5th International Conference

Hybrid 2022

Materials and Structures

Book of Abstracts

Chairpersons

Dr. Ewald Fauster
Montanuniversität Leoben

Prof. Dr. Joachim M. Hausmann
Leibniz-Institut für Verbundwerkstoffe GmbH

Prof. Dr. Kay André Weidenmann
University of Augsburg

Prof. Dr.-Ing. Axel von Hehl
University of Siegen

Table of contents

[Hybrid] M: Characterization

Characterisation of fatigue failure of complex fibre metal laminate structures

C.O.W. Trost[1*], K. Ruderes[1,2], J. Rosc[3], B. Kosednar-Legenstein[3], M. J.Cordill[1]

[1] Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Leoben, Austria,
[2] Austria Technologie & Systemtechnik (AT&S) Aktiengesellschaft, Fabriksgasse 13, Leoben, Austria
[3] Materials Center Leoben Forschung GmbH, Leoben, Austria

*claus.trost@oeaw.ac.at

Fibre-metal laminates (FML) are used in lightweight applications (e.g. aerospace) as structural components and in microelectronic systems such as printed circuit boards (PCBs). In aviation applications they are used due to their favourable fatigue and damage properties. In microelectronics, they are able to withstand a wide range of (thermo-)mechanical loads such as dropping, ultrasonic vibrations and thermo-mechanical fatigue over a vast temperature and time regime. FMLs consist of alternating layers of metal, in the presented case Copper, and Pre-Preg, which is epoxy resin reinforced with glass fibres. To enable fatigue lifetime predictions and enable material model calibration a novel FML setup was developed and tested. The samples were tested until failure with different R ratios including R=-1 and different force amplitudes. The resulting fatigue fractures were characterised using scanning electron microscopy (SEM) and showed complex fracture patterns. The patterns were analysed taking the different materials, R ratios and different loads into account. Selected samples were analysed pre-failure using computed tomography, giving further insights in fracture behaviour of FML systems.

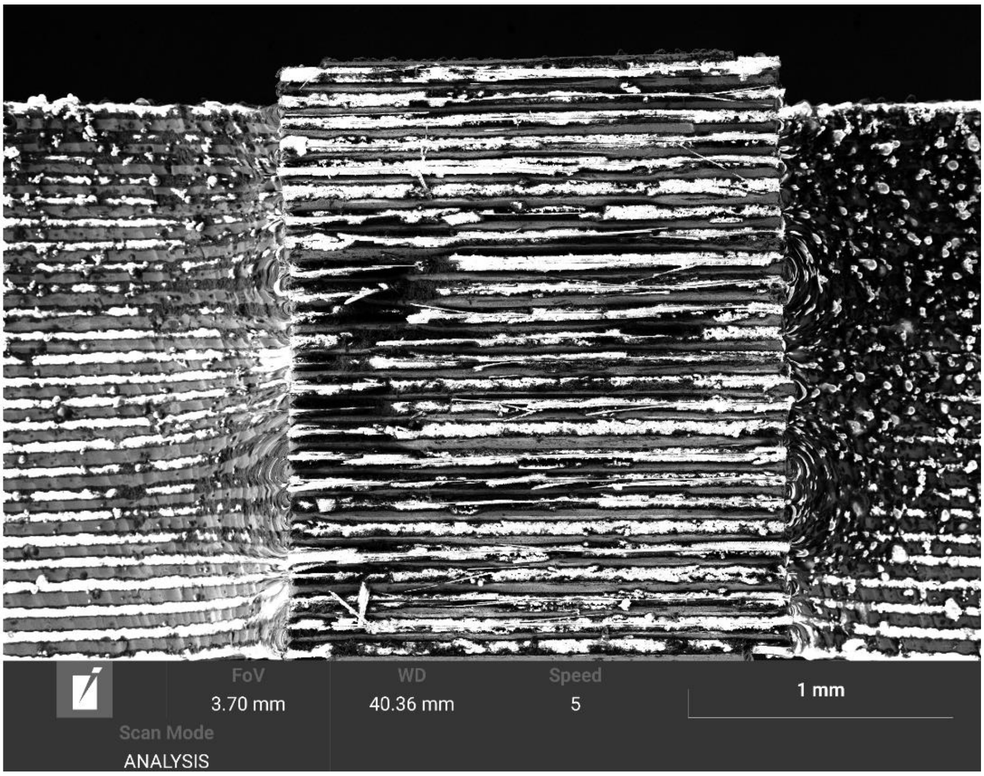


Figure 1. SEM picture of a FML fatigue fracture

Correlation of surface enlargement and mechanical strength of laser-pre-treated Al6082-T6 – epoxy E320 joints

Jonathan Freund[1*] (J. Freund), Alexander Delp[2] (A. Delp), Shuang Wu[3] (S. Wu), Miriam Löbbecke[1] (M. Löbbecke), Jan Haubrich[1] (J. Haubrich), Frank Walther[2] (F. Walther), Thomas Tröster[3] (T. Tröster),

[1] DLR (German Aerospace Center) – Institute of Materials Research, Linder Hoehe, D-51147 Cologne, Germany
[2] Chair of Materials Test Engineering (WPT), TU Dortmund University, Baroper Str. 303, D-44227 Dortmund
[3] Chair of Automotive Lightweight Design (LiA), Paderborn University

*Jonathan.Freund@dlr.de

Abstract:

In order to reduce fuel consumption and enhance the energy effectivity of future vehicles and aircrafts, further weight reduction through the use of alternative materials and joining techniques is necessary. To be able to join different groups of materials, adhesive bonding plays an important role in present and future development of lightweight construction.

The fundamental relationships between physical and chemical properties of joint interfaces and resulting mechanical strength and corrosion resistance are often times still not fully understood and under investigation. Particularly joining defects or damage occurring due to long-term environmental and mechanical load influences pose a major problem limiting the wide-spread use in safety relevant applications as, e.g., structural bonding in aerospace [1]. Since these damages are extremely difficult to detect non-destructively, further research is necessary to understand the mechanisms and avoid damages in first place.

