DEVELOPMENT OF A HYBRID TAIL ROTOR DRIVE SHAFT BY THE USE OF THERMOPLASTIC AUTOMATED FIBER PLACEMENT

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Abstract

The combination of composite materials and metals to hybrid structures creates new opportunities regarding performance and lightweight design for primary aircraft structures. Within this paper an alternative way of creating a hybrid structure is investigated. By the use of a Thermoplastic-Automated Fiber Placement process carbonfiber reinforced PEEK laminates are applied on titanium substrates. Joining and consolidation of the laminate is realized in one process step, vacuum bagging and subsequent autoclave processes are avoided. In order to achieve sufficient interfacial strength of the joint surface pre-treatment of the titanium is essential. Hybrid single-lap shear specimens are manufactured and the effect of surface pre-treatment on the mechanical performance is investigated. It is shown, that the use of an additional PEEK coating on top of the titanium provides higher joint strength in comparison to a direct placement of CF/PEEK on the metallic surface. Based on these findings a hybrid tail rotor drive shaft is designed, manufactured and tested. Static tests prove the performance of this hybrid component.

1. Introduction

Thermoplastic composites are recognized as a promising material system in aerospace industry to meet the requirements for durability and toughness. Nevertheless, metallic components are needed in order to provide an interface to other components or as load introduction elements into composite structures.
Mechanical fastening, adhesive bonding or fusion bonding in case of thermoplastic composite materials are the most common joining technologies for creating a hybrid metal-composite structure [1]. Nevertheless, these technologies require many process steps like stacking of the composite layers, consolidation of the laminate and finally joining to the pre-treated metal component.
The aim of this research is to investigate a smart design of a hybrid joint, minimizing process steps and weight of the structure:
With Thermoplastic-Automated Fiber Placement (TP-AFP) technology, composite parts are manufactured according to the mechanical load paths of the structure with a high degree of automation. Due to the in situ consolidation of the laminate, expensive manual labor time and costs compared to a thermoset autoclave curing cycle can be reduced. Studies at the Institute of Carbon Composites have shown the capability to realize high quality composite laminates as well as joining CFRP and metals by the laser assisted TP-AFP process. By this, joining and consolidation of the laminate are realized in one process step. [2-3]
This paper investigates the TP-AFP process for manufacturing hybrid structures by joining unidirectional CF/PEEK tapes and Ti-6Al-4V substrates. Different surface pre-treatments are analyzed

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for their impact on the interfacial strength by single-lap shear (SLS) tests. Finally a hybrid tail rotor drive shaft is designed, manufactured and tested to investigate this joining technology for aerospace applications.

2. Experimental

2.1. Used Materials

Within this study a carbon fiber reinforced UD-prepreg tape material with a fiber mass content of 66% is used. The matrix material is PEEK (polyether ether ketone), the tape width is 1”.
α+β titanium alloy Ti-6Al-4V is chosen as metal joining partner. For sample manufacturing, 1.6mm sheet material according to MIL-T-9046J AB-1 [4] is used.

2.2. Surface Pre-Treatment of Ti-6Al-4V

As mentioned in literature the surface pre-treatment of the metallic substrate has a major impact on the bonding strength of the joint. A lot of research has been carried out in the field of adhesive bonding of thermoset composites and metallic substrates. Also the fusion bonding of thermoplastic composites like PEEK to metallic structures was investigated. [1,5-8]
Nevertheless, there is no comparable information if these surface pre-treatments are suitable for the manufacturing of hybrid joints by the TP-AFP process. In this study, several surface pre-treatments and polymer coatings were investigated. Following Ageorges [1], the use of a polymer coated material offers several advantages: The surface pre-treatment and coating of the material can be performed well before the joining step and provides a conservation of the activated metallic surface [8]. As mentioned by Todd [9], fusion bonding of thermoplastic surfaces, in this case fusion bonding of polymer coating and CFRP, is not as sensitive as adhesive bonding to surface pre-treatment. Cleaning or soft roughening is sufficient and there is only a limited influence of the surface preparation on the final joint strength. By this, the metal joining partner can be stored for a long period of time before joining.
By modifying the coating itself, the absorptive and reflective behavior of the laser’s wavelength used in the TP-AFP process can be adjusted. This allows a greater absorption by the substrate and reduces the energy input needed for joining coated metal and polymer. Furthermore, an insulating layer between carbon fiber and metal is generated providing a barrier against galvanic corrosion. The low stiffness of the coating reduces residual stresses caused by the mismatch in thermal expansion as well. With respect to industrialisation, powder coatings may be a promising way of applying a polymer coating on pre-treated metal surfaces.

