Journal of
Manufacturing and Materials Processing

MDPI

Article

Orbital Ultrasonic Welding of Ti-Fittings to CFRP-Tubes

Moritz Liesegang [1,*], Sophie Arweiler [1], Tilmann Beck [1] and Frank Balle [2]

[1] Institute of Materials Science and Engineering, Technische Universität Kaiserslautern, 67653 Kaiserslautern, Germany; arweiler@mv.uni-kl.de (S.A.); beck@mv.uni-kl.de (T.B.)
[2] Walter and Ingeborg Herrmann Chair for Power Ultrasonics and Engineering of Functional Materials, Department of Sustainable Systems Engineering (INATECH), Faculty of Engineering, University of Freiburg, 79110 Freiburg, Germany; frank.balle@mail.inatech.uni-freiburg.de
* Correspondence: liesega@mv.uni-kl.de

Abstract: Hybrid structures are important for the automotive and aeronautical industry as they have the potential to reduce vehicle or aircraft weight and to improve fuel efficiency. Continuous ultrasonic metal welding is a promising technique for hydraulic applications in aircraft to realise tubular metal/fiber reinforced polymer (FRP) hybrids. Fluid proof connections between dissimilar components can be joined by continuous welding seams. Tubular metal/FRP hybrids, produced by a new advanced variant of ultrasonic metal welding, are investigated as a potential substitute for metallic hydraulic tubes. The oscillating welding system moves around the tubular joining partners to generate a sealed orbital connection. Homogeneous joint quality is required to assure the requested component strength. Therefore, the amplitude of sonotrode displacement and the welding force are controlled to keep the induced welding energy constant and the joint quality uniform. High mechanical strength is required for a safe application in the 5000 psi hydraulic system of current and future aircraft concepts. For this study metal injection molded (MIM) titanium fittings (TiAl6V4) and carbon fiber reinforced PEEK (CF-PEEK) tubes were investigated. Process parameters for metal/FRP hybrid joining were evaluated considering their mechanical and technological properties, as well as the microstructure of the hybrid interfacial area. The entire joining area of tubular joining partners has to be in close contact before welding to assure a continuous tight joint. Hence, the titanium fitting is thermally shrunk onto the CFRP tube before ultrasonic welding. The presented orbital ultrasonic welding technology was developed for prospective industrial use and future applications of ultrasonically welded tubular multi-material-components.

Keywords: ultrasonic welding; hybrid joints; lightweight; titanium; CFRP; tubular joints

check for updates

Citation: Liesegang, M.; Arweiler, S.; Beck, T.; Balle, F. Orbital Ultrasonic Welding of Ti-Fittings to CFRP-Tubes. *J. Manuf. Mater. Process.* **2021**, *5*, 30. https://doi.org/10.3390/jmmp5020030

Academic Editor: Steven Liang

Received: 4 March 2021
Accepted: 1 April 2021
Published: 3 April 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The demand of multi-material structures for applications in transport, energy or medicine industry increases constantly as environmental protection and cost pressure determine the trend to produce components resource efficiently [1–4]. The combination of different materials or even material classes allows to increase the performance of components, e.g., specific mechanical or functional properties [5–10]. A huge variety of both, possible combinations of joined materials and applicable joining processes exist for hybrid material systems. Principles of hybrid structures produced by joining polymer based materials to metals which are in the focus of this paper, were summarized by Amancio-Filho and Blaga introducing adhesive bonding, friction spot joining, induction welding, laser welding, mechanical fastening, and ultrasonic welding [1].

Modern airplanes, e.g., Airbus A350 or Boeing 787, are built of approximately 50% fiber reinforced polymers (FRP) [11]. To join such structures with metallic components, ultrasonic welding (USW) is a promising technique without filler materials or additives—such as adhesives, rivets, or bolts—and, hence, without serious damage of the carbon fibre reinforced polymer (CFRP). In principle, ultrasonic welding energy is transferred

in the joining area by the relative movement of the joining partners at the interface. The formation of joints by ultrasonic welding is caused by the relative motion between the joining partners, regardless of the ultrasonic welding type (i.e., polymer or metal ultrasonic welding subdivided in spot-, torsional, or seam welding) [8,12–16]. State of the art polymer ultrasonic welding is the most common USW process, used in the packaging industry to reliably join polymers quickly and cost-effectively [17]. Metal USW is typically applied to join soft non-ferrous metals such as aluminium and copper for electrical applications [18].

USW of metal/CFRP hybrid structures for light weight applications, has been a focus of research during the last decade. For example, aluminium/CFRP joints have been intensively studied, see [19–22]. The strength and the joint formation depend on the materials combination. Ultrasonic welding of metal to CFRP sheets with a thermoplastic matrix results in higher joint strength. The thermoplastic matrix melts locally due to the induced energy, followed by proximation of the metal and FRP sheet and finally the interlocking of fibers and metal due to plastic deformation complemented by the additional adhesive connection, caused by the solidified thermoplastic polymer matrix in the joining area. The resulting joint formation of a metal/FRP hybrid connection is shown schematically in Figure 1 [17–19].

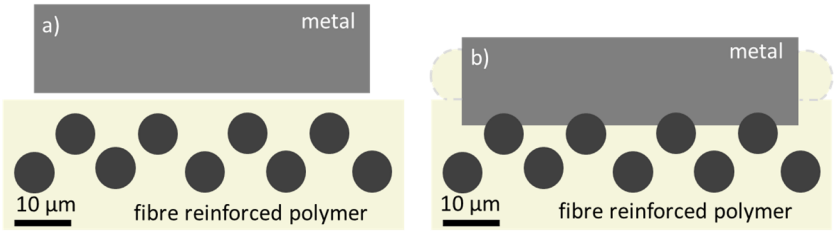


Figure 1. Schematic microstructure of an ultrasonically welded metal/fiber reinforced polymers (FRP)-joint (**a**) before and (**b**) after ultrasonic metal welding process [17–19].

The comparison of joint strength between adhesive bonding and ultrasonic welding is common and also practicable for tubular hybrid structures. Assuming perfect surface conditions, the strength of adhesively bonded joints is limited by the shear strength up to 36.5 MPa for epoxy based adhesives [1] or 53.2 MPa for polyether ether ketone (PEEK) [20]. Ultrasonically welded AA5024/(GF-)CF-PEEK joints can reach higher strengths up to 83 MPa [17] while a strength of just 34.8 MPa for AA5754/PA6/CF-epoxy was reported by [21] due to a pure adhesive bonding in the interface.

In this work, USW of planar and tubular Ti6Al4V/CF-PEEK joints was investigated for the first time to the knowledge of the authors. Hybrid Ti6Al4V/CF-PEEK-tubes are technologically and economically interesting, since they provide a higher specific strength at lower costs in comparison to Ti3Al2.5V tubes that are typically used in 5000 psi aircraft hydraulic systems. In comparison to adhesive bonding, a higher strength is expected for ultrasonically welded joints. During USW, an adhesive bonding is created by melting the thermoplastic matrix of the CF-PEEK combined with plastic deformation of the metal resulting in a mechanical interlocking and possibly an atomic or molecular interaction between carbon fibers and metal due to juvenile contact surfaces which are beneficial for the joint strength.

To continuously weld tubular joining partners, a rotatable mounted oscillation unit is used to transfer the welding energy. Typically, such welding machines are used to join thin non-ferrous metal sheets, e.g., to connect copper absorbers in a solar thermal system [18]. The oscillation unit of the welding machine can be seen in Figure 2. A Langevin piezoelectric transducer converts high frequent electric voltage into a mechanical, standing wave oscillation of the same frequency (e.g., 20 kHz), as illustrated by the black line along the oscillation unit in Figure 2. In addition to mechanical amplification of the vibration amplitude, the sonotrode induces the oscillation and hence, the welding energy into the joining area. Most commonly one or more so called boosters are built between sonotrode and

transducer to enhance or reduce the amplitude of the mechanical displacement. Transducer, booster and sonotrode are mounted at the maxima of the displacement (Figure 2, Point 1 and 3), where the stress is consequently minimal. Point 5 indicates the sonotrode tip—the functional part of the oscillation unit, where the displacement reaches its maximum of up to 60 µm (for sonotrodes used in this work).

