Deformation behavior of FRP-metal composites locally reinforced with carbon fibers

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Abstract. This study investigates variations of hybrid laminates, consisting of one aluminum sheet and a unidirectional glass fiber (GF) reinforced polyamide 6 (PA6) basic structure with partial carbon fiber (CF) reinforcement. To create these heterogeneous FRP laminates, it is necessary to design and produce semi-finished textile-based products. Moreover, a warp knitting machine in conjunction with a warp thread offset unit was used to generate bionic inspired compounds. By the variation of stacking prior to the consolidation process of the hybrid laminate, an oriented CF reinforcement at the top and middle layer of the FRP is realized. In both cases the GFRP layer prevents contact between the aluminum and carbon fibers. In so doing, the high strength of carbon fibers can be transferred to the hybrid laminate in load directions with an active prevention of contact corrosion. The interface strength between thermoplastic and metal component was improved by a thermal spray coating on the aluminum sheet. Because of the high surface roughness and porosity, mechanical interlock was used to provide high interface strength without bonding agents between both components. The resulting mechanical properties of the hybrid laminates are evaluated by three point bending tests in different load directions. The effect of local fiber orientation and layer positioning on failure and deformation mechanism is additionally investigated by digital image correlation (DIC).

1. Introduction
The method “The right material at the right place” calls for an interdisciplinary cooperation of science branches to make the potential of clever combinations of materials viable for industrial applications. The Cluster of Excellence MERGE supports this research and development approach. The aim is to design and characterize a new class of effective and efficiently produced hybrid materials. Due to the increasing level of lightweight constructions in the automotive and aviation industry, multi-material concepts become more and more complex comparable with natural structures and solutions of planar and shaped formations. The created bionic inspired materials should be producible in large-scale manufacturing processes. While most metallic materials fit this requirement, work is still needed on the transfer of a complex thermoplastic FRP. Textile-based production systems are suitable for large-scale production. Especially warp knitting machines promise a high productivity of technical textiles for oriented fibrous reinforcements of thermoplastics [1]. To create load path suitable FRP structures, local additional fibrous reinforcement can be integrated into or applied to global reinforced textile-based structures. The research institute Cetex, Chemnitz, developed a unit, which enables the fixation of additional partial continuous fiber reinforcements during the production of warp knitted non-crimp fabrics. The warp thread offset allows for a continuous positioning of defined patterns according to the
local requirements of the fiber orientation and fiber volume content (FVC) [2]. Transferred to
composites, also the combination of a partially reinforced FRP with metallic sheets is possible.
Furthermore, hybrid laminates with load paths at the FRP part and a class A surface at the metallic
part can be produced.

A suitable interface and composite design requires an inhibition of contact between elements,
which would cause a corrosive behavior of one joining partner. The negative influence of aluminum-
carbon fiber interfaces on the corrosion behavior was already investigated in the past [3]. A general
way of inhibition is the separation of fiber layer structures in a composite, for example, by a GFRP
layer between the CFRP and aluminum. When combining various classes of materials, in addition to
corrosion protection also high interface strength is necessary. Adhesive bonding is state of the art in
joining metals and plastics [4, 5]. Several disadvantages such as susceptibility to environmental
conditions or the required precise adjustment to the joining conditions (temperature and pressure
route) can be observed. Beside the influence of the joining conditions and process, the surface
preparation has significant influence on the properties of the interface. The pretreatment can be
performed by chemical, mechanical or physical processes [6, 7]. Lucchetta et al. studied the influence
of the metal surface topography in hybrid joints and concluded that high roughness increases
interlocking of the polymer [8]. Furthermore, a general approach for high interface strength is a
structured surface which leads to a higher microscopic surface area and undercut grooves for
mechanical interlocking. Mechanical pretreatments such as grit blasting can leave a certain amount of
residual stresses in the material, promoting the risk of deformation [9]. An adequate way to realize
high surface roughness without deformation was shown by Lindner et al., who used a thermal spray
coating for an increase of surface roughness [10]. In agreement with other studies, the bonding
strength between the aluminum and the FRP was significantly increased by using a NiAl95/5 thermal
spray coating without prior grit blasting [10, 11]. With respect to these results, this study focusses on
the influence of local CF reinforcement on the deformation behavior of an aluminum-FRP composite.
In order to evaluate the resulting mechanical properties of the hybrid laminate, bending tests in
different load directions were performed and additionally investigated by DIC.