Before pre-treatment the surfaces are cleaned and degreased with isopropylalcohol. Within this paper, the following surface pre-treatments and coatings are analysed:

1. Laser-treatment with nanoscopic structure (“LNS”), as investigated by [10].
2. Sand-blasting with corundum, size F36, 2 bar pressure. Afterwards laser treatment according to 1. (“SB+LNS”).
3. Laser treatment according to 1., afterwards coating with PEEK-film via vacuum bagging on a hot stage (“LNS+PEEK”)
4. Sandblasting according to 2., afterwards PEEK powder coating and consolidation in furnace (“SB+POWDER”).

The four combinations LNS, SB+LNS, LNS+PEEK, SB+POWDER are tested and compared with the adhesively bonded reference. The reference samples are manufactured according to a state-of-the art process: $[0/90]_{sym}$ laminate with a thickness of 1.6 mm made out of prepreg material are cured in an autoclave and adhesively bonded to titanium substrates by an epoxy based film adhesive. Before bonding, the titanium is electrochemically pre-treated.

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3. Manufacturing Process of Hybrid Specimens

Fig. 1 left shows a TP-AFP system and the principle of joining CFRP and metal. Endless-fiber reinforced tape material is fed through a fiber placement head to the compaction roller and is positioned on top of the pre-treated metal. By laser radiation, the incoming tape material and the metal substrate are heated to the melting temperature of the composite’s matrix. During the compaction by the roller the thermoplastic matrix solidifies and the joint is generated. A modified fiber placement head, derived from tape winding technology from AFPT GmbH (Dörth, Germany) is used within this study to manufacture hybrid structures. By a closed loop control an in situ consolidation of the laminate can be achieved: Laser power and laser angle are adjusted according to the measured temperature in the substrate and incoming tape material, Fig. 1 right.

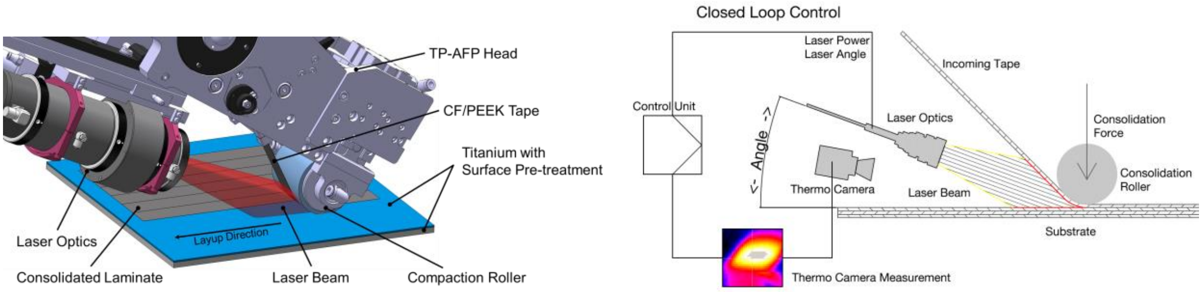

Figure 1. Schematic illustration of the TP-AFP process for joining CFRP and metal (left), principle of closed loop control (right).

Depending on the optical behaviour of the pre-treated metal surface, the laser spot distribution needs to be orientated towards the substrate, the placement speed is reduced and the temperature setpoint is higher compared to laminate manufacturing. Without PEEK-coating, the laser power is set manually in order to achieve a sufficient bonding. Table 1 shows the process parameters for joining CFRP and metal with respect to the chosen surface pre-treatment and for laminate manufacturing.

Table 1. Process parameters for joining and laminate manufacturing

		LNS, SB+LNS	LNS+PEEK	SG+POWDER	Laminate
Temperature setpoint	[°C]	-	415**	415**	420**
Laser power	[W]	2450	-	-	-
Velocity	[m/min]	2	2	2	9
Spot distribution	[%]	0/100*	30/70*	30/70*	CL**
Consolidation force	[N]	500	500	500	500

* Tape / substrate, fixed distribution
** Closed loop control

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4. Single-Lap Shear Tests

4.1. Test Setup and Results

Modified single-lap shear specimens are used to characterize the joint strength of CFRP and titanium. In order to achieve a laminate thickness of 1.6 mm, 11 layers of unidirectional tape are applied on the pre-treated titanium substrates. Afterwards these hybrid panels are notched to realize the overlap length of 12.5 mm and are cutted by a water jet to the desired dimensions of 25 mm in width and 187.5 mm in length, Fig. 2.