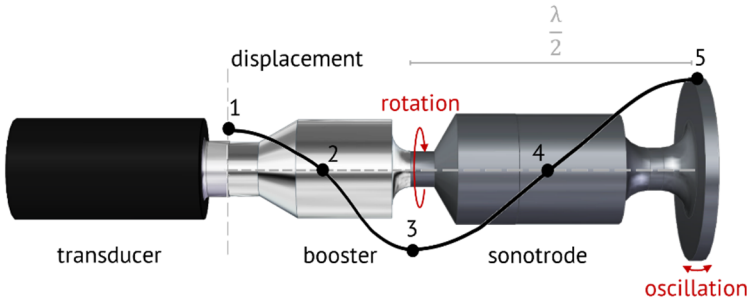


Figure 2. Structure and mechanical displacement along the rotatable oscillation unit of a continuous ultrasonic welding machine.

Due to its high strength and hardness as well as the relatively low thermal conductivity, titanium is a desirable but challenging joining partner. During the welding process of Ti alloys at 20 kHz the sonotrode has to resist local temperatures up to 700 °C and considerable cyclic loads at the sonotrode tip.

In the work presented here, tubular hybrid structures of titanium and CFRP were ultrasonically welded by a novel orbital process for future applications in aircraft hydraulic systems. A substitution of titanium tubes by CFRP allows a reduction of components weight, noise level and also costs in a medium-term prospective.

2. Materials and Methods

As mentioned above, the major aim of the presented research work is the manufacturing of high strength tubular Ti6Al4V/CF-PEEK joints. The development of that novel orbital ultrasonic welding process was, however, supported by preliminary planar welding experiments of sheet material, the development of suitable sonotrodes and finite element models of the joints. For both the planar and the orbital welding experiments a special sonotrode made from Fe-Co-Mo alloy (Boehler MC90) with a hardness of 68 HRC and a groove structured 5 mm width sonotrode tip was used. During the welding process, the welding zone was shielded by an Argon flow to reduce the oxidation of the titanium as well as to thermally protect the sonotrode.

The welding setup for planar ultrasonic welding, a Ti6Al4V/CF-PEEK joint and the microstructure of the planar joining partners is shown in Figure 3.

The determination of process parameters is challenging as both, the displacement amplitude and the welding force (pressure) affect the welding energy. In order to obtain a high joint strength, welding parameters for the preliminary planar welding experiments were investigated by a design of experiments (DoE) approach using the software Umetrics MODDE 7 to plan 72 process parameter setups with 5 repetitions for each setup in 3 blocks, i.e., 360 welding experiments in total. In this model the displacement amplitude, the sonotrode velocity (feed rate) and the welding force are the factors to be varied in order to achieve a certain shear strength. The investigated parameter setups are determined by a randomized "central composite circumscribed" model (CCC) varying the amplitude from 26 to 38 µm, the sonotrode velocity from 2 to 7 mm/s and the welding force between 100 and 350 N.

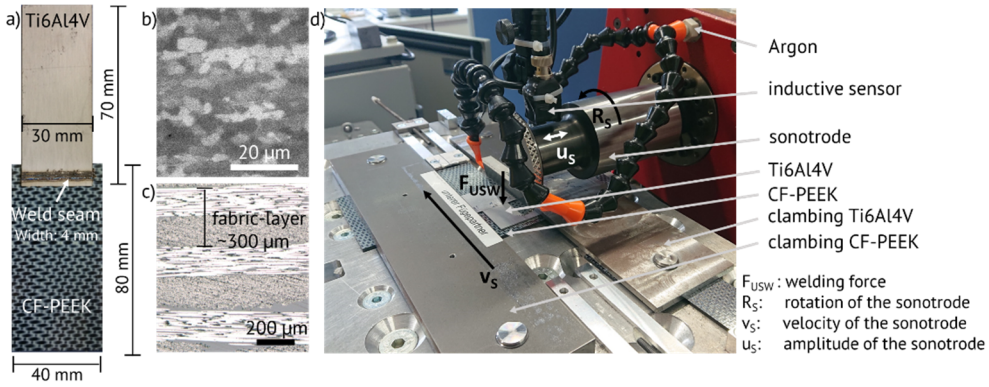


Figure 3. (**a**) Ti6Al4V/CF-PEEK joints of preliminary welding experiments and the microstructure (**b**) of a Ti6Al4V sheet, (**c**) of a CF-PEEK sheet and (**d**) the setup for planar ultrasonic welding.

Titanium fittings were manufactured by metal injection molding (MIM) by our project partner Parker Hannifin (Bielefeld, Germany) in the framework of the German aeronautical research programme (LuFo-V 2, 20Y1506F). Figure 4 shows the Ti6Al4V-fitting in its three states of manufacturing by MIM: (a) the green body, (b) after sintering and (c) the final geometry after turning to final dimensions. The shaft with a length of 40 mm allows to apply multiple weld seams. Concerning the titanium microstructure of the final MIM fitting, a predominantly lamellar grain structure was observed (Figure 4d). Figure 4e shows the dimensions of a CF-PEEK-tube sample and (f) the microstructure of the carbon fiber tape layers with a thickness of ~125 µm, separated by a thin layer of PEEK matrix. The CFRP tubes were provided by our project partners at PFW Aerospace (Speyer, Germany). The CF-PEEK-tube is based on a generic aeronautical 1" PEEK liner with a wall thickness of 1 mm. CF-PEEK tapes were raised on the liner by laser tape winding with an orientation of $\pm 54°$ to provide the maximum resistance against internal pressure according to the netting theory [22].

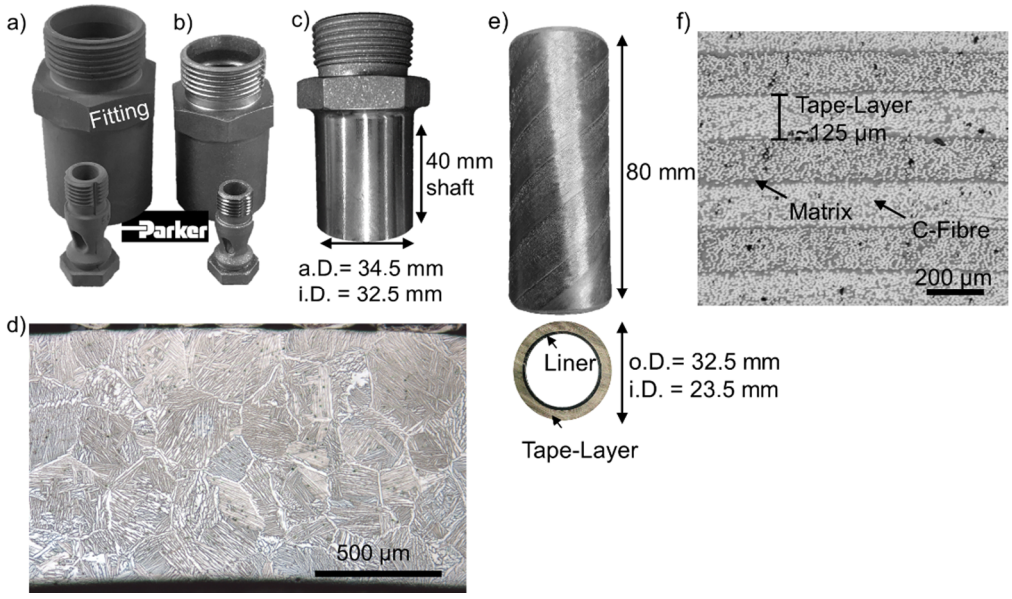


Figure 4. Dimensions and microstructure of the joining partners: (**a**) Ti6Al4V-fitting green body, (**b**) sintered Ti6Al4V-fitting, (**c**) Ti6Al4V-metal injection molded (MIM)-Fitting, turned to final dimensions, (**d**) microstructure of Ti6Al4V-fittings, (**e**) laser tape winded CF-PEEK-tube, (**f**) CF-PEEK-tube microstructure ((**a**,**b**) with kind approval of Parker Hannifin GmbH).

