Dry fiber placement of carbon/steel fiber hybrid preforms for multifunctional composites

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ABSTRACT
Integration of steel fibers (SF) in carbon fiber (CF) reinforced polymer composites (CFRPC) allows improvement of electrical conductivity while maintaining excellent mechanical properties, since SF also contribute to the load-carrying capacity. Due to their high ductility, also energy absorption and structural integrity can be improved. Within this study, a preforming process for hybrid carbon/SF preforms based on dry fiber placement (DFP) is developed and validated. The investigations cover the production of bindered SF rovings, the production of hybrid preforms via DFP of spread and nonspread SF rovings on CF noncrimp fabrics (CF-NCF) as well as the production of hybrid laminates via vacuum-assisted resin infusion (VARI). The laminate quality was evaluated by microscopic images and mechanical tensile testing. A higher SF volume content within the SF areas and more homogeneous SF layers in the preform (fewer matrix-rich zones) were achieved by processing nonspread SF rovings. The more homogeneous SF layers within the samples with nonspread SF rovings compared to spread SF rovings led to higher stiffness and strength of the specimens for tension loadings and therefore to best results.

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1. Introduction
Structural components made of carbon fiber reinforced polymer composites (CFRPC) are more and more required to provide a high degree of multifunctionality. An example is the lightning protection for aerospace application. While offering excellent mechanical properties, CFRPC only show low electrical conductivity compared to aluminum. Therefore, in order to ensure the required electrical conductivity for lightning protection, CFRPC are modified by additional functional materials, such as copper or bronze meshes. Such meshes do not contribute to the mechanical function of the hybrid laminate due to the poor
mechanical properties and hence the additional weight reduces the lightweight potential [1]. For this reason, the project “FUTURE” was focused on hybrid fiber reinforced polymer composites (FRPCs), which entail excellent mechanical properties and fulfill new requirements by combining steel fibers (SF) and carbon fibers (CF). It was the target that metallic fibers are no longer a parasitic material but an integral part of a hybrid composite concept in which each material is optimally utilized according to its properties. The potential for a hybrid CF/SF system in which the advantageous properties of the individual components add up and the weaknesses are compensated is shown in Figure 1.

A main aspect of the hybrid composite concept is the manufacturing strategy. FRPC-components for aeronautic applications are increasingly produced via Liquid Composite Molding [2,3]. Within this process, a dry near-net shape preform is produced in a so-called preforming process and subsequently impregnated with a thermoset resin. To increase the lightweight potential, a load-optimized fiber orientation is crucial and this has to be realized during the preforming. In this context, dry fiber placement (DFP) is of high interest as it allows undulation-free placement of bindered rovings on a tooling or a textile base structure variable in position and orientation [4,5]. Applying DFP for the hybrid composite concept allows hybridization of carbon and SF on a material level and also bypassing of textile processing of the SF, which are highly abrasive and easily damage conventional textile machines, such as weaving machines. Within the presented study, the DFP process has been investigated and optimized with regard to the processability of SF rovings to manufacture hybrid laminates. Furthermore, test specimens have been produced by vacuum assisted resin infusion (VARI) in order to characterize the influence of the material and the process on the mechanical properties and laminate quality.

2. State of the art

Combination of FRPC with steel or aluminum is known to reduce weight and performance of the components, as FRPC have a lower density than metals and, e.g. several metal parts can be replaced by local reinforcements made of FRPC [6,7]. In automotive design the hybridization mainly takes place on component level, meaning that FRPC and metal parts are joined. In aircraft applications hybridization takes place already on material level, mostly in form of fiber-metal laminates (FML). Hybrid laminates made of metal layers (e.g. thin films or sheets) and fiber-reinforced polymer layers enable a significant extension of the property profile of hybrid materials. FML are composed of alternating layers of the two components, which are combined by bonding or hot pressing. That means, that the joining of the FRPC and metal parts to the hybrid component is no longer necessary as a process step and the combination of materials already takes place at material level. The interface between the different components thus disappears and risks such as adhesion failure and corrosion can be reduced. Such a composite structure allows high specific stiffness and strength as well as good material damping and high damage tolerance at low weight (examples of hybrid laminates and applications are shown in Table 1) [4,8–11].

However, a complex pretreatment is necessary to process the metal foils to the FML. Furthermore, FML show only a limited drapeability, they require high production effort and cause high material costs, which results in the disadvantages of the FML [12,13].