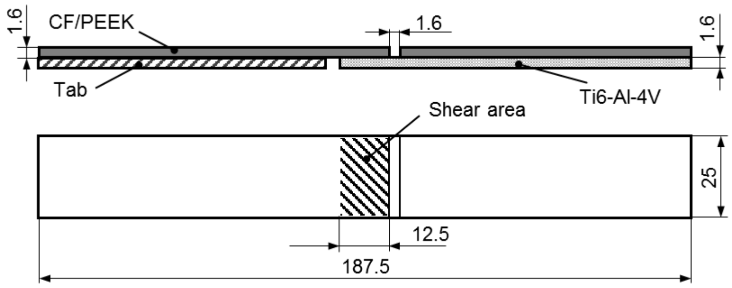

Figure 2. Dimensions of test specimen.

All specimens are tested at room temperature until failure with a crosshead speed of 1 mm/min. After failure, all specimens are inspected visually for the failure mode. There are three types of failure, as illustrated in Fig. 3. Interlaminar failure within the composite (“IF”) is observed for specimens with good adhesion between CFRP and metal. Besides that, some specimens show a cohesive failure within the adhesive respectively coating (“CF”). Depending on the pre-treatment of the titanium, adhesive failure between metal surface and tape, respectively coating (“AF”) is also observed.

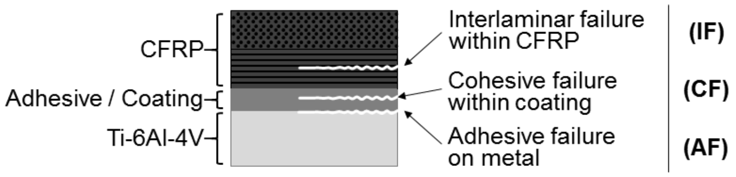

Figure 3. Failure locations during SLS testing.

Fig. 4 shows the normalized Single-lap shear strength in relation to the adhesively bonded reference samples.

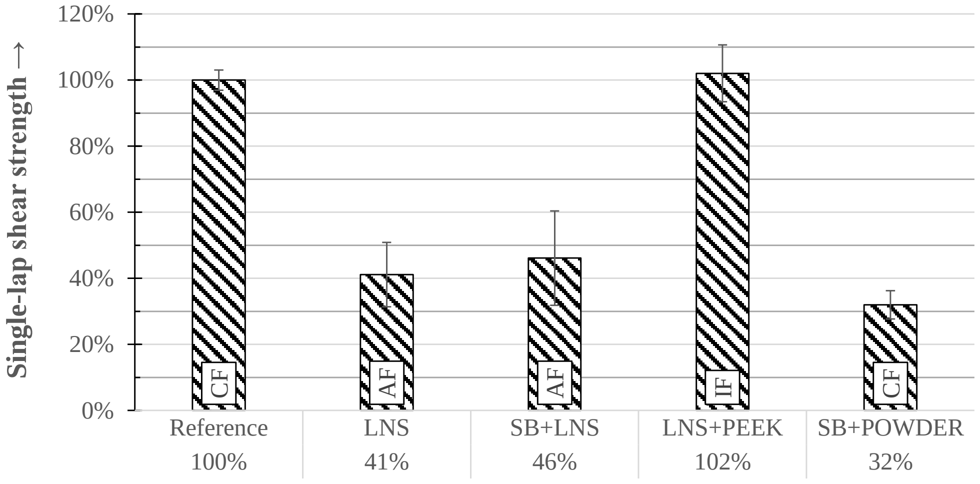

Figure 4. SLS test results (normalized).