Surface pretreatments of metallic bonding partners prior to bonding can significantly increase the mechanical strength and the long-term durability of metal-polymer bonds. Typically, this phenomenon is attributed to cleaning effects (e.g. degreasing) and generating suitable roughness on the metal surface, allowing mechanical interlocking with the polymer matrix [2]. The correlation between surface enlargement and resulting mechanical strength of adhesive joints, both enhancing mechanical interlocking as well as chemical bonding remains difficult to obtain.

Therefore, our study focuses on a new approach for investigating the possible correlation between the surface enlargement through laser pretreatment of the metallic surface and the resulting mechanical strength of Al6082-T6–E320 adhesive joints. Scanning electron microscopy (SEM) of joint cross-sections (e.g., after Focused Ion Beam preparation) is used to determine the approximate surface enlargement due to the micro- and nanostructures. For the examination of a possible correlation with the mechanical strength of pretreated joints, results of the SEM analysis are linked with results of performed single lap shear tests.

References

[1] R. A., Pethrick; Design and ageing of adhesives for structural adhesive bonding – A review *Journal of Materials, Design and Applications*, 2015, *229 (5)*, 349-379.

[2] J. Min, H. Wang; Application of laser ablating in adhesive bonding of metallic materials: A review *Optics and Laser Technology*, 2020, *128*, 1-23.

Dissimilar aluminium alloys / thermoplastic CF-PA12 joints: Influence of surface modification under climatic and corrosive stresses on the mechanical properties

D. Meinhard[1], J. Schanz[1,2], T. Pott[3], H. Riegel[1], A. K. M. De Silva[2], D. K. Harrison[2], V. Knoblauch[1]

[1] Aalen University of Applied Science, Beethovenstr. 1, D-73430 Aalen; [2] Glasgow Caledonian University, Cowcaddens Rd, Glasgow G4 0BA, Scotland, United Kingdom; [3] Ifo Institut für Oberflächentechnik, Alexander-von-Humboldt-Straße 19, D-73529 Schwäbisch Gmünd, Germany
*dieter.meinhard@hs-aalen.de

Hybrid compounds made of metal and fiber reinforced plastics, e.g. carbon-based, are used today across all industries. That is why innovative joining processes are being researched to produce hybrid structures that contribute significantly to resource efficiency in various sectors such as the automotive and aircraft industries by reducing weight. For such innovative multi-material designs the assembling of the different materials is critical because for each of the different material combinations a specially adapted and efficient joining technology is required. For state-of-the-art joining technologies, such as mechanical joining by screws or rivets and adhesive bonding, specific restrictions can be found with the use of additional material, limitations in the geometric flexibility or comparable long bonding times. For mobile applications, the long-term resistance of hybrid multi-material systems such as those made of metal and CFRP is a decisive criterion for ruling out premature failure under operating conditions.
Prior to joining, different surface topographies with a characteristic aspect ratio (depth-to-width ratio) in a range of 0.1 to 2.0 were created on the aluminum by using a short pulse near-IR laser. The surface conditions achieved were characterized by optical methods and correlated with the mechanical properties of the single-lap joints produced. The results indicate that by usage of a specific range of N-IR-laser parameters the shear strength under tensile load can be increased up to a maximum value corresponding to the interlaminar shear strength of the CFR-PA12 (see figure 1).

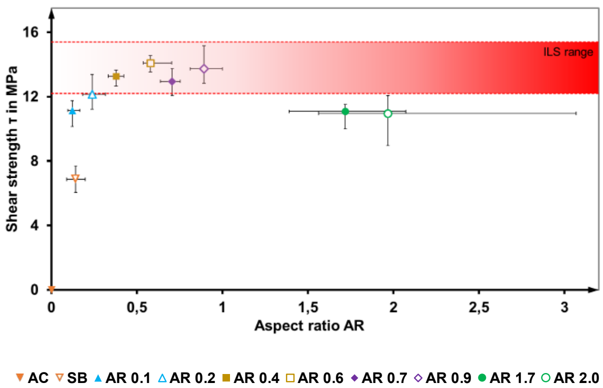


Figure 1. Shear strength (τ) of single-lap joint specimens with CFR-PA12 bonded to EN AW-7075 T6 with different surface pretreatments with AC for acetone cleaning, SB for sand blasting and AR for laser structure aspect ratio.

This means that the composite failure no longer takes place in the interface between the materials but in the CFR-PA12. In addition, the hybrid compounds produced in this way were exposed to different artificial ageing regimes such as temperature conditioning at T = 40 °C and r.H. > 95 %. It can be shown that high strength in the initial state of approx. 14 MPa can be maintained over a long period of up to 1,500 h. A critical influence is shown during the neutral salt spray test according to DIN EN ISO 9227, which leads to a decrease of the bond strength depending on the structuring. To summarize, it has been shown that the manufacturing of hybrid compounds using IR emitters leads to compounds that have a strength that corresponds to the material strength of the CFR-PA12 used. Secondly, these hybrid compounds have shown different strength degradation under varying climatic and corrosive stress.

Investigation on the deformation and damage behavior in thermoplastic-based hybrid laminates considering very high cycle fatigue using high speed cameras

S. Mrzljak[1*], M. Trautmann[2], D. Hülsbusch[1], G. Wagner[2], F. Walther[1]

[1] TU Dortmund University, Chair of Materials Test Engineering (WPT), Dortmund, Germany
[2] Chemnitz University of Technology, Institute of Material Science and Engineering (IWW), Group of Composites and Material Compounds, Chemnitz, Germany

*selim.mrzljak@tu-dortmund.de

Prolonged crack propagation and increased fatigue lifetime of hybrid laminates compared to monolithic metals are key aspects for their use in, e.g., the aerospace industry. Especially for safety relevant components, detailed knowledge about the fatigue capabilities is necessary. Steady material degradation with progressive numbers of cycles affects the integrity of the laminate structure as well as the mechanical properties, which need to be understood to estimate lifetime expectancy up to the very high cycle fatigue (VHCF) regime. For thermoplastic-based hybrid laminates, which offer the possibilities of formability, recyclability, and mass production due to short consolidation cycle times, this knowledge up to the VHCF regime still needs to be established to enable these laminates for use in safety critical components.