In contrast to FML, the use of metal fibers offers many advantages. Furthermore, the large surface of many single fibers can improve fiber-matrix adhesion, while the impregnability of the hybrid preform is maintained due to the fibrous structure (in contrast to the metal foils in case of the FML) [14].

To take advantage of the hybrid materials based on metal fibers, the development of hybrid parts and processes, load-optimized structures and automation of the production of hybrid components are increasingly investigated. Relevant research on this topic is presented below:

Hannemann et al. [15] found that the specific electric conductance of hybrid carbon and SF...
reinforced polymer composites (CF-/SFRPC) with a SF fraction of 10.4 vol.-% is 2.7 times higher than the conductance of pure CF reference material. For a SF fraction of 18.8 vol.-%, the specific electric conductance is 4.2 times higher. Application of copper coated low carbon SF instead of conventional SF the electric conductivity could even be increased by a factor of 10.1 (10.4 vol.-% SF), respectively by a factor of 29.8 (18.8 vol.-% SF) compared to conventional carbon fiber reinforced polymers. In further investigations, dynamic impact tests on hybrid SF-CFRPC with regard to increased electrical conductivity, bending-tensile strength, and damage tolerance. Within this investigation, hybrid laminates consisting of SF carbon fiber hybrid rovings (mechanically commingled) were investigated. The electrical conductivity of the SF hybrid material (fiber volume fraction: SF 14%, CF 38%) was more than four times higher compared to conventional CFRP (fiber volume fraction: 60%). Compared to CFRP, the absorbed energy within the mechanical tests was ~20% higher in case of the hybrid material. Therefore, improved structure integrity was achieved since SF remain intact due to their higher failure strain [18].

The listed investigations are basic research to describe the material behavior; the results are not examined and evaluated by the authors with regard to their suitability for certain applications (e.g. lightning protection).

Most of the investigated SF hybrid laminates in the listed studies were made of flat semi-finished materials made of SF rovings, such as quasi-unidirectional woven structures (SF weft yarns and thin polymer warp yarns) or woven fabrics (SF weft and warp yarns) on the one hand and by filament winding technology on the other hand. For filament winding thin steel filaments were wound around a CF preform, whereby different layer structures and stacking sequences could be generated [9,15–20].

All of these approaches lead to an areal distribution of the dense metallic fibers, which limits the possibilities for local variations. Also availability of suitable semi-finished SF products is limited since SF are mainly used as ropes and twisted cords, e.g. as reinforcement for tires and conveyor belts and SF woven fabrics are primarily used as heat-resistant reinforcements for glass making, antistatic clothing, electromagnetic shielding, high temperature filtration (e.g. diesel exhaust filtration) as well as for cut-resistant gloves and heatable textiles for car seats, jackets and gloves [21,22].

DFP potentially overcomes these limitations by enabling flexible combination of materials and production of load orientated and adaptable fiber structures. DFP is a direct preforming technology which allows the manufacturing of a near-net shape preform directly out of single rovings. Within this process, several rovings are placed on a surface or already existing semi-finished material using a placement system (comparable to tape placement systems). The fixation of the rovings is realized by the application of a powder binder material (thermoplastic or thermoset powder). In the context of hybrid preforms with SFs DFP would allow creating an adapted, load-orientated anisotropic laminate structure with a local and functionally optimized arrangement of the SF. This is particularly important for maintaining the lightweight potential, as the

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**Table 1. Examples of hybrid laminates.**

| Name       | Manufacturer/researcher | Materials                                      | Advantageous properties                                      | Research/application                           |
|------------|-------------------------|------------------------------------------------|-------------------------------------------------------------|-----------------------------------------------|
| Glare      | TU Delft                | A: Aluminum sheet B: UD glass fiber/epoxy prepreg | Fatigue strength, damage tolerance, corrosion resistant     | Aircraft parts (fuselage structure)            |
| CARALL     | TU Delft                | A: Aluminum sheet B: Carbon fiber reinforced epoxy prepreg | high stiffness, low density                                  | aircraft construction                         |
| TiGr HTCL  | Boeing, Nasa            | A: Titanium foil B: Carbon fiber reinforced epoxy prepreg | good failure behaviour, low density                       | Aerospace applications                        |
| CAPALL     | TU Chemnitz             | A: Aluminum foil B: fiber-reinforced thermoplastic film | good formability, good damping                             | Research for high-volume applications         |
| Bondai     | Thyssen Krupp           | A: Deep-drawing steel B: fiber-reinforced thermoplastic film | formable, weldable                                           | Oil pan, gear cover                           |
| – UConn    |                         | A: Steel fibers B: glass-fiber reinforced epoxy composite | good energy absorption                                      | Research on structural components            |
| Stadco     | Crashbox                | A: Organo sheet B: Steel fiber fabrics           | very good energy absorption                                 | B-pillar reinforcement                        |

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additional weight can be kept to a minimum incorporated by the dense SF are only locally integrated.