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The reference samples show a cohesive failure of the adhesive, as shown in Fig. 5a. Direct placement on the pre-treated titanium substrates provides a lap shear strength of approximately 41% (LNS), respectively 46% (SB+LNS) in relation to the reference samples. Both, LNS and SB+LNS, are showing an adhesive failure between laminate and metal surface, see Fig. 5b. The combination of sandblasting and powder coating results in an adhesive failure, too. A single-lap shear strength of 32% compared to the reference was measured. The most promising results were achieved with the combination LNS+PEEK, providing similar single-lap shear strength as the adhesively bonded reference. Visual inspection shows that the failure takes place within the laminate, typically between the first and second ply, see Fig. 5d.

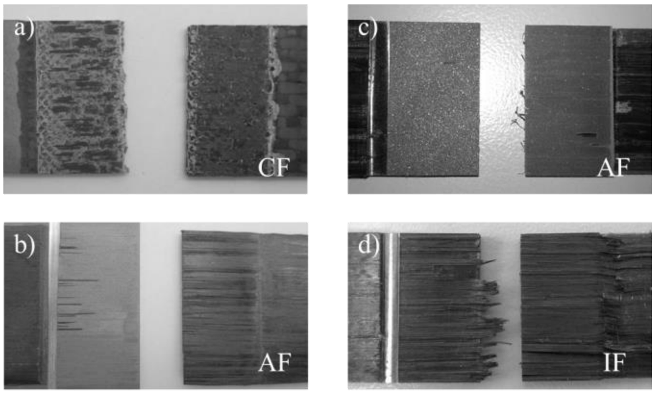

Figure 5. Fracture surface of test specimen. a) Reference, b) LNS, c) SB+POWDER, d) LNS+PEEK.

4.2. Discussion

Direct placement on LNS and SB+LNS pre-treated metal surface showed comparable low lap shear strength and big scattering in the test results. For sample manufacturing, a high energy input is needed for a sufficient heating of the substrate for joining with the PEEK tape (Table 1). Small deviations in geometry and the optical behavior of the material cause either unsufficient heating or degradation of the incoming tape material due to reflections on the substrate. Residual stresses caused by a mismatch in thermal expansion may result in a weakening of the titanium - CFRP bond interface as well.
Placement on powder coated substrates worked but reaches comparable low joint strength. The failure location showed further optimization potential of the interface between titanium surface and the powder coating itself and is a point of ongoing investigations: Promising methods to increase the interfacial strength of coating and metal are laser treatment of the substrate as pre-treatment, post-treatment of the applied coating by laser radiation or subsequent consolidation of the coating under application of pressure.
Best results were achieved with the pre-treatment combination of laser treatment and subsequent coating with PEEK film under vacuum on a hot stage. Micrographs show a interlocking of PEEK-coating and titanium respectively PEEK-coating and tape, but no abnormalities between the first and second ply where most of the failures took place, Fig. 6.

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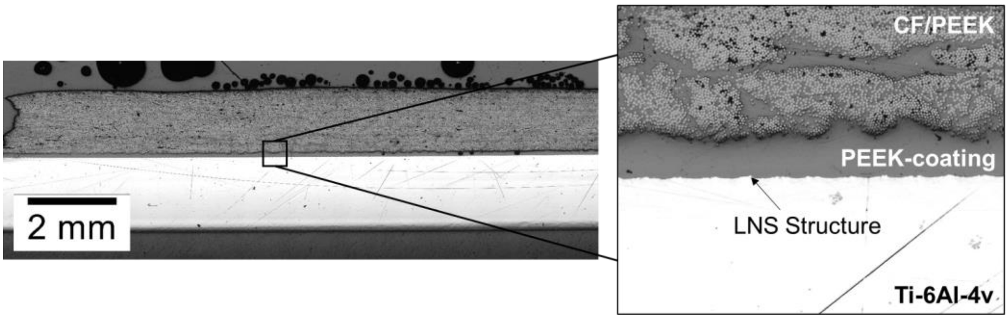

Figure 6. Micrograph of LNS+PEEK specimen.