In this study, thermoplastic-based hybrid laminates containing AA6082 aluminum alloy sheets and unidirectional glass and carbon fiber-reinforced polyamide 6 were investigated. Fatigue tests up to the VHCF regime (max. 1E9 cycles) were conducted under tension-tension loading on a resonant fatigue testing system offering a frequency of 1 kHz. To maintain the thermoplastic matrix properties the surface temperature was measured, and air cooling applied to reduce self-heating in accordance with ISO 13003. Fatigue progress and accompanying damage were monitored through high speed cameras with frame rates up to 100 kHz for deformation analysis with digital image correlation. Microscopic investigations of the damaged volume were conducted after defined numbers of cycles to expand the microstructural observation of surface damage and deduce onto the volume inner damage mechanisms. The test results show that during VHCF load the mechanical properties are influenced mostly by changes in microstructure within the aluminum alloy sheets due to damage initiation and propagation. As a result, the fatigue lifetime of the metal sheets differs greatly from the total fatigue lifetime of the hybrid laminate. Compared to the HCF regime the interface damage changes in terms of crack and delamination rate.

Meeting the challenge of thermal joining of steel and aluminum using a new approach based on melt displacement by electromagnetic forces

Jennifer Heßmann[1*] (J. Heßmann), Kai Hilgenberg[1] (K. Hilgenberg)

[1] Bundesanstalt für Materialforschung und -prüfung (BAM), Unter den Eichen 87, 12205 Berlin, Germany
* Jennifer.hessmann@bam.de

Environmental protection, resource conservation and CO_2 reduction require new joining concepts for effective multi-material design in automotive lightweight construction. The thermal joining of dissimilar materials, especially the combination of aluminum alloys and steel, is associated with difficulties [1]. Different material properties, such as melting point and coefficient of thermal expansion, complicate joining processes [2,3]. Furthermore, the insolubility between these materials results in the formation of intermetallic phases. These brittle phases reduce the load-bearing capacity and quality of the joints [4,5]. The thickness of the intermetallic phases should not reach the critical value of 10 µm to ensure good mechanical properties of the joint [6]. It is known that a two-phase reaction layer consisting of Al_5Fe_2 and Al_3Fe (also known as $Al_{13}Fe_4$ [7]) forms at the interface between solid steel and liquid aluminum [1]. Due to high cooling rates, as it is the case in laser beam welding, metastable intermetallic compounds can form different from the equilibrium state [8]. The formation of the intermetallic reaction layer is a diffusion-controlled process [9]. So, it is only possible to control the growth of these phases. This problem has led to use joining methods that do not require the melting of both joining partners. A promising joining method is laser beam welding-brazing, whereby only one joining partner is melted and wets the solid joining partner [10]. Conventional laser beam welding-brazing only results in material-fit joints and often requires the use of expensive filler materials. An additional form-fit could optimize the mechanical performance of the joint. For this reason, a new joining method for overlap configurations of dissimilar materials was developed. A laser beam melts the lower joining partner through a cavity of the upper joining partner. The created melt pool is moved upwards into the cavity of the upper joining partner due to contactless induced Lorentz forces of an AC-magnetic system. The displaced melt creates a form- and material-fit joint after solidification. The advantage of this joining technology is the absence of filler materials, flux agents and expensive auxiliary joining elements.

In this study, this new approach was tested for spot- and line-shaped joints between 1 mm steel (1.0330) and 3 mm aluminum alloy (EN AW 5754). For the spot-shaped joints, a hole with a diameter of 1.6 mm with a partial bevel on the upper side was used. For the line-shaped joints, a 3 mm wide and 100 mm long hole with a 30° bevel was used. The aluminum sheet was always placed below the steel sheet and Argon was used as shielding gas. The process stability and reproducibility were analyzed by high-speed camera recordings. The filling of the cavity was investigated using cross sections. Energy-dispersive X-ray spectroscopy (EDX), electron backscatter diffraction (EBSD) and microhardness measurements according to Vickers were carried out for the characterization of the joint and the identification of the intermetallic phases. The mechanical properties of five additional line-shaped joints with 40 mm length were analyzed by tensile shear tests, with a test speed of 1 mm/min.

The results show that the new approach works in principle. Exemplary cross sections of spot- and line-shaped joints with optimal weld parameters are shown in Figure 1. The ideal weld parameters for spot joints are a laser power of 3 kW, a laser duration of 200 ms and a magnetic field power of about 1900 W. The ideal weld parameters for line-shaped joints are a laser power of 3.3 kW, a velocity of 1.3 m/min and a magnetic field power of 1200 W. For both types of joints, spatter could be observed in the high-speed camera recordings. However, the process is more stable for line joints than for spot joints. The reason for this is the well-known melt pool dynamics in deep laser welding of aluminum alloys. The keyhole collapses at regular intervals [11] and thereby spatter can occur. The welding process of spot joints is unstable, the reproducibility is limited. In many cases, the filling of the cavity was not completely achieved. Cracks and pores can be observed in many joints, which reduce their quality and load capacity.

For the spot joints, only the upper edge of the hole could be beveled to achieve a melt displacement with additional form-fit. If the hole was completely beveled, the welding process had such instability that the melt was completely pressed out and holes were created in the aluminum sheet. For line-shaped joints, the main zone of influence of the magnetic field can be placed behind the laser beam. Thereby, the melt displacement takes place behind the keyhole in the melt pool. The dynamics of the keyhole have less influence on the melt displacement. It can be seen in Figure 1 that the welding process for line-shaped joints is more effective and requires less magnetic field power than for the spot-shaped joints. The line joints had no cracks. When cross sections were cut, the residual stresses due to the different coefficient of thermal expansion were released. In this way, the steel sheet was separated from the displaced melt.