Available literature concerning DFP mainly focuses on processing of CF. Current investigations are to bring the DFP to new, large-volume application levels, such as the production of large components (shell-parts, wings) in aviation or automotive applications. In these applications and for the production of inertia-loaded structures, the most common is the processing of CF rovings [2,3,23–25]. Also, it is known that compared to woven fabrics or noncrimp fabrics (NCF) preforms made by DFP show a deficient impregnation behavior, which results from the lack of meso-flow channels (gaps between the fiber bundles) in the DFP preforms. To increase the permeability, tufting or a modified lay-up sequence (gaps between the rovings) is a promising approach [26,27].

Furthermore, different preform configurations (gaps, overlaps and adjoining rovings) on mechanical behavior (compression behavior) were investigated. It was found, that preforms with gaps between rovings show a higher plastic deformation (plasticity), which can be attributed to a fiber re-arrangement during compression [3].

However, the gaps and overlaps of the rovings within the preforms that may appear during DFP can be considered as defects in the laminate. They lead to resin or fiber rich regions and therefore affect the mechanical performance of the composite part. In addition, these defects cause locally different permeabilities that can influence the subsequent impregnation process. This may cause defects like dry spots or incomplete impregnation of the final part [28,29]. A homogeneous, gapless fiber lay-up within the individual fiber layers should therefore be aimed within the DFP.

It is assumed that these findings from the processing of CF also apply to the processing of SF. While DFP is widely used and examined for processing of CF, processing of SF is still largely unknown.

3. Materials and methods

The following chapter describes the materials used within the study as well as the investigations carried out together with the associated experimental facilities. The entire manufacturing chain is described starting with the production of binder SF rovings, the DFP process to produce hybrid preforms, the production of hybrid laminates using the VARI process up to mechanical tests (tensile tests) to validate the advantageous mechanical properties of the hybrid laminates. In each individual process step, the quality of the semi-finished products or components is checked and process chain influences on the material side are monitored.

3.1. Materials

As base structure and reference material two CF noncrimp fabrics (NCF) with ± 45 and 0°/90° fiber orientation and an areal weight of 220 g/m² were used within this study (see Figure 2, left). For the production of the NCFs the carbon fiber type "T700" (Toray Carbon Fibers America, Inc.), bundled to 12 K rovings, was used. The spreading and nonspread SF rovings were examined with regard to their processability and mechanical properties of specimens manufactured from the roving material. The spreading (Fukui
principle) was carried out by Gernitex. The measured roving width is 3 mm for the nonspread SF roving and, 5 mm for the spread SF roving. For the production of binder rovings a bisphenol, a based powder binder (XB 3366) from Huntsman Advanced Materials, Switzerland, was used (see Figure 2, right).

Hexcel HexFlow RTM 6 resin was used as matrix material for the production of laminates by VARI process.

3.2. Binder roving manufacturing

In a first process step, the powder binder was applied to the SF rovings using a Binder Conveying Unit and a Binder Application Unit developed in former studies at the IVW (see Figure 3) [30].

Within the Binder Conveying Unit (see Figure 3, left), the binder powder material is fed to the ratchet wheel, which is driven by a stepper motor and controlled by a CNC-based software system. The entire Binder Conveying Unit is vibrated by an air vibrator; thereby the conveyance of the binder material is facilitated without agglomeration of the binder powder. The binder particles are subsequently passed as a binder air mixture to the Binder Application Unit by an adjustable air stream. The Binder Application Unit (see Figure 3, middle) allows the application of a constant amount of binder particles through a nozzle to the roving, which passes through the unit at an adjustable, constant speed. To fix the binder particles on the roving, the particles coming from the nozzle are activated by an electronic heat gun at 125 °C.