2. Experimental

2.1. Design and production of hybrid components

The selection of compatible materials and suitable process parameters is of great importance for the
implementation of a multi-material design. The dimension and performance of the components were
specified under the use of a FE-simulation [12]. In the context of this work, each hybrid component
was produced in a single process line prior to joining. The 2 mm thick structure of the thermoplastic
FRP component consisted of unidirectional (UD) textile-based semi-finished products made of
GF/PA6 (basic reinforcement) and CF/PA6 (bionic inspired reinforcement). To determine the
performance of partial reinforcement and the influence of its location, a sample pattern of partial CF
reinforcement was chosen and positioned as middle or top layer in the FRP structure, see figure 1. For
the further hybrid joining process, the FRP structures were provided as preimpregnated sheets.

As metallic component of the hybrid laminate an EN AW6016-T4 (AlSi1.2Mg0.4) aluminum alloy
sheet with a thickness of 1 mm was used. In order to generate an integration zone at the joining
process by mechanical interlock between the bonding parts, a surface pretreatment of the metallic
component was necessary. A suitable technology to realize a high surface roughness for the
mechanical interlock is thermal spraying. By means of thermal spraying, it is possible to apply
metallic coatings on different substrates. Further advantages of thermal spray coatings are the low
deformation of substrate materials and low heat input. Feedstock materials in thermal spraying can be
processed as powders or wires. A combination of aluminum and nickel leads to an exothermic reaction
during the spray process. In this way, a metallurgical bonding without prior grit blasting of the surface
is possible [13]. In this study, an arc wire spraying system with a cored-wire of NiAl95/5 (1.6 mm
thickness) was chosen because of its good processability. For more detailed information on the
processing parameters, see table 1.
Figure 1. Characteristic of FRP components: Basic GF unidirectional reinforcement in the direction of the X-axis (0°), partial CF reinforcement along a simplified bionic inspired path (fiber directions illustrated by arrows). Two types of laminates were produced: CF reinforcement at middle (M) and at top layer (T).

Table 1. Feedstock material and parameters used for electric arc wire spraying.

| Chemical composition | Current (A) | Voltage (V) | Spraying distance (mm) | Air pressure (bar) | Transverse velocity (m/s) | Line-gap (mm) | Growth by step (µm) |
|----------------------|-------------|-------------|------------------------|--------------------|---------------------------|---------------|---------------------|
| Ni – 95% Al – 5%     | 150         | 30          | 130                    | 3.5                | 0.6                       | 5             | 50                  |

2.2. Joining process

The primary objective of the joining process was to combine the hybrid components without a significant deformation of the reinforcement structure inside of the FRP and moreover, to create a defect-free interface. Under variation of the temperature, time and pressure in hot pressing process, fitting parameters were determined. Subsequent to the pretreatment of the FRP and the metal, components were pressed to hybrid laminates with a length of 300 mm and a width of 150 mm by direct heating of the consolidation dies. Temperature and pressure profiles are shown in figure 2. During the joining process, a steady pressure of 5 bar was applied. The temperature measurement was conducted by a thermocouple directly in the interface zone between the metal- and FRP-component. After reaching a temperature of 250 °C in the interface, the tool was cooled down to 80 °C by compressed air. The joining pressure was constant during the air cooling process.

Figure 2. Interface temperature and pressure route during the joining process.
2.3. Mechanical testing
In order to evaluate the mechanical properties, three point bending tests according to DIN EN ISO 14125 were conducted [14]. Samples positioned in different fiber directions of the hybrid laminate (see figure 3) with a length of 45 mm and a width of 8 mm were taken by water jet cutting. The bending samples were tested in a universal testing machine (Zwick UPM1475-100 kN) in a three point bending device with a span length of 40 mm at a constant crosshead-speed of 0.6 mm/min. Thereby the FRP-component was loaded with tensile stress. For a precise bending-strain calculation, an inductive displacement measurement was applied. Values shown in this study are based on at least four samples per sample direction and fiber arrangement.

Figure 3. Sample positions in hybrid laminates with different layer stacking. Arrows illustrate the position and direction of the cut samples for three point bending tests: M1: 0° GFRP; M2: 0° GFRP + 0° CFRP at the middle layer; M3: 45° GFRP; M4: 45° GFRP + 0° CFRP at the middle layer; T1: 0° GFRP; T2: 0° GFRP + 0° CFRP at the top layer; T3: 45° GFRP; T4: 45° GFRP + 0° CFRP at the top layer.