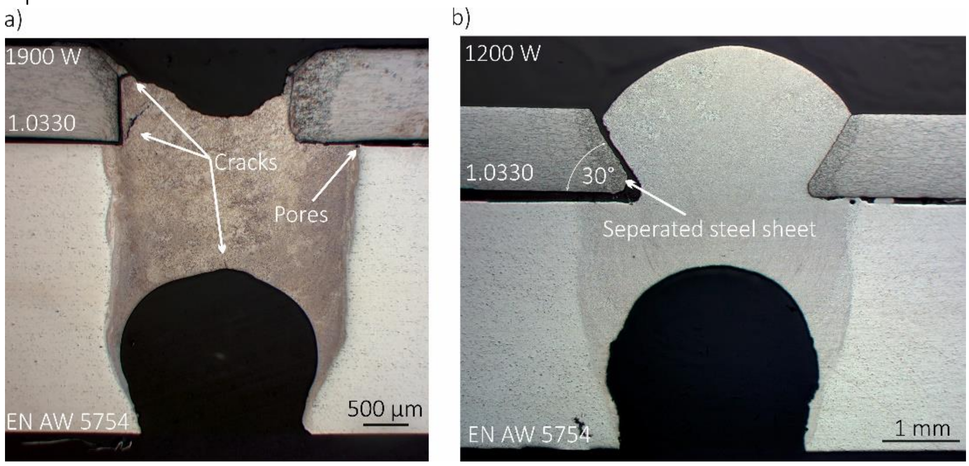


Figure 1. Exemplary cross sections at optimal weld parameters a) spot-shaped joint and b) line-shaped joint.

The intermetallic phases were analyzed by EDX. A compact phase seam on the steel side consists of about 74 at - % aluminum and 26 at - % iron. The second area has a needle-like structure and extends into the displaced aluminum melt. This part consists of about 83 at - % aluminum and 18 at - % iron. Additional EBSD analysis helped to identify the phases in detail. The compact phase seam is the $Al_{5.6}Fe_2$ phase and the needle-shaped structure is the $Al_{13}Fe_4$ phase. The thickness of the compact intermetallic phase seam is less than 7 µm for both types of joints. The hardness of the steel sheet increases in the heat-affected zone to about 200 HV 0.01. The hardness of the aluminum melt increases to about 117 HV 0.01, compared to the hardness of the aluminum base sheet of about 72 HV 0.01. The line-shaped joints reached an average maximum tensile force of about 2421 N and an elongation of about 4 mm. This corresponds to about 30 MPa. The values of the tensile shear tests are comparable to tests on laser weld-brazed lap joints of steel and aluminum with and without filler material at maximum tensile forces of about 900 N - 2000 N and 31.6 MPa, respectively [12-14]. The length of the tested joints was given with 38 mm in [14]. The sheets (5754 aluminum and DX54 galvanized steel) were directly joined by the laser beam without filler material. Cracks and pores were observed. The pores are caused by the evaporation of the Zn layer. The authors did not give any information about the thickness of the identified intermetallic phases ($AlFe_3$, Al_2Fe, Al_5Fe_2). They tested single and double pass welding and achieved maximum tensile forces of 2 kN [14]. It is known that the $AlFe_3$, Al_2Fe have ductile properties and increase the strength of the joint, whereas the Al_5Fe_2 is brittle [15]. In this study, the more brittle Al-rich intermetallic phase compositions (Al_5Fe_2, $Al_{13}Fe_4$) were identified, and still higher strength values were achieved. This shows that the additional form-fit can improve the joint strength. The results of our study are difficult to compare with the values of other works because either filler materials or other base materials were used.

This study represents a first step for the further development of this novel joining method. This new approach works in principle for spot- and line-shaped joints. The joining process for spot joints is more unstable than for line joints. The reason for this is the melt pool dynamics of the aluminum alloy. This limits the melt displacement and thus the complete filling of the cavity. Cracks and pores often occur in the spot joints. The process for the line-shaped joints is more stable and reproducible. The displacement process can take place directly behind the keyhole which allows for a more effective displacement of the melt pool. No cracks were observed in the line joints. In both types of joint, the intermetallic phase seams were thinner than 10 µm and had the typically reported structure. Tensile shear tests show that in addition to the material-fit, a form-fit can produce potentially higher strength joints than the direct laser beam welded dissimilar joints.

[1] Md. Abdul Karim; Y.D. Park, *A Review on Welding of Dissimilar Metals in Car Body Manufacturing*, *Journal of Welding and Joining*, 2020, *Vol.38*, No.1, pp. 8-23, https://doi.org/10.5781/JWJ.2020.38.1.1

[2] S. Meco; L. Cozzolino; S. Ganguly; S. Williams; N. McPherson, *Laser welding of steel to aluminium: Thermal modelling and joint strength analysis, Journal of Materials Processing Technology*, 2017, *Vol.247*, pp.121-133, http://dx.doi.org/10.1016/j.jmatprotec.2017.04.002

[3] Z. Lin; Y. Li; Z. Luo; Y. Feng; Z. Wang, *Resistance Element Welding of 6061 Aluminum Alloy to Uncoated 22MnMoB Boron Steel, Materials and Manufacturing Processes*, 2016, *Vol.31*, pp. 2174-2180, DOI: 10.1080/10426914.2016.1151044

[4] P. Wang; X. Chen; Q. Pan; B. Madigan; J. Long, *Laser welding dissimilar materials of aluminum to steel: an overview, The International Journal of Advanced Manufacturing Technology*, 2016, *Vol.87*, pp. 3081-3090, DOI 10.1007/s00170-016-8725-y