The right amount of binder content is crucial for the adhesion of the binder roving on the CF-NCF and therefore the stability of the preform. However, a high amount of binder material leads to poor impregnation of the preform and therefore to deficient injection processes. Former studies at the IVW with CF rovings showed best results at a binder content of 3–10 wt.-% [31]. In order to define the optimal binder content with regard to a low mass fraction of binder with good adhesion of the rovings at the same time, the amount of binder material applied on the SF roving was varied in this range. To transfer these values to the processing of SF rovings, an adjustment to the mass fractions of binder particles and rovings is necessary due to the different densities of CF and SF. In a first step, the mass fraction of the binder has to be converted to universal volume fraction of the binder (\( \phi_B \)) according to Equation 3.1:

\[
\phi_B = 1 - \frac{w_{\text{CF}} \cdot \rho_B}{w_{\text{CF}} \cdot \rho_B + w_{\text{SF}} \cdot \rho_{\text{SF}}} \quad (3.1)
\]

The mass fractions of the components are \( w_B \) and \( w_{\text{CF}} \), \( \rho_B \) and \( \rho_{\text{CF}} \) the corresponding densities.

In a second step, the volume fraction of the binder has to be transferred to the new mass fraction (\( w_B \)) related to the SF according to Equation 3.2:

\[
\frac{w_{\text{SF}} \cdot \rho_{\text{SF}}}{\rho_{\text{SF}} \cdot \phi_{\text{SF}} + \rho_B \cdot \phi_B}
\]

The volume fractions of the correlating components are \( \phi_B \) and \( \phi_{\text{SF}} \), \( \rho_B \) and \( \rho_{\text{SF}} \) the densities.

Therefore, the chosen mass fractions for the production of the binder SF rovings were 0.7, 1.6, and 2.4 wt.-% (mass fractions of 3.0, 7.0, and 10.0 wt.-% in case of CF rovings).

According to the target binder mass content, the binder mass flow per minute \( \dot{m}_B \) has to be adjusted depending on the SF mass flow per minute \( \dot{m}_{\text{SF}} \) (see Equations 3.3 and 3.4).

\[
\dot{m}_B = \frac{\dot{m}_{\text{SF}} \cdot (1 - w_B)}{w_B} \quad (3.3)
\]
with

\[ m_{\text{SF}} = \text{texSF} \times 2\pi \times r_{\text{spool}} \times n_{\text{motor}} \]  \hspace{1cm} (3.4)

For the experiments on binder application, a roving speed of 2.5, 5, and 10 m/min was chosen (roving speed is equivalent to: \(2\pi r_{\text{spool}} n_{\text{motor}}\)). The corresponding roving and binder mass flows are shown in Table 2.

In order to quantify the binder mass flow provided by the Binder Conveying Unit, various tests were carried out on the binder flow rate at different ratchet wheel rotation speeds. For this purpose, the binder particles conveyed within 1 min were collected and weighed. The experiments were repeated 5 times and a mean value was calculated. To ensure the target quantity of binder particles on the SF rovings, further tests were done to identify the actual quantity of binder mass (applied by the binder application unit) by weighing the binder SF rovings (10 m each measurement) after the binder application process.

### 3.3. Preform manufacturing via DFP

For production of the hybrid preforms, binder SF rovings manufactured in the previous step are led to the Tape Placement Unit (see Figure 4).

The tapes are placed by moving the heating plate in x- and y-direction (Tape Laying Head is fixed). For a good adhesion between the rovings and the tempered (40 °C) tool surface or on an existing preform, a thermal activation of the binder material is required. The activation is realized by a hot gas torch in which a defined gas mixture (hydrogen and

| Tex SF (g/km) | Roving speed (m/min) | Roving mass flow (g/min) | Binder mass flow (0.7 wt.-%) (g/min) | Binder mass flow (1.6 wt.-%) (g/min) | Binder mass flow (2.4 wt.-%) (g/min) |
|--------------|----------------------|--------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| 1300         | 2.5                  | 3.75                     | 0.026                               | 0.061                               | 0.092                               |
|              | 5                    | 7.5                      | 0.053                               | 0.122                               | 0.184                               |
|              | 10                   | 13                       | 0.092                               | 0.211                               | 0.320                               |

Figure 4. Schematic illustration of DFP (top), tape placement unit (left) with tape laying head (right).
oxygen) is burned. The hot gas streams to the nip point (on the roving, directly in front of the compaction roll) and heats the binder. After the binder activation, the roving is compacted and cooled by the compaction roll, which completes the placement step. All process parameters, such as placement speed, compaction roll pressing force and hot gas amount, can be controlled and changed via the Labview control program.