The orbital welding experiments were performed with an orbital ultrasonic welding system, that has been developed in cooperation with Airbus-CTC GmbH (Stade, Germany),

in order to allow circumferential weld seams around the joining partners. Figure 5 shows the unique orbital ultrasonic welding system, based on a 20 kHz roll-seam welder of the type, Branson Ultraseam 20 (Emerson Electric Co., Dietzenbach, Germany). The functional parts of the orbital welding system are indicated by letters. The measurement and regulation of process parameters is done by the ultrasonic generator in combination with a programmable logic controller (PLC) (A). The joining partners are inserted from above and clamped into the machine (B). The welding actuator (D) rotates around the rotational axis (E) in order to create a circumferential weld seam around the joining partners in the hybrid welding area (C). A closeup of the reduced CAD model is given in Figure 5b, including the sonotrode, the joining partners, the measurement devices, and the additional supply of shielding gas (Argon) during the welding process.

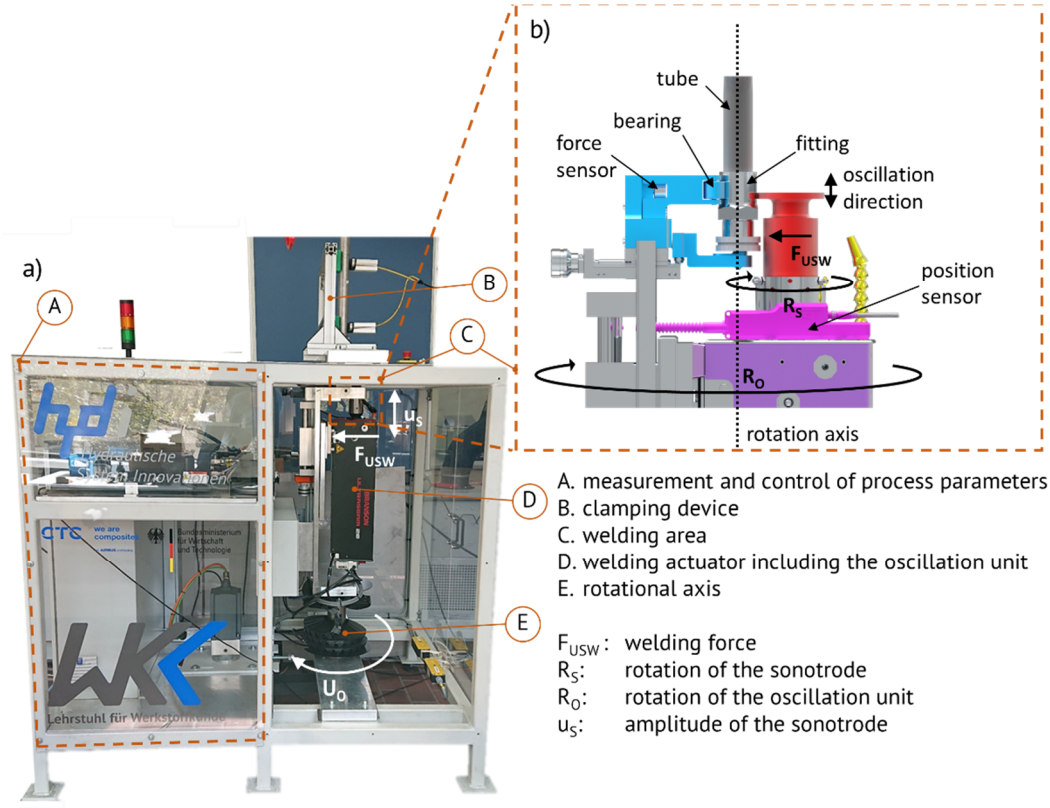


Figure 5. Orbital welding system for Ti/CFRP-tubes: (**a**) general overview and (**b**) reduced CAD model of the welding area.

Homogeneous joint quality is required to assure the requested component performance. Therefore, the amplitude of sonotrode displacement and the welding force are controlled by closed-loop to keep the induced welding energy constant and the joint quality uniform.

An essential requirement for the orbital ultrasonic welding process is a gap-free contact between both joining partners. In case of sheet shaped joining partners, the contact is given by forces of the clamping device and the sonotrode to the sheet surfaces. In case of tubular joining partners the formation of a gap-free contact is more challenging. In this work, the contact was formed by a cylindrical interference fit between the Ti6Al4V-fitting and the CF-PEEK-tube (Figure 6). Therefore, the fitting is heated up to 380 °C to thermally expand and the CF-PEEK-tube is pressed into the hot Ti6Al4V-fitting (a), which finally leads to a gap-free contact (Figure 6b) that was verified by X-ray computed tomography (CT) (Figure 6c).

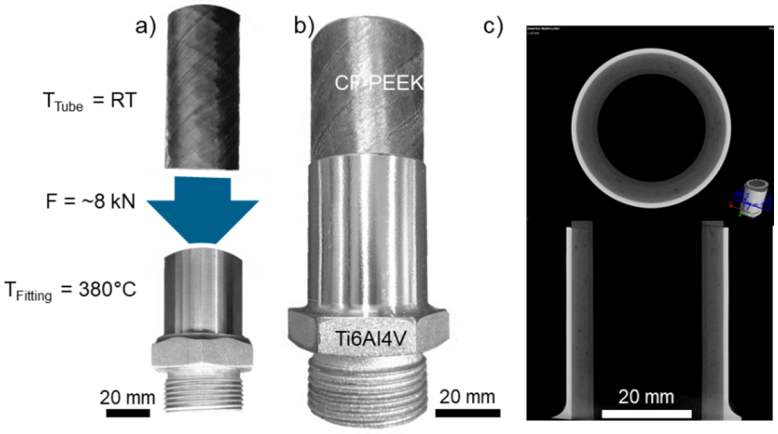


Figure 6. Preparation of the welding samples: (**a**) interference fit of the Ti6Al4V-fitting and the CF-PEEK-tube, (**b**) prepared Ti6Al4V-Fitting/CF-PEEK-tube for the welding process and (**c**) computed tomography (CT)-scan of the interference fit to screen gaps between the joining partner prior welding.

Typically, ultrasonic welding experiments to examine suitable process parameters for high strength joints are planned by design of experiments (DoE) [23]. Due to a small number of available samples, the tubular welding experiments could not be planned using DoE. Therefore, the welding experiments were supported by finite element (FE) modelling (Figure 7). A simplified model of a hybrid joint consisting of a titanium sheet or fitting and a CF-PEEK sheet or tube separated by a PEEK layer is suitable to compare geometrical differences of joints considering the state of stress [24]. In order to evaluate the most promising weld seam setup, the maximum von Mises stress is calculated depending on the number (n) and the position of the weld seams (x) on the Ti6Al4V-Fitting which both determine the distance between the weld seams.