[5] C. Yuce; F. Karpat; N. Yavuz, *Investigations on the microstructure and mechanical properties of laser welded dissimilar galvanized steel–aluminum joints, The International Journal of Advanced Manufacturing Technology,* 2019, *Vol.104*, pp. 2693-2704, https://doi.org/10.1007/s00170-019-04154-7

[6] G. Filliard; M. El Mansori; L. Tirado; S. Mezghani; C. Bremont; M. De Metz-Noblat, *Industrial fluxless laser weld-brazing process of steel to aluminium athigh brazing speed, Journal of Manufacturing Processes,* 2017, *Vol.25*, pp. 104-115, http://dx.doi.org/10.1016/j.jmapro.2016.12.002

[7] K. Lee; S. Kumai, *Characterization of Intermetallic Compound Layer Formed at the Weld Interface of the Defocused Laser Welded Low Carbon Steel/6111 Aluminum Alloy Lap Joint, Materials Transactions*, 2006, *Vol. 47*, pp. 1178-1185

[8] A. Szczepaniak; J. Fan; A. Kostka; D. Raabe, *On the Correlation Between Thermal Cycle and Formation of Intermetallic Phases at the Interface of Laser-Welded Aluminum-Steel Overlap Joints, Advanced Engineering Materials*, 2012, *Vol.14(7)*, pp.464-472, DOI: 10.1002/adem.201200075

[9] G. Filliard; M. El Mansori; M. De Metz-Noblat; C. Bremont; A. Reullier; L. Tirado, *Influence of process parameters on thermal cycle and intermetallic compounds formation in high-speed laser weld-brazing of aluminium-steel angle joints, Procedia Manufacturing*, 2018, *Vol.26*, pp. 690-699, 10.1016/j.promfg.2018.07.079

[10] M. Pouranvari; M. Abbasi, *Dissimilar gas tungsten arc weld-brazing of Al/steel using Al-Si filler metal: Microstructure and strengthening mechanisms, Alloys and Compounds*, 2018, *Vol.749*, pp.121-127, 10.1016/j.jallcom.2018.03.224

[11] P. Okon; G. Dearden; K. Watkins; M. Sharp; P. French, *Laser Welding of Aluminium Alloy 5083, 21st International Congress on Applications of lasers and Electro-Optics, Icaleo*, 2002, *ISBN 0-912035-72-2*

[12] P. Zhang; H. Shi; Y. Tian; Z. Yu; D. Wu, *Effect of zinc on the fracture behavior of galvanized steel/6061 aluminum alloy by laser brazing, Welding in the World*, 2020, *Vol. 65*, pp. 13-22, https://doi.org/10.1007/s40194-020-00992-2

[13] C. Wang; L. Cui; G. Mi; P. Jiang; X. Shao; Y. Rong, *The influence of heat input on microstructure and mechanical properties for dissimilar welding of galvanized steel to 6061 aluminum alloy in a zero-gap lap joint configuration, Journal of Alloys and Compounds*, 2017, *Vol.726*, pp. 556-566, http://dx.doi.org/10.1016/j.jallcom.2017.08.015

[14] H. Chen; A. J. Pinkerton; L. Li; Z. Liu; A. T. Mistry, *Gap-free fibre laser welding of Zn-coated steel on Al alloy for light-weight automotive applications, Materials and Design,* 2011, *Vol.32*, pp. 495-504, doi:10.1016/j.matdes.2010.08.034

[15] Y. Li; Y. Liu; J. Yang, *First principle calculations and mechanical properties of the intermetallic compounds in a laser welded steel/aluminum joint, Optics and Laser Technology*, 2020, *122*, pp. 1-12, https://doi.org/10.1016/j.optlastec.2019.105875

Modelling for the design of metal-graphite composites under consideration of application-related operating conditions (MeGraV II)

R.Füßel[1*], M. Haesche[2], M. Busse[2], N. Modler[1]

[1] Technische Universität Dresden, Institute for Lightweight Engineering and Polymer Technology, Holbeinstraße 3, 01307 Dresden, Germany

[2] Fraunhofer-Institute for Manufacturing Technology and Advanced Materials IFAM, Deptartment of Casting Technology and Lightweight Construction, Bremen, Germany

* rene.fuessel@tu-dresden.de

Topic: B – Characterization, Mechanical testing

The increase in the performance and efficiency of machines and plants leads to higher material application temperatures across all industries. Especially for plain bearings and mechanical seals, higher operating and emergency running temperatures are required than is realizable with conventional materials. In the AiF project “Design of metal-graphite composites (MeGraV II)”, a novel, temperature-stable composite material is in focus of research. In cooperation with the Fraunhofer Institute for Manufacturing Engineering and Applied Materials Research (IFAM) in Bremen, researchers at the Institute for Lightweight Structures and Polymer Technology (ILK) at TU Dresden develop a metal-graphite composite consisting of graphite structures with varying porosities impregnated with light metals, such as aluminum or magnesium. By combining the excellent sliding properties of graphite with the higher strengths of the metals, it gets possible to raise the operating limits for plain bearing applications to temperatures above 300 °C. The focus of the investigations is on both the influence analysis of the relevant process parameters during the composite production and the experimental determination of the thermo-tribological properties of the new material. In conjunction with the manufacturers and users of plain bearings and mechanical seals, it becomes possible to show the excellent application potential of this high-performance material.