For the preforming of the test specimens (DFP of binder SF rovings on CF-NCF) the following parameters were chosen (based on previous investigations):

- Lay-up speed: 10 m/min
- System pressure of the compaction roll: 3 bar
- Hot gas amount: 3 Nl/min

To evaluate the cohesion of the SF rovings (cohesion of the single fibers after the DFP process) in dependence of different applied binder amounts, wear trials on specimens manufactured by DFP were conducted. To simulate handling of the preforms and thus the friction on the preform surface, the specimens were brushed ten times along and ten times across the fiber orientation. By weighing the specimens before and after the trials, the fiber loss and therefore the cohesion of the SF rovings could be determined in dependence of the binder amount. For each binder amount, seven specimens were tested and the mean values were calculated.

The quality of the preforms and possible differences in the processing of spread and nonspread SF rovings are verified by an optical analysis of the produced preforms before the VARI process takes place.

A hybrid 14-layered stacking sequence including two inner and two outer SF reinforced layers is used to compare the manufacturing influence for the use of spread (SCFRPC1) and nonspread (SCFRPC2) SF rovings (see Table 3).

As a reference to the SCFRPC material concept, pure CF stacks with same stacking sequence without SF hybridization were produced and tested. Following the basic idea of the SCFRPC material concept (the electric conductivity of the SF enables the substitution of additional components which normally are used to fulfill required electrical functionality), the CFRPC composite contains a 10-layered stacking sequence which equals the CF part of the SCFRPC configurations.

### 3.4. Laminate manufacturing via vacuum-assisted resin infusion

To produce specimens for optical and mechanical analysis, the semi-finished products previously hybridized in the DFP process were impregnated with the resin system (Hexcel HexFlow RTM 6) using the VARI process. The preforms are stacked (see Table 3) on a heating plate and covered with peel ply and a perforated foil. An air-permeable fleece on the perforated foil ensures that the vacuum is applied evenly and excess resin is absorbed from the laminate. The stack is then covered with vacuum foil and evacuated by a vacuum pump (an overview is shown in Figure 5).

The infusion starts at a heating plate temperature of 180 °C by opening the resin connection, whereby the liquid resin, which is heated to approx. 80 °C, flows into the evacuated preform stack. After complete impregnation, both connections (resin and vacuum) are closed. After approx. 30 min (gel time of the resin), the heating plate is switched off and further curing takes place over 4 h while slowly cooling down to room temperature. After complete curing, the plates can be molded and prepared for optical and mechanical analysis.

### 3.5. Analysis and mechanical characterization of laminates

The laminates were evaluated with regard to their fiber distribution and the corresponding fiber and matrix volume fractions. For this purpose, various microsections were taken and examined with an optical microscope.

In addition, mechanical tests were carried out with the hybrid and reference materials (Table 3). The aim is to determine the suitability of the generated hybrid preforms for the expected improvement of postfailure and energy absorption as well as

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### Table 3. Stacking sequences of preforms manufactured for laminate manufacturing (optical and mechanical analysis).

| Specimen          | Stacking sequence | Material          |
|-------------------|-------------------|-------------------|
| SCFRPC1 / SCFRPC2 | 0°/45°            | SF roving         |
|                   | −45°/45°          | CF NCF            |
|                   | 0°/45°            | SF roving         |
|                   | −45°/45°          | CF NCF            |
|                   | 90°/0°            | SF roving         |
|                   | −45°/0°           | CF NCF            |
|                   | −45°/45°          | CF NCF            |
|                   | 45°/45°           | SF roving         |
| CF reference      | +45°/45°          | CF NCF            |
|                   | −45°/45°          | CF NCF            |
|                   | −45°/0°           | CF NCF            |
|                   | 90°/90°           | CF NCF            |
|                   | −45°/−45°         | CF NCF            |
|                   | +45°/−45°         | CF NCF            |
which corresponding materials and processing parameters provide the best results (differences in the processability and laminate quality of the spread and nonspread SF may have effects on the mechanical properties of the laminate).

To assess the mechanical properties of the hybrid (SF and CF) reinforced composites tensile tests are conducted in compliance with DIN EN ISO 527-4. For the tensile tests rectangular specimens with a width of 25 mm are monotonically loaded with a crosshead speed of 2 mm/min (see Figure 6(a)).