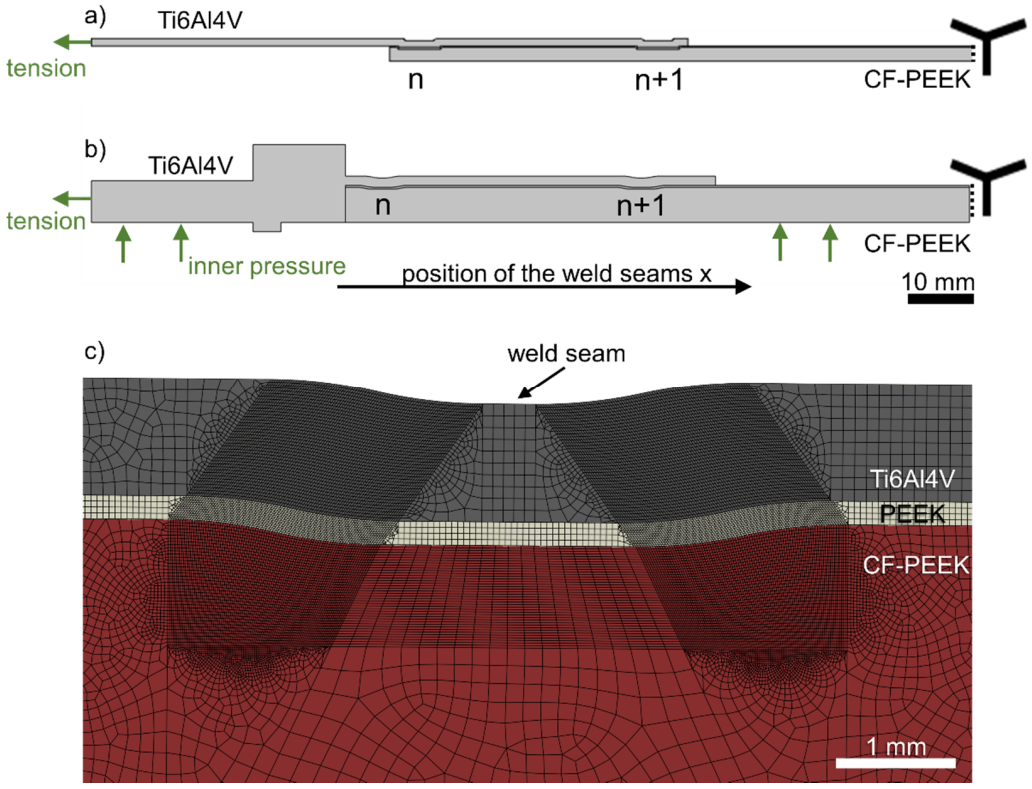


Figure 7. Finite element (FE) models of (**a**) Ti6Al4V-fitting/CF-PEEK-tube, (**b**) Ti6Al4V/PEEK/CF-PEEK sheet joint and (**c**) cross section of the weld seam.

Figure 7 shows an overview of the FE models (a) of a planar Ti6Al4V/CF-PEEK joint, (b) of a Ti6Al4V-fitting/CF-PEEK tubular joint, that was designed assuming rotational symmetry of the area displayed and (c) a cross section of the weld seam.

The detailed mechanical properties of the interfaces in ultrasonically welded hybrid joints are largely unknown. Hence, in our approach, a pure PEEK interlayer between titanium and CF-PEEK was modelled. The PEEK interlayer is connected to both joining partners with tied constraints in the weld seam area, that prohibit parallel sliding or penetration of the surfaces. Thus, the failure has to occur in the component with the lowest strength, which is the PEEK layer in this model. While this simplification affects the absolute values of strain and stress, it has no significant influence on the pattern of the stress distribution. Hence, in the latter respect, comparability of calculated and experimental hybrid joints is given. Elastic isotropic material properties were considered (Table 1). Since plastic deformation was the failure criterion, the elastic limit determines the maximum stress acceptable in the joint. The FE model was loaded by longitudinal tensile forces as well as by an internal pressure (see Figure 6a). To determine the most suitable number and position of the weld seams planar joints were simulated by assuming a tensile shear force of 6 kN according to experiments on planar joints. To fulfil the requirements for applications the 5000 psi (~350 bar) hydraulic system in an airplane and a security factor of three, the hybrid Ti/CFRP hydraulic component has to resist an internal pressure of 1050 bar. Therefore, in the simulations of the tubular joints an internal pressure of 1050 bar and an axial force of 90 kN, according to Barlow's formula, were applied, respectively.

Table 1. Mechanical properties of the materials used in the FE model [25].

	Ti6Al4V	**CF-PEEK**	**PEEK**
Young's Modulus in GPa	110	50	4.2
Elastic limit in MPa	880	200	100
Poisson's ratio	0.30	0.42	0.38

The FE model was used to determine the most promising weld seam number, position and distance considering the resulting in minimized peak von Mises stresses in the tubular joint configuration. Based on these results, welding experiments were performed to identify a suitable amplitude of the sonotrode displacement and the welding force of the oscillation unit considering the maximum force in tensile shear tests.

3. Results

As mentioned above, preliminary planar welding experiments of sheet material were performed to identify a suitable range of process parameters for the orbital welding process. Using DoE, displacement amplitude, welding force, and sonotrode velocity were varied in order to maximize the resulting relative shear force. The relation between the process parameters investigated and the resulting force at shear fracture calculated by multiple linear regression of the experimental results, is illustrated by the surface plots given in Figure 8. The calculated maximum shear force is shown depending on the combination of (a) welding force and displacement amplitude for a sonotrode velocity of 4.5 mm/s and (b) sonotrode velocity and displacement amplitude at a welding force of 150 N.

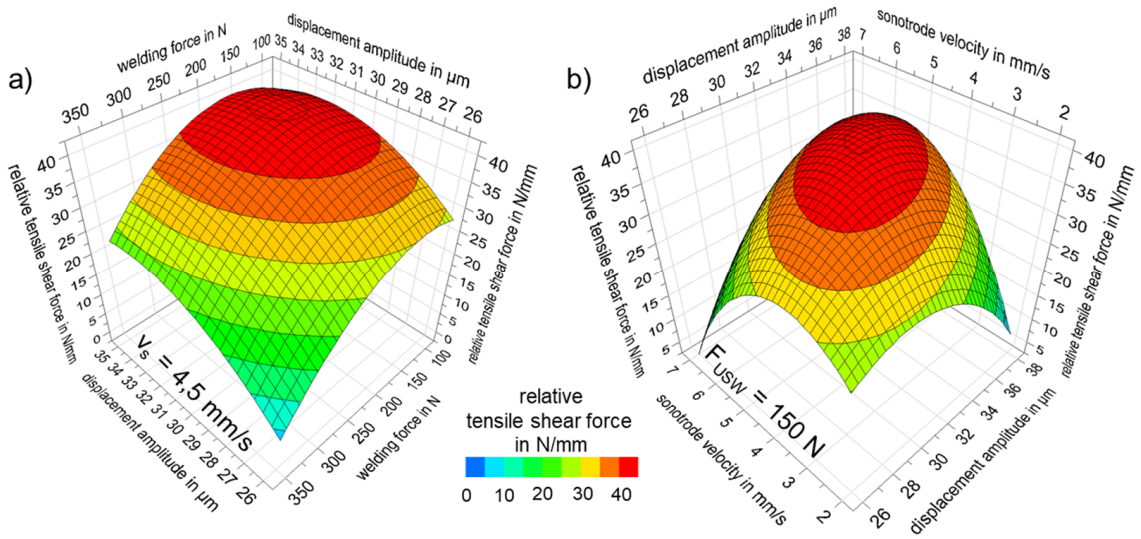


Figure 8. Maximum relative shear force of planar Ti6Al4V/CF-PEEK joints depending on the combination of (**a**) welding force and displacement amplitude for a sonotrode velocity (v_S) of 4.5 mm/s and (**b**) sonotrode velocity and displacement amplitude at a welding force F_{USW} of 150 N.

The surface plots show explicit maxima, which allow to identify the most promising process parameters. A displacement amplitude of 33 µm, a welding force of 150 N, and a sonotrode velocity of 4.5 mm/s were determined to obtain a predicted maximum relative shear force of 40 N/mm, referring to a weld seam length of 40 mm per weld seam. Three samples were welded to verify the determined parameters achieving a maximum relative shear force of 80 N/mm ± 10, which is even higher than predicted.

In addition to the preliminary planar welding experiments, which indicated a promising range of process parameters to be transferred to the orbital welding process, the maximum von Mises stresses occurring in the simulated joints identify the most promising position and number of the weld seams. The stress distribution and corresponding deformation behavior of a fitting/tube joint under a tensile load of 6 kN is shown in Figure 9 for (a) one, (b) two, and (c) three weld seams. The maximum equivalent von Mises stresses occur in the titanium sheet for one weld seam. For two and three (or more) seams, the stress is about 15% lower, due to the altered deformation behaviour caused by two or more weld seams.

Orbital ultrasonic welding of multiple weld seams is risky as the welding process of the following weld seams may affect the joints quality of the existing weld seams. Hence, a low number of weld seams with a large distance between each other is considered beneficial considering the joint strength and process efficiency. Therefore, all experimental welding samples were joined by two weld seams with a distance of 20 mm.