Optimization of the mechanical structural properties of polymer concrete by a prestressed fiber composite

M. Engert[1*], R. Wegner[2], K. Werkle[1], H.-C. Möhring[1]

[1] Institute for Machine Tools (IfW), University of Stuttgart, Holzgartenstr. 17, 70174 Stuttgart, Germany
[2] Institute for Textile and Fiber Technologies (ITFT), University of Stuttgart, Pfaffenwaldring 9, 70569 Stuttgart, Germany
*michelle.engert@ifw.uni-stuttgart.de

The topics of energy efficiency, resource conservation and lightweight design are driving the development of new types of hybrid materials in all industries. For example in machine tool design the combination of structural components made out of steel with a machine bed made of polymer concrete has been a well-known and widely used approach for years. Improved damping properties compared to cast iron components, good thermal stability and easy processing coupled with a reduction of more than 30 % in CO2 equivalent compared to grey cast iron parts also make polymer concrete an interesting material for use in structural machine components. But at first view polymer concrete does not appear to be suitable for use as a structural component of a machine tool due to its comparatively low tensile strength and its strong tendency to creep. A possible solution discussed in this investigation is the integration of prestressed carbon fibres in a matrix of polymer concrete. In experimental investigations, unfilled polymer concrete specimens are compared to reinforced polymer concrete specimens and specimens out of steel. Different mineral casting materials are also considered. In bending tests of a long cantilevered test beam, the compliance of the structure under defined loading conditions was investigated. In addition, the load collective of an existing bed milling machine was determined. The focus here is on the cantilever of the structure. Based on the test results, the requirements and design problems of structural machine parts made of polymer concrete prestressed carbon fibres are discussed.

Short-term fatigue assessment and corrosion analysis of intrinsically bonded, laser structured CFRP-Al hybrid laminates

A. Delp*[1], S. Wu[2], J. Freund[3], D. Hülsbusch[1], T. Tröster[2], J. Haubrich[3], F. Walther[1]

[1] TU Dortmund University, Chair of Materials Test Engineering (WPT), Dortmund, Germany
[2] Paderborn University, Chair of Automotive Lightweight Design (LiA), Paderborn, Germany
[3] German Aerospace Center (DLR), Institute for Material Research, Cologne, Germany

*alexander.delp@tu-dortmund.de

In order to maintain individual and public mobility compatible with the technical challenges emerging from the requirement of reducing greenhouse gas emissions, the development of energy efficient and reliable lightweight structures is a promising approach. By using hybrid structures such as fiber-metal laminates the advantages of both components, i.e., high-specific-strength and high impact resistance, can be utilized for tailored constructions and, ideally, existing manufacturing processes can be adjusted for further use. In this study, the investigated fiber-metal laminate consists of EN AW-6082 T6, which is intrinsically bonded with unidirectional CFRP via epoxy resin, contained in prepreg system E201. The deployability of fiber-metal laminates highly depends on the materials resistance against corrosion due to the different electrochemical potential between the single components, environmental loads, such as moisture, temperature and aggressive media, as well as the resulting mechanical strength. Therefore, to optimize the bonding properties and minimize the well-known susceptibility to corrosion, the aluminum surface was laser pretreated with varying parameters and subsequently adhesively bonded and cured with E201 by a prepreg-pressing process. Using potentiodynamic polarization techniques (PDP) in 0.1mol/l NaCl solution on varying surface conditions of the aluminum, differences in corrosion current and open circuit potential were detected. Microscopic images revealed distinguishable differences in corrosion products depending on the surface condition. For the hybrid laminate no significant differences in corrosion behavior were found via PDP, since the plastic component acts as an insulator between the carbon fiber and aluminum surface. During corrosion exposure tests distinguishable differences between pure aluminum (reference) and hybrid structures were detected (Fig. 2).

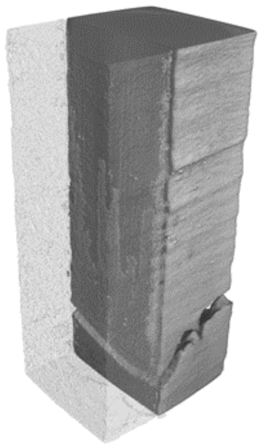


Fig. 1: In-situ µCT-scan of CFRP-Al hybrid system after fracture of the Al-component.

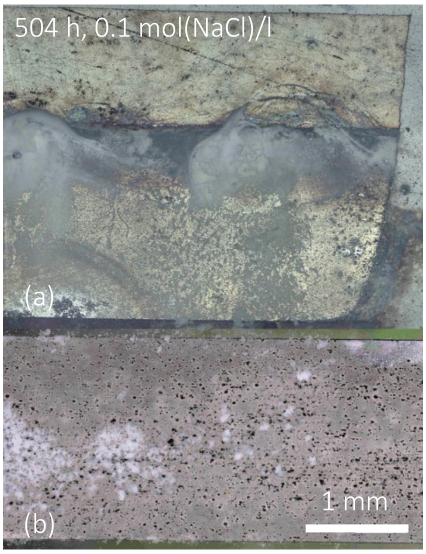


Fig. 2: Corrosion products after corrosion exposure test (a) CFRP-Al hybrid system and (b) Al.

Regarding mechanical properties, a short-term fatigue testing method was employed, using load increase tests under tension-tension loading combined with thermography to determine the load and frequency dependent self-heating behavior of the fiber-metal laminate. Hereby it was possible to localize damage initiation. Investigations via in situ X-ray computed tomography (CT) were applied to analyze the crack behavior due to the mechanical load at the CFRP-aluminum interface (Fig. 1).

The environmental impact on the strain rate dependent energy absorption capability of a hybrid crash absorber element