The elongation of the specimen is analyzed within a gauge length of 150 mm by a digital image correlation (DIC) system (see Figure 7(b)). For each tested material configuration, five specimens were tested to failure and the mean values and standard deviations were calculated.

4. Results

4.1. Binder roving manufacturing

Results of investigations regarding the conveyed binder amount (Binder Conveying Unit) and the applied binder mass on the roving (right).

Figure 5. Exemplary build-up for laminate production via VARI process.

Figure 6. Geometry and load direction of the tensile specimens (a), experimental procedure with a digital image correlation (DIC) system (b).

Figure 7. Conveyed binder mass (left) and the applied binder mass on the roving (right).
applied binder mass on the SF roving (Binder Application Unit) are shown in Figure 7.

Figure 7 (left) shows that the conveyed powder mass is linearly dependent on the ratchet wheel rotation speed. Hence, in the selected parameter range, there are no nonlinear rotation-speed-dependent factors influencing the powder flow rate. This results in a robust process with high repeatability of the conveyed powder masses that can be scaled to the required applications. Therefore, a constant powder flow can be precisely set by adjusting the rotation speed of the ratchet wheel, implemented in the binder application unit (see Figure 3).

Figure 7 (right) shows the applied binder mass per meter SF roving depending on ratchet wheel rotation speed at different roving speeds. In this process there is also an almost linear relationship between ratchet wheel rotation speed and applied powder mass. As already determined for the conveyed powder masses, the parameter range investigated allows the measured values to be interpolated in order to precisely adjust the binder content on the SF rovings. All three roving speeds examined are in a stable range, as can be seen from this quasi-linear relationship.

However, with an increasing roving speed, a disproportionately lower binder mass per meter SF roving is applied than a linear relationship would suggest. This means that less than half of the powder mass per meter roving is applied at double roving speed. This observation can be associated to dynamic effects during the application process. Due to the higher speed of the SF rovings, the binder particles are accelerated more when hitting the roving, which means that a larger proportion of the binder particles can be thrown off the roving. Taking into account, the required binder masses for binder content of 0.7, 1.6, and 2.4 wt.-%, a roving speed of 5 m/min covers a stable, linear range within the selected parameters.

The scanning electron microscope (SEM) pictures of the manufactured binder SF rovings with binder mass fractions of 0.7, 1.6, and 2.4 wt.-% (see Figure 8) show a good distribution and adhesion of the binder particles on the SF roving at every binder amount. No large agglomerations of binder particles can be observed, even at a binder content of 2.4 wt.-%.

According to these observations, the following parameters for binder application could be identified for an optimized manufacturing of SF binder rovings, with a good adhesion and a minimal loss of binder material:

- SF-roving speed: 5 m/min
- Ratchet wheel rotation speed:
  - 14 rpm for a binder mass fraction of 0.7 wt.-%
  - 28 rpm for a binder mass fraction of 1.6 wt.-%
  - 38 rpm for a binder mass fraction of 2.4 wt.-%

4.2. **DFP preform stability and quality**

Regarding the cohesion of the SF rovings after the DFP process in dependence of the applied binder
amount, it was found that the total amount of binder material has no significant influence on the cohesion of the SF rovings within the range of investigated binder quantities (see Figure 9).

The fiber loss in all three cases is \(\sim 1\) wt.-%, the standard deviation is also almost identical. Therefore, a binder mass fraction of only 0.7 wt.-% is sufficient to manufacture stable preforms with a good cohesion of the single SF within the DFP preform and ensure a reliable process. Thus, the preforms for the test specimens were produced with binder SF rovings (spread and nonspread) with a binder mass fraction of 0.7 wt.-% (see Figure 10).

Due to the smaller initial roving width of \(\sim 3\) mm for nonspread SF rovings compared to the initial roving width of \(\sim 4.5\) mm, the lay-up distance in the case of nonspread SF rovings is also smaller. This leads to a theoretical areal weight of 288.9 g/m\(^2\) in the case of spread SF rovings and an areal weight of 433.3 g/m\(^2\) in the case of nonspread SF rovings.

As can be seen in Figure 10, the preforms made from spread SF rovings also show more inhomogeneities in roving width. This leads to gap formation on the surface of the DFP preform due to the constant lay-up distance during the DFP process. In comparison, the nonspread rovings show quasi-homogeneous SF layers. This observation and an explanation are shown in Figure 11 schematically.