The joint strength of ultrasonically welded hybrid joints between titanium fittings and CF-PEEK-tubes was determined by monotonic tensile shear tests. In principle, the joint strength consists of the ultrasonic-based connection and a smaller proportion caused by the interference fit in the range of ~20% of the total joint strength. Figure 10a shows an ultrasonically welded tubular Ti6Al4V/CF-PEEK joint with two weld seams and (b) a schematic force-displacement curve.

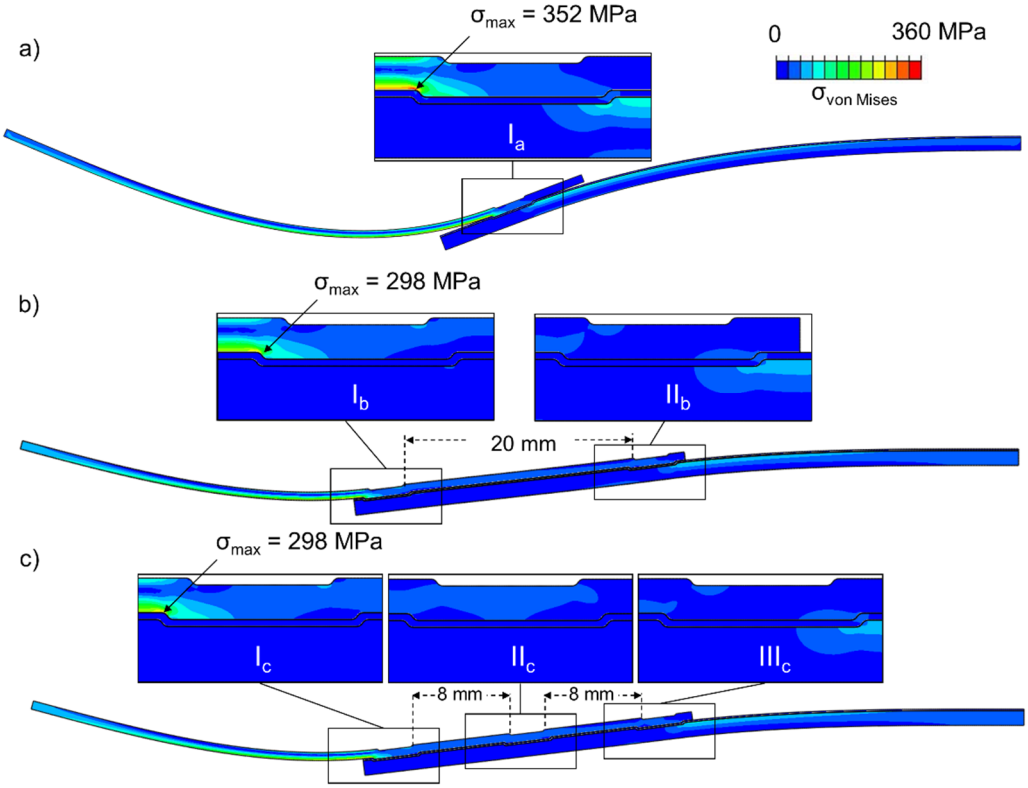


Figure 9. FE model of a Ti6Al4V/PEEK/CF-PEEK sheet joint: Von Mises stress distribution and von Mises stress maxima under a tensile load of 6 kN for (**a**) one, (**b**) two and (**c**) three weld seams.

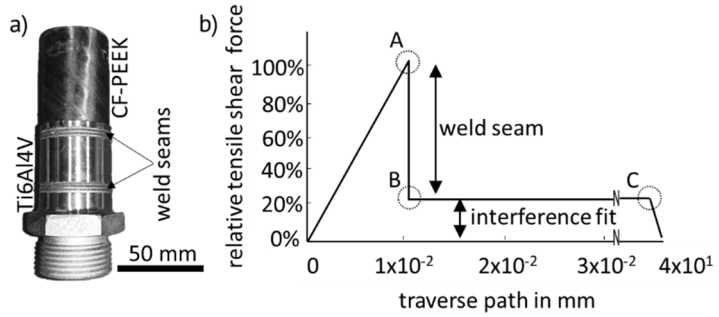


Figure 10. Ti6Al4V-fitting/CF-PEEK-tube joint, formed by orbital ultrasonic welding: (**a**) Welded sample with two weld seams, (**b**) schematic force-displacement curve.

The force increases until the weld seams macroscopically fail after approximately pure elastic deformation (A) and decreases to a second force level (B) that is caused by the interference fit. The force remains nearly constant at this level until close to the complete separation of the fitting and the tube when it decreases rapidly until zero (C).

To determine process parameters that lead to a high strength hybrid connection, welding experiments were performed. Figure 11 shows the resulting maximum tensile shear force depending on the number of weld seams and the process parameters welding force and displacement amplitude of the sonotrode.

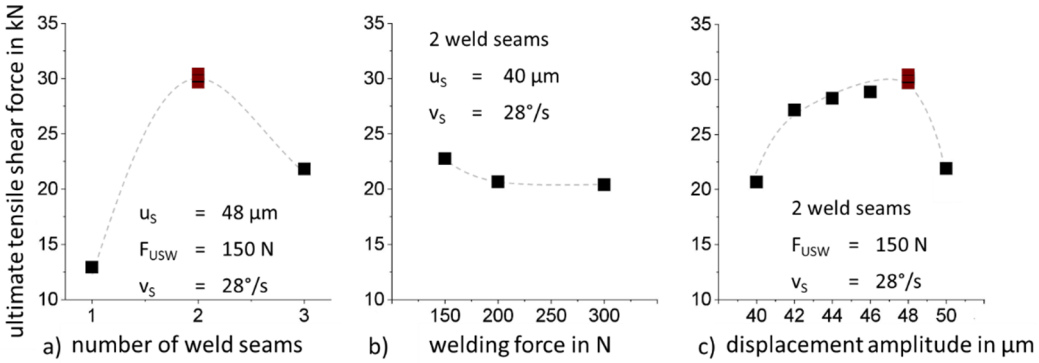


Figure 11. Ultimate tensile shear force depending on the process parameters: (**a**) Number of weld seams, (**b**) welding force and (**c**) displacement amplitude of the sonotrode.

The range of process parameters investigated was determined by planar welding experiments and the weld seam number and position by FE simulations. The most promising sonotrode velocity (v_S) of 4.5 mm/s for planar ultrasonic welding is equivalent to an angular velocity of 28°/s for orbital ultrasonic welding. The minimum stepsize of angular velocity adjustment is ±14°/s, which is too much to reliably identify the optimum value. Therefore, the angular velocity was not varied for orbital ultrasonic welding experiments. The highest tensile shear force of 30 kN was achieved for a welding force F_{USW} of 150 N, a displacement amplitude of 48 µm and two weld seams, consistent with the results of planar joints in the FE-model. The optimal displacement amplitude u_S for orbital ultrasonic welding (48 µm) is significantly higher than for planar ultrasonic welding (33 µm), which is caused by the different contact conditions for clamped sheets in comparison to the interference fit of the tubular samples. During the creation of the interference fit, air can escape from the interface between the joining partners (see Figure 6) achieving a gap free contact area. In contrast, air is trapped in the topography of the surface in case of the clamped sheets. As result, more heat is created at the surface of Ti6Al4V, as the thermal conductivity is inhibited by air. Due to the tighter, air free contact between the tubular joining partners heat, which is proportional to the displacement amplitude, can be distributed more effectively preventing a damage of the PEEK-Matrix. The fracture surfaces of the Ti6Al4V/CF-PEEK interface manufactured by orbital and planar ultrasonic welding, shown in Figure 12 confirm this assumption. The annealing color on the surface and the remaining CF-PEEK indicate the temperatures occurring at the interface. While there is almost no colour change for orbital welded samples, the planar welded joints both show a brownish coloring for u_S: 33 µm and a brownish to purple coloring as well as remaining burned PEEK for u_S: 38 µm. The temperature-color bar in Figure 12 has been determined by annealing Ti6Al4V sheets under air atmosphere. As the atmosphere at the joint interface during the welding process is unknown, temperature cannot be determined quantitatively. In comparison to orbital welded joints, the planar welded joints show surface colors, that indicate higher temperatures. Additionally, the burned PEEK indicates temperatures above the decomposition temperature of PEEK (545 °C [25]).