In addition to the evaluation of the mechanical properties, the deformation behavior was recorded by an ARAMIS digital image correlation (DIC) system developed by GOM (Braunschweig, Germany). This non-contact optical method provides measurements of surface displacements and calculated strains by tracking random speckle patterns on the surface of the samples. All experiments were performed with a frame rate of 1 Hz using a single CCD camera, which was placed with its optical axis normal to the side surface of the specimens (see figure 4). Subsequent to every single bending test, recorded DIC data were analyzed using the ARAMIS software.

Figure 4. Captured DIC area at the bending samples.

3. Results and discussion
3.1. Microstructure of partially reinforced hybrid laminates
At first, we discuss the results of the consolidation process of the hybrid laminates by a comparison of different layer stacking with the corresponding microstructures. Figure 5 shows optical microscope images of the hybrid laminates. Different areas of materials are schematically shown next to the images. A clear distinction of the GFRP and CFRP layers and a homogeneous and fully impregnated

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Figure 3.

Figure 4.
fibrous structure is visible in the micrographs. Both stacking orders offer an inhibition of contact corrosion by the prevention of contact between the metallic surface and the carbon fibers. The FRP of the composites show in both cross-sections a constant thickness.

To investigate the interface between the FRP and the metal surface, a higher magnification is shown in figure 6. The smooth surface of the aluminum sheet is enlarged by the thermal sprayed NiAl95/5-coating without cavities to aluminum substrate. The rough and porous surface design allows for a mechanical interlock to the FRP-component because of the infiltration of the melted PA6 matrix in the joining process. No glass fibers are interlocked within the coating. This indicates that no fibers are damaged by mechanical stress during processing. The upper GF accumulation (fiber volume content 47%) is homogeneous and mainly fully impregnated with the PA6 matrix. As a result of the microstructure in the interface, high interface strength by the interlocking of the FRP-component to the aluminum sheet can be expected.

Figure 5. Optical microscope images of the hybrid microstructure with different stacking orders: M: Local CF reinforcement at the middle layer of the FRP, T: Local CF reinforcement at the top layer of the FRP.

Figure 6. Optical microscope image of the interface zone. The porous NiAl95/5-thermal spray coating is fully impregnated with PA6.

3.2. Mechanical behavior in different load directions

Depending on the different load directions of the hybrid laminates, three point bending tests have been performed. Figure 7 shows the maximum bending stresses and bending modules of the different sample orientations (see figure 3 for sample extraction out of hybrid laminates). The mechanical properties of the basic GFRP structure in both laminate types are at the same level (M1 & T1). Also samples with 45° GFRP orientation (M3 & T3) show the same bending strengths and bending
modules. This suggests that there is no influence of the local CF reinforcement on the basic GFRP structure. However, resulting mechanical properties show an increase of the bending strength under local CF reinforcement. When CFRP and GFRP are in the same orientation, there is only a slight increase of the bending strength (M1 & T1 compared to M2 & T2). Moreover, no difference in maximum stress is visible between the middle (M2) and the top layer of the CFRP (T2). The maximum bending strength is about 425 MPa. As expected, the local CFRP has a larger influence at 45° GFRP orientation (M3 & T3 compared with M4 & T4). An increase in bending strength is also visible due to the layer variation (M4 & T4). A CFRP layer in tension direction at the top of the hybrid laminate (T4) is characterized by a higher strength than a laminate with CF reinforcement closer to the neutral fiber of the bending sample (M4). In the comparison of maximum stress values in GFRP-direction and local CFRP-direction, we obtained bending strengths of equal values at the same thickness of hybrid laminates when the CFRP is positioned at the top layer (M1 & T1 compared with T4). The highest influence of the partial CF reinforcement is obtained in the enhancement of the local stiffness. Due to the higher elastic modulus of carbon fibers compared to glass fibers, the elastic properties are also transferred to the hybrid laminate. In contrast to the bending strength values, the bending modulus has a significant dependence on the layer position of the local CFRP. With increasing distance of the CFRP to the neutral fiber in bending tests, the bending modulus is increased (M2 & T2, M4 & T4). Under the same orientation of the GF and CF reinforcement at the top layer the bending modulus reached the highest level of 68 GPa (T2). The stiffness of the basic GFRP structure (M1 & T1) is in 45° local reinforcement direction already reached with the middle layer CFRP (M4). In the case of the top layer CFRP (T4), the bending modulus of the samples has even a higher value than the basic GFRP structure in 0°. As a result of that, local CF reinforcement can be used for the enhancement of the local bending stiffness.