5. Tail Rotor Drive Shaft Demonstrator

The feasibility and performance of this joining technology has been succesfully demonstrated on coupon-level. In order to improve the industrial acceptance a hybrid tail rotor drive shaft is designed (according to the manufacturing restrictions), manufactured and tested. The aim is to show the capability of TP-AFP for manufacturing hybrid structures for a large scale aerospace application. Static tests analyze the performance of the manufactured demonstrator. Fig. 6 shows the basic design of the tail rotor drive shaft. There are two main elements, the integrated titanium flanges and the CFRP drive shaft:
Titanium flanges at both ends of the drive shaft are needed for load introduction and connection to the main gear. In order to provide a sufficient run on and run off length of the fiber placement head, the flanges are completely covered by the CFRP shaft. The polygon shape on the connection side of the flange is intended as additional form fit to provide a second load path. According to the SLS test results, a laser treatment with subsequent PEEK coating is applied on the flange surface before joining. The CFRP drive shaft carries the static and dynamic torque loads. To improve the buckling stability, the polygon shape of the flanges transforms into a cylindrical tube for the area of the drive shaft.

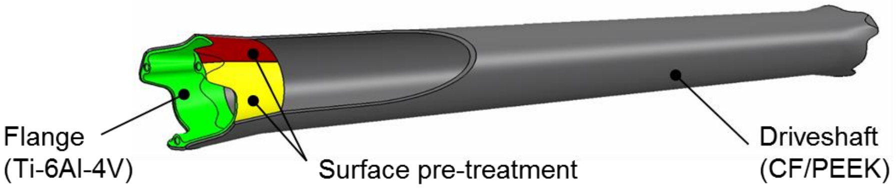

Figure 6. Main elements of hybrid drive shaft.

Due to this design of the drive shaft, a segmented winding tool is developed to realize demolding of the assembled part, Fig. 7. Adapters for flange positioning and the cylindrical segments are alingned on a central axis. By removing the central axis, the adapters can be dismounted and the segments are removed through the inner openings of the flanges.

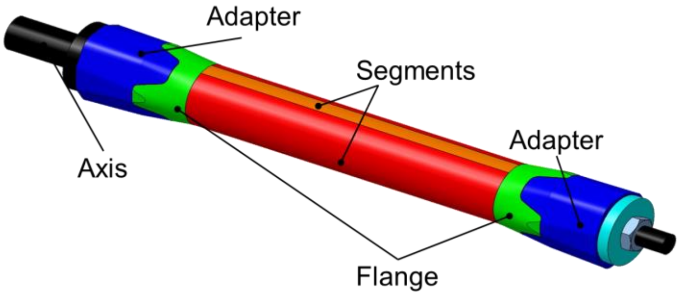

Figure 7. Tooling concept.

For demonstrator manufacturing, parameter settings according to Table 1 are chosen. After laminate lay-up, the drive shaft is demolded, finished and prepared for testing. The manufactured drive shaft is tested under torsional stress for the maximum load factor during flight (limit load) and the load at failure (ultimate load).

As outlined in Fig. 8 left, the manufactured drive shaft was able to withstand the limit load. Failure occurred at load level approximately twice the limit load, the measured deformation (angle) showed nothing conspicuous. Interlaminar failure was observed in the flange area, Fig. 8 right.

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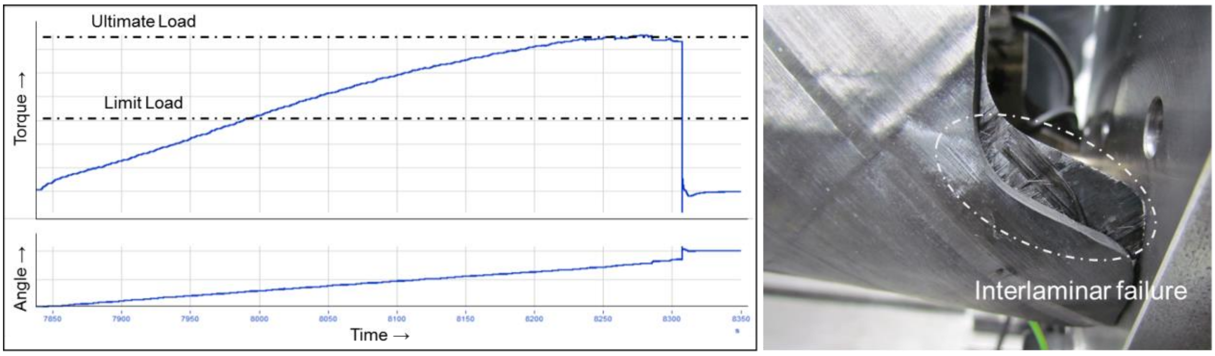

Figure 8. Torque and displacement of the driveshaft during test (left) and failure mode at ultimate load (right).