The FE simulations of planar joints showed that the maximum von Mises stress does not further decrease for weld seam numbers higher than two. The welding experiments reveal that a third weld seam even reduces the tensile shear strength. A possible reason is the lower distance of 8 mm between the weld seams that possibly leads to a damaging of the consisting weld seams by the vibrations of the welding process of further weld seams. Due to a limited number of welding samples only one joint per parameter combination was welded to identify the most promising parameter set. The highlighted parameter set (Figure 11) that leads to maximum strength was verified by two additional welded joints, showing a reproducibility of more than 98%. Therefore, the results are considered reliable, despite the small number of welded samples.

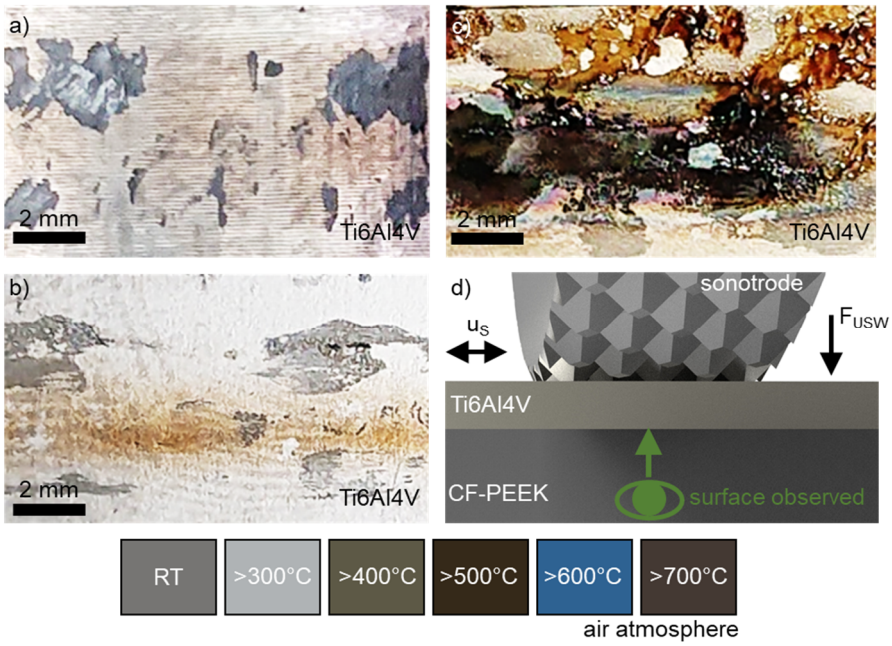


Figure 12. Titanium fracture surface of the Ti6Al4V/CF-PEEK interface (**a**) orbital welding with u_S: 48 µm, (**b**) planar welding with u_S: 33 µm and (**c**) planar welding with u_S: 38 µm, all joints were welded with F_{USW}: 150 N and v_S: 28°/s or 4.5 mm/s, the temperature-color bar of annealed Ti6Al4V sheets and (**d**) schematic overview of the surfaces observed in (**a**–**c**).

As mentioned above, the process parameters affect the amount of energy that is induced into the joining zone. During the welding process, the thermoplastic matrix melts and the metal surface gets closer to the carbon fibers. The temperature in the joining zone has to exceed the melting temperature of the thermoplastic matrix (350 °C for PEEK [25]), but must remain below the decomposition temperature of PEEK (545 °C [25]) to prevent damage of the CF-PEEK-tube. Considering the effect of process parameters on the maximum tensile shear force of orbital welded joints, the displacement amplitude has the highest influence. For displacement amplitudes lower than 40 µm and higher than 48 µm, the maximum tensile shear force is significantly lower than for displacement amplitudes between 42 µm and 48 µm. In order to understand the relation between amplitude and joint strength, the microstructure of selected ultrasonically welded samples were observed. Figure 13 summarizes the characteristic microstructure of tubular Ti6Al4V/CF-PEEK-samples with two weld seams and parameter triples of (a) 40 µm, (b) 48 µm, and (c) 50 µm displacement amplitude, a welding force of 150 N, a sonotrode velocity of 28°/s.

The welding force was 150 N and the velocity of the sonotrode was 28°/s or 4.5 mm/s, respectively, for all samples. The sample welded with 40 µm displacement amplitude (Figure 13a) shows a layer of PEEK-matrix between the titanium surface and the carbon fibers, which indicates an insufficient amount of welding energy or an interfacial temperature below the melting temperature, respectively. In contrast, the hybrid sample, welded with a displacement amplitude of 48 µm (Figure 11b) shows a close contact between carbon fibers and titanium surface. Moreover, the metal surface is plastically deformed, which promotes mechanical interlocking between titanium and CF-PEEK. This parameter set leads to the highest maximum tensile shear forces of 30 kN corresponding to a relative shear force of 142 N/mm, referring to the weld seam length of 105 mm for each of the two weld seams. Despite the higher amplitude of 50 µm (Figure 11c) leading to a close contact of carbon fibers and titanium surface, the maximum tensile shear force is significantly lower in comparison to 48 µm displacement amplitude. The interfacial microstructure reveals cavities between the carbon fibers below the titanium surface, that indicate local temperatures exceeding the decomposition temperature of PEEK. In the case shown here,

a large amount of the near-interface matrix has been decomposed during the ultrasonic welding process, which negatively affects the joint strength.

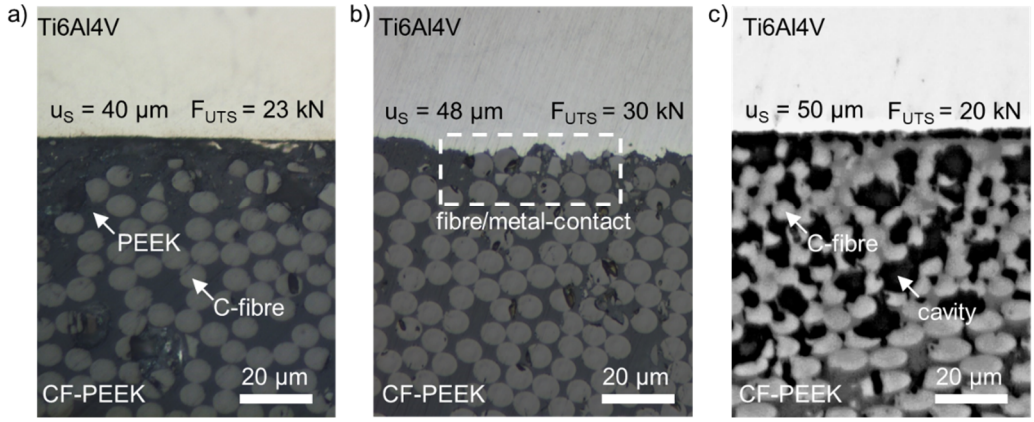


Figure 13. Microstructure of ultrasonically welded Ti6Al4V-fitting/CF-PEEK-tube joints depending on the displacement amplitude u_S: (**a**) 40 µm, (**b**) 48 µm, and (**c**) 50 µm with F_{USW}: 150 N and v_S: 28°/s (4.5 mm/s) with the resulting ultimate tensile shear force F_{UTS}.

Based on the knowledge gained by finite element simulations, welding experiments, tensile shear tests and microstructural analysis, a displacement amplitude of 48 µm, a welding force of 150 N a sonotrode velocity of 28°/s and two weld seams with a distance of 20 mm were identified to achieve a highest joint strength. As the Ti6Al4V-fitting/CF-PEEK-tube hybrid joints are meant for applications in aircraft hydraulic systems, a demonstrator hybrid connection consisting of a CF-PEEK-tube with ultrasonically welded titanium fittings on both ends was designed, welded, and evaluated in an internal pressure test by Parker Hannifin GmbH. The pressure was applied stepwise with a rising time of 25 min followed by 85 min dwell time for each step, using water as testing medium. Figure 14a shows the pressure-time-profile until 960 bar internal pressure and (b) the tested demonstrator that remained intact during the pressure test. An internal pressure of 960 bar corresponds to an axial force of 81.7 kN according to Barlow´s formula and a maximum tensile shear force of 390 N/mm in relation to the length of the weld seam (two weld seams with 105 mm length), meaning that the joints are, expectedly, significantly more resistant against internal pressure than against tensile shear loads.