S. Haller[1*], S. Tinkloh [2*], T. Tröster[2], R. Brandt[1]

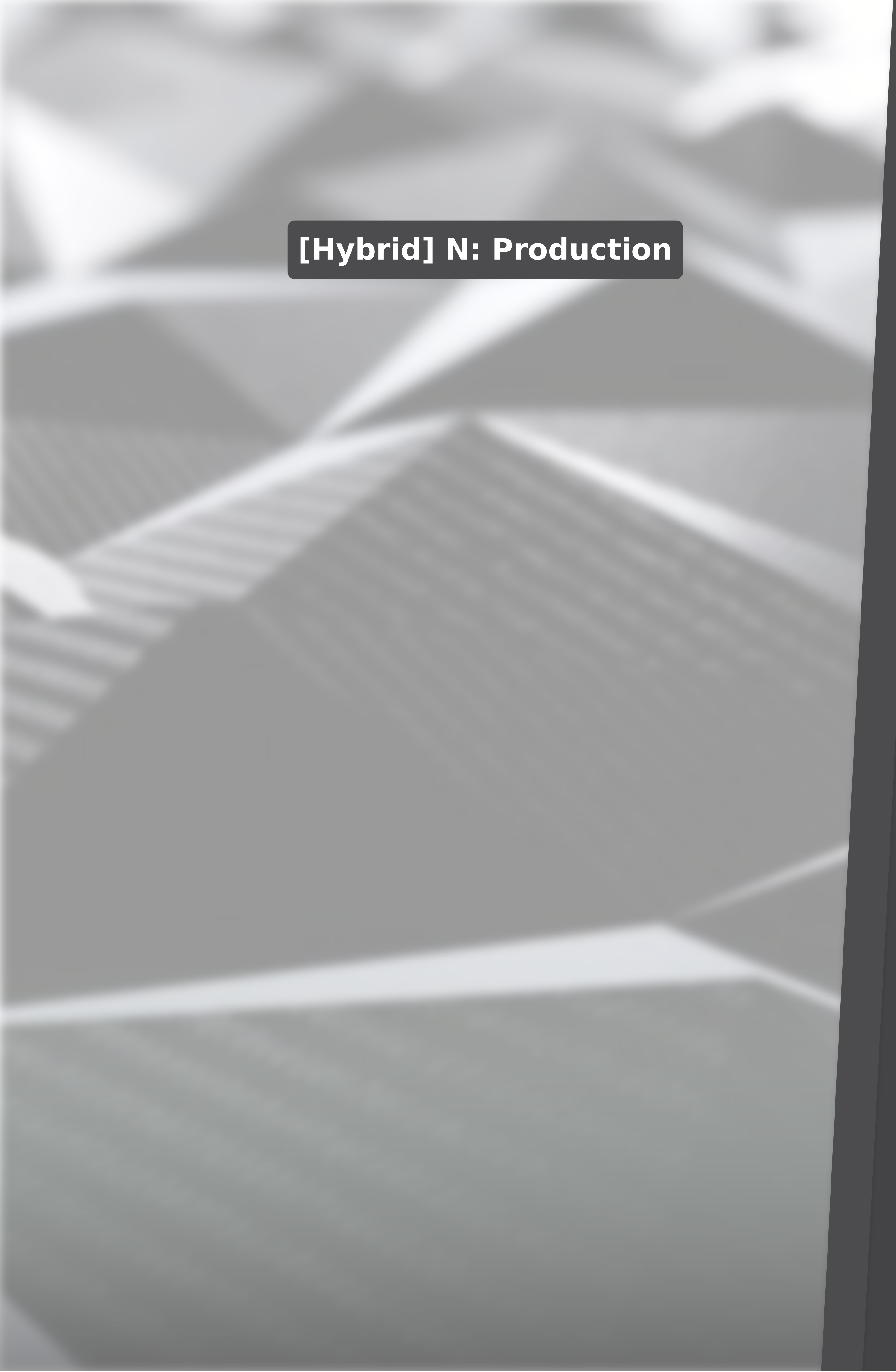
[1] Uni Siegen, Chair of Werkstoffsysteme für den Fahrzeugleichtbau, Am Eichenhang 50, 57076 Siegen, Germany
[2] Uni Paderborn, Chair of Automotive Lightweight Design (LiA), Warburger Str. 100, 33098 Paderborn, Germany
*sebastian.haller@uni-siegen.de
*steffen.tinkloh@uni-paderborn.de

A new type of an innovative hybrid crash absorber element is under development for a vehicle restraint system to cover extremely hazardous areas at road junctions on federal and country roads. The hybrid crash absorber element is made up by axial compressible metal tubes that are enclosed with glass fiber reinforced plastic (GFRP). For the design process, static as well as strain rate dependent materials properties of GFRP, steel, and the hybrid material, respectively, are required in the as fabricated and in the aged conditions.
In particular, the interfaces of the hybrids are of great importance, since they are prone to corrosion under environmental conditions. Therefore, the metal component of the hybrid, a galvanized steel, must be sustainably bonded to GFRP. This could be achieved by using a bonding agent that significantly increases the adhesion of the components. To simulate the environmental impact on the interfaces, the hybrid material is artificially aged in a salt spray chamber for at least six weeks. The strength of the interface has been characterized by means of Singe-Lap-Joint-, Interlaminar-Shear-Strength- and Edge-Shear-Testing before and after aging, respectively, to determine the impact of environment and to develop a robust and sustainable prototype of the hybrid crash absorber.
According to the literature, the absorbed energies of metals and GFRP increase with rising strain rates [1, 2]. This is confirmed for GFRP specimens by our servo-hydraulic high-speed tensile and compressive test at quasi-static to medium strain rates (0.001 to 100 s^{-1}). Furthermore, the strain rate dependent energy absorption has been measured for hybrid specimens before and after aging, too.

References

[1] M. M. Shokrieh, M. J. Omidi, *Compressive response of glass-fiber reinforced polymeric composites to increasing compressive strain rates*, 2009, Composite structures 89 (4), 517.
[2] M. Madivala, W. Bleck. *Strain rate dependent mechanical properties of TWIP steel*, 2019, Jom 71. Jg. (4), 1291-1302.