According to the SLS-tests, the joint strength with pre-treatment LNS+PEEK outperforms the interlaminar shear strength of the composite.

A possible reason for this failure mode is the difference in thermal conductivity and thermal capacity between pure laminate and hybrid section: The energy needed for heating the incoming material and the substrate changes suddenly when moving from laminate (1 ply) to hybrid area (1 ply, perfectly bonded to metal). As outlined in Fig. 9, the closed loop control is able to react to this after a short period of time. Nevertheless, especially on the edges of the joint, the laminate quality is reduced due to the temperature drop.

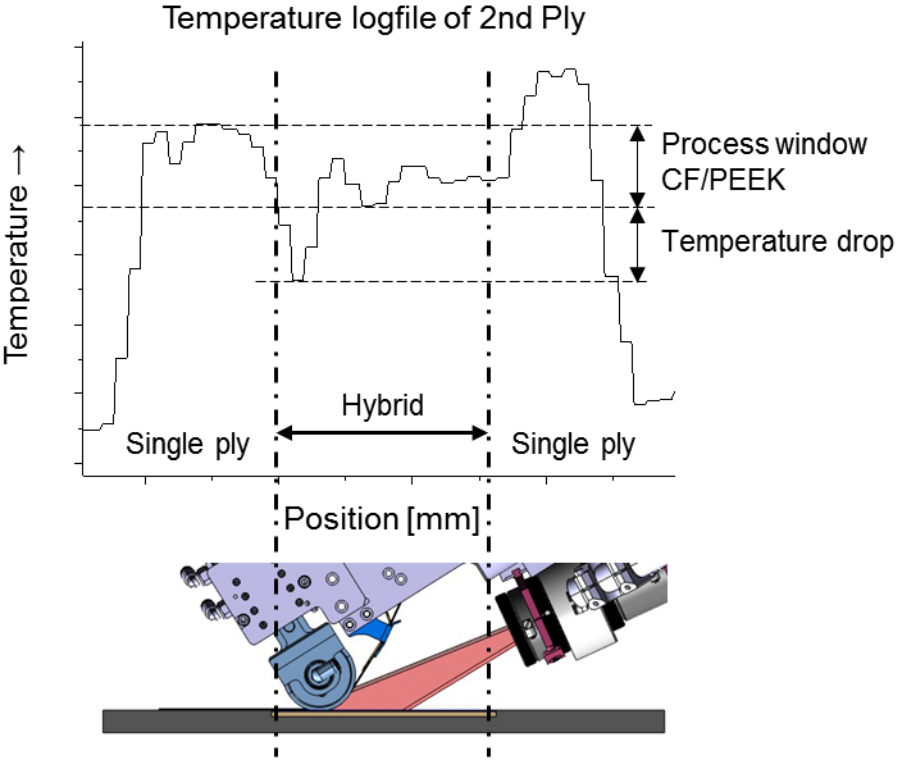

Figure 9. Measured temperature during placement of 2nd ply on hybrid area.

By an optimization of the 2nd ply even higher joint strengths can be achieved. Switching from closed loop control to fixed values in the hybrid area, a faster closed loop control or a reduction of heat penetration depth by increasing the placement speed are points of ongoing investigations to minimize the temperature drop on the transition to the hybrid material.

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3. Conclusions

Single-lap shear tests of hybrid specimens made out of CF/PEEK + Ti6-Al-4V have shown the possibility of joining CFRP and metal by the TP-AFP process. Depending on the surface pre-treatment, joint strength comparable to adhesively bonded joints can be realized. Best results were achieved by the combination of laser treatment and subsequent PEEK coating as surface pre-treatment of the titanium. Powder coating gives the opportunity of coating even complex geometries, nevertheless the interfacial strength between coating and titanium needs to be investigated more in detail. Direct placement on titanium has been demonstrated successful, but could not provide as good results as the pre-treatment by laser radiation with subsequent PEEK coating on a hot stage.
A fullscale demonstrator part was designed, manufactured and tested to prove the feasibility given by the SLS-tests. A segmented tooling was developed in order to demold the drive shaft with integrated flanges on both sides. Mechanical test of the drive shaft showed the performance of the demonstrator and the successful implementation of the TP-AFP process for manufacturing hybrid structures. By optimizing process parameters at the hybrid area, further improvements of the quality are expected.

Acknowledgement

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