On the one hand, an internal pressure is beneficial for this kind of hybrid structure as the CF-PEEK-tube is pressed against the Ti6Al4V-fitting, increasing the friction between the joined components. On the other hand, the deformation behavior under pressure in comparison to a tensile shear load is different. Figure 15 shows the different deformation behavior of the hybrid joint under (a) 90 kN tension, and (b) 1050 bar internal pressure. A pronounced maximum of von Mises stress can be seen at the first weld seam (I_a) in Figure 15a, as well as a larger deformation in general. In contrast, the stress distribution under an internal pressure is more uniformly distributed. The stress maximum is lower by ~200 MPa and occurs at the second weld seam (II_b), where the joint is most deformed due to radial forces. Additionally, the CF-PEEK-tube is pressed against the inner wall of the stiffer fitting, which increases the above-mentioned interface friction resulting in higher joint strength.

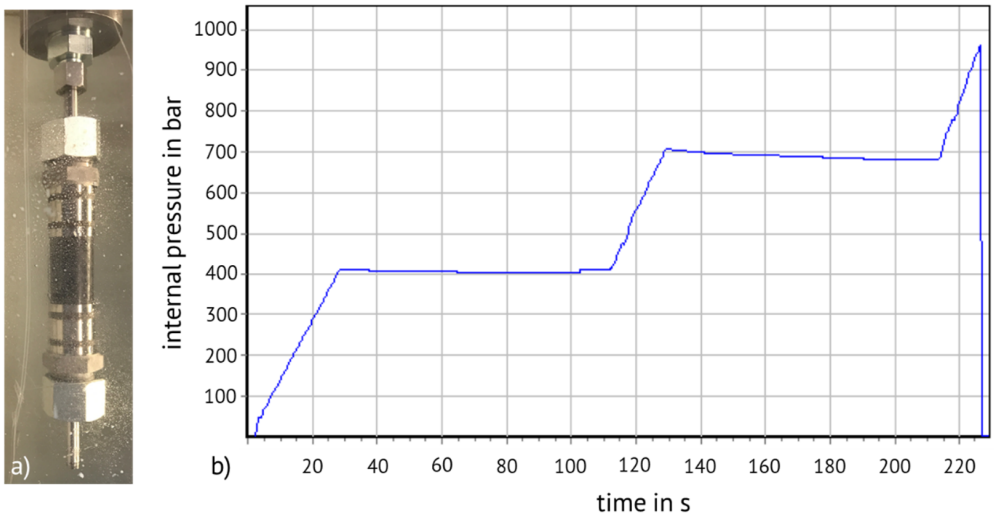


Figure 14. Pressure test of ultrasonically welded hybrid Ti6Al4V-fitting/CF-PEEK-tube joint: (**a**) CF-PEEK-tube with ultrasonically welded Ti6Al4V-fitting on both ends and (**b**) pressure-time-profile, pictures provided by courtesy of Parker Hannifin GmbH Bielefeld.

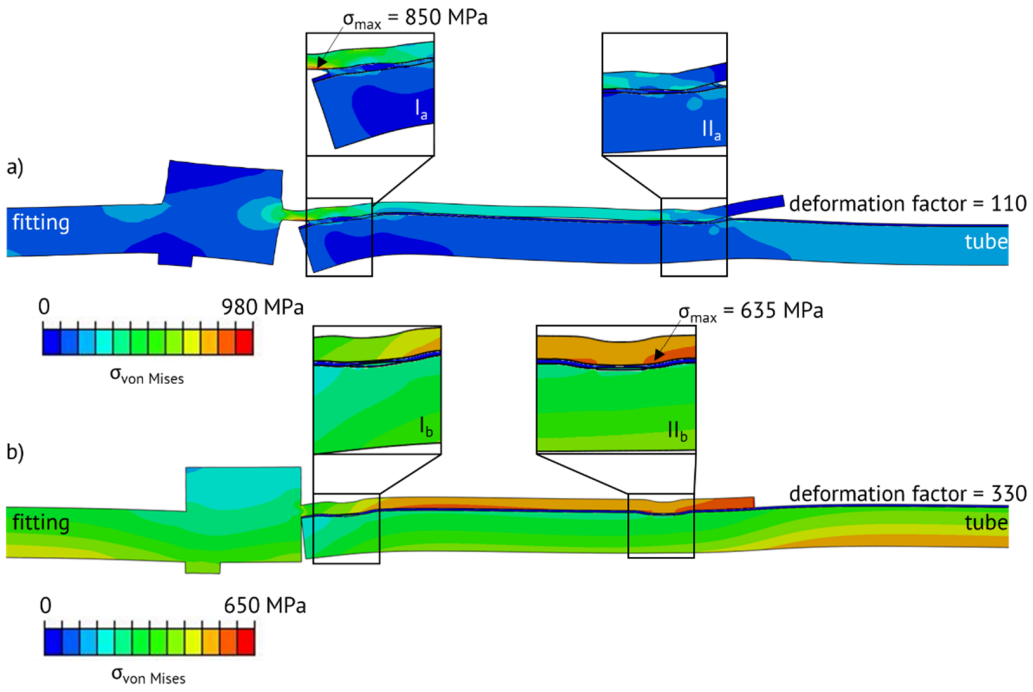


Figure 15. Von Mises stress distribution and deformation behavior of the hybrid joint: (**a**) under 90 kN tensile load and (**b**) under 1050 bar internal pressure with a resulting axial force of 90 kN.

4. Discussion

The investigation of high strength Ti6Al4V/CF-PEEK tubular hybrid joints included the development of a suitable orbital welding systems as well as robust data control and acquisition. Suitable process parameters were identified, considering the maximum tensile shear strength of the hybrid joints. A gap-free contact between the joining partners was found to be an essential condition for a successful welding process of tubes. Hence, the tubular joining partners had to be pre-joined by interference fitting which was achieved by pressing the CF-PEEK-tube into the heated Ti6Al4V-fitting (T = 380 °C) with a force of 8 kN. A suitable combination of displacement amplitude and welding force was determined.

Number and distance of weld seams were studied based on an estimation of the von Mises stress distribution by FE models.

Ti6Al4V/CF-PEEK joints that were manufactured by orbital ultrasonic welding remained intact at an internal pressure of 960 bar minimum, which is equivalent to an axial force of 81.7 kN and a maximum tensile shear force of 390 N/mm in relation to the length of the weld seam or 97.5 MPa considering the area of both weld seams, which is an outstanding strength for a hybrid material system. So far, no comparable results have been published. However, adhesively bonded Ti6Al4V/PEEK-joints achieved a joint strength up to 51.4 MPa, i.e., very close to the shear strength of PEEK. The strength of ultrasonically welded Ti6Al4V/CF-PEEK joints produced in the presented work is 53% higher, proving a joint formation far beyond mere adhesion by USW.

Taking into account that fatigue failure of the considered Ti6Al4V/CF-PEEK joints may become an issue in application, research on mechanical behavior could be extended to cyclic loadings, e.g., based on the findings given in [26].

Moreover, microstructural investigations of the hybrid interface revealed contact between carbon fibers and matrix occurred for joints that were created by orbital welding with a displacement amplitude of 48 µm which was considered as an optimum. Similar interfaces were observed for high strength AA5024/(GF-)CF-PEEK joints [17], confirming the theory of improving the joint strength by plastic deformation of the metallic joining partner and mechanical interlocking between fibres and metal. Unfavourable process parameters lead to an insufficient approach of the Ti6Al4V-surface and the carbon fibers at lower amplitudes (40 µm) and to a decomposition of the PEEK matrix for higher amplitudes (50 µm) due to local temperatures above 550 °C.

5. Conclusions

The findings of the presented work reveal the potential of the novel orbital ultrasonic welding process with respect to high strength lightweight Ti6Al4V/CF-PEEK hybrid tubular joints.

