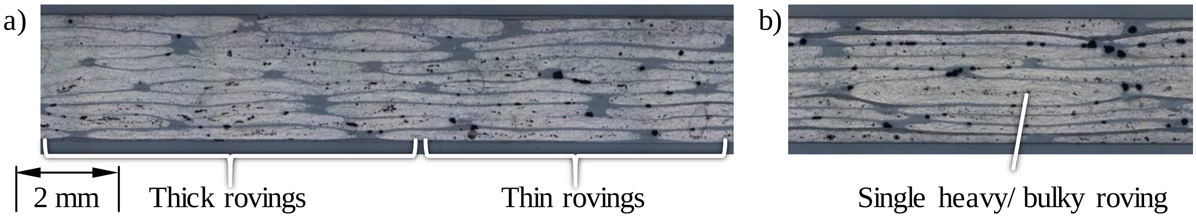

Figure 7. RTM part microsections of layups A-4 (a) and A-3 (b) at regions of large local thickness.

Within this study, layer nesting was not controlled explicitly, and varied in each stack layup based on the microsections. Therefore, its influence on flow front progression could not be studied in detail. The analysis of the stack thickness measurement by structured light scanning indicates that the accuracy of the technique is not suited for quantification of the results. A resolution of approximately 0,1 mm in the in-plane direction and 0,01 mm in the in thickness direction would enable more detailed measurements.

In summary, the combination of the utilized measurement methods allows direct correlation of local variability of textile properties and HP-RTM flow front progression to be made. Therefore, the non-destructive test concept is suited for quantification of local textile variability. It combines the textile structure-related flow channel/ porosity measurement with the local thickness measurement. Consequently, local variation in areal weight/ fiber volume fraction at the micro and meso level can be measured and characterized with regard to textile imperfections.

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7. Conclusions

Textile properties subject to variability and with relevance to RTM include local flow channel width of UD-NCF plies and stack thickness variations. The non-destructive testing and characterization of local variations in these properties was the starting point of this study. To evaluate interactions of these properties with the RTM process, two-dimensional preforms were produced, and local flow front progression was studied. Direct correlations between the flow channel pattern and the local thickness of stacks to flow front shape was verified experimentally.

Possible solutions for dealing with the observed variability lie in the development of advanced RTM tools and injection concepts, which are designed in a robust way to deal with textile variability in order to minimize the risk of defects in parts. Further quantification of the described textile variability is subject to future work, as well as validation using established permeability and compaction testing methods. In addition, multiaxial stack layups will be considered with respect to possible benefits for preforming and flow front simulation tools from the non-destructive measurement concept. The utilized non-destructive measurement concept will be developed further into a quality test cell. The combination of a vacuum table, a portal robot and laser triangulation as well as eddy current scan sensors will be conducive to future studies.

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