At the top and middle layer, UD fiber orientations of the GF and CF reinforcement are characterized by same bending stress values (see figure 7, M2 & T2), although the layer structure influences the bending modulus. Therefore, the deformation behavior of these layer structures was additionally investigated by using the DIC technique. Figure 8 shows strain field images of M2 and T2 with increasing deformation and the corresponding stress-strain behavior. Strain localizations, resulting from high displacements of local surface patterns, can be monitored by color gradients in DIC images. In the case of a middle layer CFRP, two localization zones parallel to each other can be observed at the bending sample with increasing strain (M2, images 1-5). The same strain levels lead under the top layer CFRP to an early localization in mainly one zone (T2, images 1-5). Furthermore, with increasing strain, the localization leads to delamination along the interface between the CFRP and
GFRP layer. The early localization in the case of the top layer CFRP and the following delamination of the layer structure prevents an increase in bending strength in comparison with the middle layer CFRP. Moreover, only a high bending modulus is reached because at low bending strain levels there is less influence of interlaminar shear stresses between layer structures with different mechanical properties, resulting from layer displacements under bending. The bending modulus is mainly influenced by the extreme upper fiber. As a result of that, a high bending modulus is only reached in the case of a top layer CFRP. In comparison with the microstructures (figure 5) of the two hybrid laminates, the negative influence on delamination by a top layer CFRP can be explained by the distinction of the top layer CFRP and the GFRP. In the case of the middle layer CFRP, a good formation of the CFRP in the surrounding GFRP leads to a more uniform stress and strain distribution in the FRP.

Figure 8. Strain field images from DIC: A top layer of the CFRP leads to early localization and delamination between the GFRP and the CFRP. M2: 0° GFRP + 0° CFRP at the middle layer; T2: 0° GFRP + 0° CFRP at the top layer.
4. Summary and conclusions
In this paper, we have investigated the effect of local carbon fiber reinforcement on the deformation behavior of a FRP-metal composite. A warp knitting machine with a warp thread offset unit was used to generate bionic inspired compounds with various directions of a CF in basic GF reinforced PA6. As metallic component an aluminum sheet with a thermal spray coating was used. By the variation of the stacking order prior to the consolidation process, different layer structures in hybrid laminates were produced. The deformation behavior was investigated in different load directions with three point bending tests. Additionally, the digital image correlation technique was used during the deformation to observe localizations in two different layer structures. Several noteworthy results are summarized as follows:

1. The manufacturing of textile-based semi-finished products with bionic inspired endless fiber reinforcement is viable under the usage of a warp knitting machine with a warp thread offset. The local pattern can be transferred into a hybrid laminate structure. After the joining process with the metal component, microstructural investigations show a homogeneous and fully impregnated fibrous structure regardless of the different stacking orders. An active prevention of corrosion is obtained by a GFRP layer, which impedes contact of carbon fibers and the aluminum.

2. The thermal spraying process offers a suitable pretreatment of aluminum surfaces to generate an interface between the metal and the FRP. By using NiAl95/5 as feedstock material, a high bonding strength to the aluminum substrate is achieved. Furthermore, the rough and porous surface of the spray coating with undercuts allows for a mechanical interlock to the FRP-component because of the infiltration of melted PA6 matrix in joining process.

3. A load-optimized structure can be reached at a constant thickness of the laminate. The basic GF-structure is not influenced by the local reinforcement. A comparatively low content of the load-oriented local CF reinforcement in hybrid laminates (0° CFRP/45° GFRP) leads to bending strengths of the same level compared to hybrid laminates with an only unidirectional GF reinforcement. Higher bending modules are possible in the case of the CFRP top layer structures, which is due to the highest influence of the extreme upper fiber under bending load.

4. DIC investigations showed an early localization between the layer structures. In the case of the top layer CFRP, load-uniform orientations of the glass and carbon fibers lead to an early delamination compared with the middle layer CFRP. As a result of that, the bending strength is not increased in contrast to the enhancement of the bending modulus with a higher distance of the CFRP from the neutral fiber in the bending samples. According to the delamination in the FRP, further investigations should focus on an improvement in accumulation as well as on the arrangement of carbon and glass fibers in the PA6 matrix system. To increase the hybrid performance, an optimization of the fiber-matrix adhesion and a reduction of internal stresses in the FRP are planned in future research activities.

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