1. The orbital ultrasonic welding machine and process in order to manufacture tubular Ti6Al4V/CF-PEEK joints were successfully developed.
2. An FE model of the hybrid structure was successfully created to calculate stress and elastic deformation behavior supporting the design of the weld seam setup.
3. High strength tubular Ti6Al4V/CF-PEEK joints were successfully ultrasonically welded and resisted an internal pressure of 960 bar, equivalent to a joint strength of 97.5 MPa.
4. The microstructure of the Ti6Al4V/CF-PEEK interface region revealed a close contact between the plastically deformed Ti6Al4V surface and the carbon fibers of the CF-PEEK matching preliminary results of comparable high strength ultrasonically welded AA5024/(GF-) CF-PEEK joints.

Author Contributions: Conceptualization, M.L., T.B. and F.B.; methodology, M.L.; simulations, M.L. and S.A.; writing, M.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by German Federal Ministry for Economic Affairs and Energy (BMWi), HydI CReMA, 20Y1506F. The APC was funded by DFG Funding Programme Open Access Publishing.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors thank the German Federal Ministry for Economic Affairs and Energy (BMWi) for financial support within the federal aviation research programme (LuFo) V, Hydraulic System Innovations for Cost Reduced Modular Applications (HydI CReMA, 20Y1506F). Gratitudes are also expressed to Oliver Neiske (Parker Hannifin GmbH, Bielefeld) for the preparation of the titanium MIM-fittings and for the implementation of the pressure test as well as to Daniel Backe (PFW aerospace, Speyer) for the design of the CF-PEEK tubes. Sincere thanks also go to our

colleagues Matasha Mazis (TU Darmstadt) for language support, to Florian Staab (University of Freiburg), Jan Schiller (CTC, Stade) and Christian Gast (Airbus, Bremen) for fruitful discussions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Amancio-Filho, S.T.; Blaga, L.-A. *Joining of Polymer-Metal Hybrid Structures*; John Wiley & Sons: Hoboken, NJ, USA, 2018.
2. André, N.M.; Goushegir, S.M.; Dos Santos, J.F.; Canto, L.B.; Amancio-Filho, S.T. Friction Spot Joining of aluminum alloy 2024-T3 and carbon-fiber-reinforced poly (phenylene sulfide) laminate with additional PPS film interlayer: Microstructure, mechanical strength and failure mechanisms. *Compos. Part B Eng.* **2016**, *94*, 197–208. [CrossRef]
3. Dawei, Z.; Qi, Z.; Xiaoguang, F.; Shengdun, Z. Review on Joining Process of Carbon Fiber-Reinforced Polymer and Metal: Methods and Joining Process. *Rare Met. Mater. Eng.* **2018**, *47*, 3686–3696. [CrossRef]
4. Kah, P. Techniques for joining dissimilar materials: Metals and polymers. *Rev. Adv. Mater. Sci.* **2014**, *36*, 152–164.
5. Villegas, I.F. Strength development versus process data in ultrasonic welding of thermoplastic composites with flat energy directors and its application to the definition of optimum processing parameters. *Compos. Part A Appl. Sci. Manuf.* **2014**, *65*, 27–37. [CrossRef]
6. Staab, F.; Balle, F.; Born, J. Ultrasonic Torsion Welding of Aging Resistant Al/CFRP Joints-Concepts, Mechanical and Microstructural Properties. *Key Eng. Mater.* **2017**, *742*, 395–400. [CrossRef]
7. Fujii, H.T.; Goto, Y.; Sato, Y.S.; Kokawa, H. Microstructure and lap shear strength of the weld interface in ultrasonic welding of Al alloy to stainless steel. *Scr. Mater.* **2016**, *116*, 135–138. [CrossRef]
8. Maeda, M.; Takahashi, Y.; Fukuhara, M.; Wang, X.; Inoue, A. Ultrasonic bonding of Zr55Cu30Ni5Al10 metallic glass. *Mater. Sci. Eng. B* **2008**, *148*, 141–144. [CrossRef]
9. Matheny, M.; Graff, K. *Ultrasonic Welding of Metals*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 259–293.
10. Liesegang, M.; Beck, T. Ultrasonic welding of magnetic hybrid material systems −316L stainless steel to Ni/Cu/Ni-coated Nd2Fe14B magnets. *Funct. Compos. Mater.* **2021**, *2*, 1–9. [CrossRef]
11. Friedrich, H.E. Challenges of Materials Technology for low Consumption Vehicle Concepts. *Adv. Eng. Mater.* **2003**, *5*, 105–112. [CrossRef]
12. Shimizu, S.; Fujii, H.; Sato, Y.; Kokawa, H.; Sriraman, M.; Babu, S. Mechanism of weld formation during very-high-power ultrasonic additive manufacturing of Al alloy 6061. *Acta Mater.* **2014**, *74*, 234–243. [CrossRef]
13. Graff, K. Process Applications of Power Ultrasonics—A Review. *Ultrason. Symp.* **1974**, 628–641. [CrossRef]
14. Magin, J.; Balle, F. Solid state joining of aluminum, titanium and their hybrids by ultrasonic torsion welding. *Mater. Werkst.* **2014**, *45*, 1072–1083. [CrossRef]
15. Bakavos, D.; Prangnell, P. Mechanisms of joint and microstructure formation in high power ultrasonic spot welding 6111 aluminium automotive sheet. *Mater. Sci. Eng. A* **2010**, *527*, 6320–6334. [CrossRef]
16. Maeda, M.; Sato, T.; Inoue, N.; Yagi, D.; Takahashi, Y. Anomalous microstructure formed at the interface between copper ribbon and tin-deposited copper plate by ultrasonic bonding. *Microelectron. Reliab.* **2011**, *51*, 130–136. [CrossRef]
17. Staab, F.; Balle, F. Ultrasonic torsion welding of ageing-resistant Al/CFRP joints: Properties, microstructure and joint formation. *Ultrasonics* **2019**, *93*, 139–144. [CrossRef] [PubMed]
18. Al-Sarraf, Z.S. A Study of Ultrasonic Metal Welding. Ph.D. Thesis, University of Glasgow, Glasgow, UK, June 2013.
19. Wagner, G.; Balle, F.; Eifler, D. Ultrasonic Welding of Aluminum Alloys to Fiber Reinforced Polymers. *Adv. Eng. Mater.* **2013**, *15*, 792–803. [CrossRef]
20. Henriques, B.; Sampaio, M.; Buciumeanu, M.; Souza, J.C.; Gomes, J.R.; Silva, F.; Carvalho, O. Laser surface structuring of Ti6Al4V substrates for adhesion enhancement in Ti6Al4V-PEEK joints. *Mater. Sci. Eng. C* **2017**, *79*, 177–184. [CrossRef] [PubMed]
21. Lionetto, F.; Mele, C.; Leo, P.; D'Ostuni, S.; Balle, F.; Maffezzoli, A. Ultrasonic spot welding of carbon fiber reinforced epoxy composites to aluminum: Mechanical and electrochemical characterization. *Compos. Part B Eng.* **2018**, *144*, 134–142. [CrossRef]
22. Peters, S.T. (Ed.) *Composite Filament Winding*; ASM International: Russell Township, OH, USA, 2011.
23. Balle, F.; Eifler, D. Statistical test planning for ultrasonic welding of dissimilar materials using the example of aluminum-carbon fiber reinforced polymers (CFRP) joints. *Mater. Werkst.* **2012**, *43*, 286–292. [CrossRef]
24. Staab, F.; Liesegang, M.; Balle, F. Local shear strength distribution of ultrasonically welded hybrid Aluminium to CFRP joints. *Compos. Struct.* **2020**, *248*, 112481. [CrossRef]
25. Granta Design CES Edupack. Available online: https://www.ansys.com/products/materials/granta-edupack (accessed on 28 January 2019).
26. Beck, T.; Klein, M.; Smaga, M.; Balle, F.; Eifler, D. Innovative Experimental Approaches and Physical Measurement Methods for Fatigue Monitoring and Life Assessment. *Mater. Sci. Forum* **2016**, *879*, 205–210. [CrossRef]