During the DFP process the roving is compacted by the compaction roll, and therefore the roving deforms a little (see Figure 11, top). In the course of the investigations it was found that the spreading of SF leads always to an inhomogeneous variation in SF roving width. Along with a constant lay-up distance based on the initial (average) roving width and the little deformation during the DFP process gaps and overlaps can occur.

In case of a nonspread SF roving, the initial (nonspread) state of the roving shows a higher flexibility in roving width under compaction pressure, therefore a higher quasiplastic deformation can take place during the fiber placement process. This deformation is maintained by the fixation by the binder within the preform and allows a closure of the gaps between adjoining rovings. Along with a smaller lay-up distance compared to spread SF rovings (smaller initial roving width) more homogeneous SF layers can be achieved.

### 4.3. Laminate quality

The microsections for analysis of the laminate (see Table 3) quality of the two hybrid materials (spread and nonspread SF rovings) as well as the reference material (CF) after the VARI process are shown Figure 12.

Compared to the samples with nonspread SF rovings (Figure 12, right), spread SF rovings (Figure 12, left) show bigger inhomogeneities within the laminate with strongly different layer thicknesses, gaps between individual SF rovings and larger areas with pure resin. This results in higher resin volume fractions in case of spread SF rovings (35.6%) compared to nonspread SF rovings (31.8%). These inhomogeneities within the spread SF layers were already observed during the previous DFP process in the case of the spread SF and therefore remain after processing. With a resin volume fraction of 33.6% the reference material (Figure 12, bottom) is between the two hybrid materials. Due to the higher
theoretical areal weight of the SF layers in case of nonspread SF rovings and the more homogeneous SF layers, SF volume fraction of 13.9% is higher compared to the spread SF rovings (10.2%).

4.4. Mechanical testing

The different results (mean values) obtained by the tensile tests in 0°/C14 direction of the CF reference and two hybrid materials (with spread and nonspread SF rovings) are shown in Figure 13.

In contrast to the brittle and singularly failure of the CF reference specimens, both hybrid composites exhibit a pronounced postfailure behavior. The failure of the CF reference specimens is initiated at a nominal total strain of 1.74% by failure of the 0° layer. The elastic energy from the CF layers within the hybrid material composite, which is released at the moment of failure, can be transferred to the
surviving layers due to the available ductility of the SF. As a consequence, the hybrid laminate can bear further elongation and enables higher energy absorption due to quasi-ductile behavior of the hybrid composite. Transferred to more realistic load conditions (dynamic load cases like crash tests); higher energy absorption often leads to higher structure integrity. The absorbed energy corresponds to the area enclosed by the stress strain curve. In the case of the spread SF a 2.05 times higher energy absorption could be achieved compared to the CF reference, in case of the nonspread SF the energy absorption was 2.32 times higher. The stress level after initial failure of the CF 0° layers (~85 MPa) mainly corresponds to yielding of the SF reinforced layers and the remaining load carrying capacity of the ±45° layers.

The higher resin volume fractions of the samples with spread SF rovings compared to nonspread SF rovings (35.6% versus 31.8%) influence the stiffness (33.6 GPa versus 34.7 GPa) and the strength (348.6 MPa versus 391.3 MPa) of the specimens for tension loading. Further influences on the strength may result from possible predamages of the SF rovings due to the spreading process.

The advantages of hybridization, such as the ductile postfailure behavior with the associated energy absorption and the structural integrity of the composites, are thus evident in both hybrid materials. The use of nonspread SF rovings and the associated more homogeneous SF layers had a positive effect on the mechanical component properties.

5. Conclusions

The study proved that the DFP is highly suitable to manufacture hybrid SF-CF preforms on material level. The DFP enables a load oriented and local application of fibers and therefore a focused use of the relatively heavy SF rovings for hybrid material preforms.

Analysis of the manufactured laminates and mechanical tests show good performance of laminates based on nonspread SF rovings. The hybrid preforms manufactured by DFP of nonspread SF rovings feature a higher homogeneity compared to the hybrid preforms made with spread SF rovings. The higher homogeneity leads to higher fiber volume content (fewer gaps between SF rovings) and therefore to higher achievable stiffness and strengths. Due to the fact that the processing of nonspread SF rovings shows best results and the spreading of SF rovings leads to higher irregularities of the rovings and the laminates, the expensive and time-consuming spreading process of SF can be omitted. Therefore, the process of binder application and tape placement (DFP) could be transferred to the processing of SF rovings to manufacture hybrid preforms.

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