[Hybrid] N: Production



A Benchmark for Fluid-Structure Interaction in Hybrid Manufacturing: Coupled Eulerian-Lagrangian Simulation

N. Meyer[1*], H. Werner[1,2], J. Seuffert[1], S. Dietrich[1], C. Poppe[1,3], C. Krauß[1], L. Kärger[1]

[1] Karlsruhe Institute of Technology (KIT), Institute of Vehicle System Technology - Lightweight Technology
[2] Karlsruhe Institute of Technology (KIT), Institute for Applied Materials - Materials Science and Engineering
[3] SIMUTENCE GmbH

*nils.meyer@kit.edu

Several hybrid manufacturing processes involve fluid-structure interaction (FSI), i.e. a bi-directional mechanical interaction between a deformable solid and a fluid flow. For example, FSI may occur during compression of a foam core in composite sandwich parts, during the deformation of an insert in an over-molding process, during the simultaneous forming and filling of novel fiber metal laminates, or during Liquid Compression Molding processes (WCM). Reliable process simulations are required to support engineering of such complex manufacturing processes.
However, simulating such manufacturing processes is challenging due to the varying spatial domains and due to the deforming interface between fluid and solid phase. This work presents an FSI benchmark setup specifically for hybrid manufacturing in order to verify and evaluate several simulation approaches.The test allows for simultaneous deformation of a circular metal blank and cylindrical squeeze flow of a highly viscous fluid. Compression force, blank deformation and fluid flow front propagation are recorded during trials and compared to several numerical simulation approaches.
This contribution highlights the results obtained with a Coupled Eulerian Langrangian approach. In this approach, the blank is modeled via conventional Lagrangian shell elements, which interact with partially filled fluid elements at a reconstructed surface. The deformation of fluid nodes is mapped back during each time step while the flow through fluid element faces is corrected such that the resulting fluid behavior is effectively Eulerian.

A novel hybrid thermoset-thermoplastic robot-based production concept for lightweight structural parts: A special view on 3d Filament Winding

P. Bauer[1*], N. Motsch-Eichmann[2], S. Schmeer[2], K. Mehl[2], J. Hausmann[2], I. Müller[1]

[1] Pforzheim University of Applied Science, [2] Leibniz-Institut für Verbundwerkstoffe (IVW)
*philipp.bauer@hs-pforzheim.de

Abstract: It will be demonstrated that it is possible to manufacture hybrid structural components from continuous carbon fiber-reinforced epoxy-based thermoset (CFRP) and short glass fiber-reinforced thermoplastic polyamide (PA6GF30) with the aid of a new hybrid production concept. This production concept consists of a robot-based 3d filament winding process and a subsequent injection-molding process and can produce high loadable structural parts in a highly automated manner, with a high degree of design freedom, high component quality and high process speed in a cost-efficient way with virtually no waste. The focus of this publication is on the process chain of this hybrid production concept and especially on the robot-based 3d filament winding.

Keywords: Hybrid Polymers; Filament Winding; TowPreg; Injection Molding; CFRP

1. Introduction

Continuous carbon fiber reinforced thermoset plastics (CFRP) are particularly suitable to produce high loadable structural components due to their high specific mechanical properties [1, 2]. The main disadvantages of this material are the high component costs which arise from the high-priced carbon fibers and the complex manufacturing processes [2]. These disadvantages can be reduced with the help of the robot-based 3d filament winding process due to the automated manufacturing and the waste-free production. Pre-impregnated (mostly epoxy-based) continuous carbon fibers (TowPreg) are deposit automatically with the help of a winding head [3-5]. This results in truss-like spatial structures (areal distributed sections are also possible if required for load purposes), which are oriented along the main load paths in the component. However, these truss-like spatial structures tend to buckle, have a suboptimal surface quality and there is no way to create cost-efficient low-loaded areal distributed sections and additional functional elements. These disadvantages could be eliminated by a downstream thermoplastic injection molding process. This process requires a loadable interface between the thermoset and thermoplastic polymer, which has already been investigated in initial studies [6, 7]. An automatable low pressure plasma pretreatment is now used for this hybrid production concept, which enables the load transmission between the thermoset skeleton structures and the thermoplastic support structures [7].

Multi-axis industrial robots are used in the robot-based 3d filament winding process, in contrast to the already established classic 3-axis winding process which is used to produce mostly rotationally symmetrical components such as pressure tanks [3]. This makes it possible to manufacture components with more complex geometries. Cores or tools with deflection points (pins, channels, etc.) are usually used in the robot-based 3d filament winding process which remain in the component or can be removed after curing. The winding head at the industrial robot is, due to the more complex geometries, always in different distances to the core so the winding system must be capable to un- and rewind the material, which will be discussed later in more detail.

Another major difference is the use of TowPreg material. In-situ impregnation is mostly used in the classic winding process, or in some cases, dry winding with a subsequent impregnation. Pre-impregnated, roving-based material (TowPreg) is used in the novel hybrid process presented here. The main advantages of this material are the uniformly high impregnation quality and the easier handling in automated processes [5, 8]. The gel-like b-stage of the epoxy-resin also leads to higher winding speeds since the gel-like resin adheres better to the roving than the liquid resin in the in-situ impregnation and will not detach that easily due to the centrifugal forces. In addition, the tackiness of the TowPreg allows it to be disposed outside of geodesic paths (Figure 1), since the material can adhere to the core and thus slightly curved paths are possible without additional deflection points [9]. Strongly curved paths, on the other hand, are realized by channels or steep turns in the core. With so-called pins as deflection points in the core, strongly curved paths with local bends can be generated. This is shown detailed in Chapter 3.2.

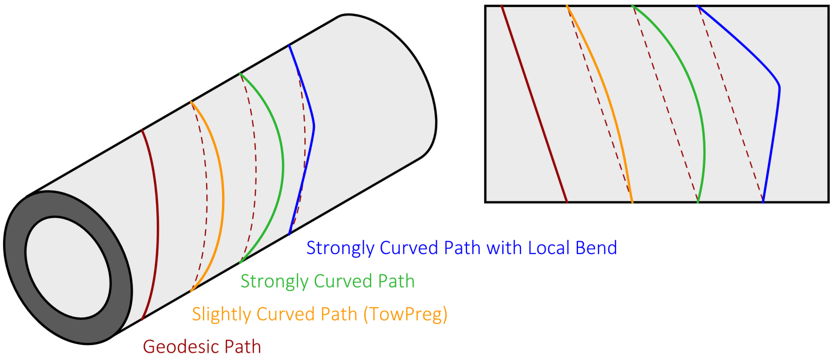


Figure 1. Geodesic and non-geodesic winding paths on cylinder (left) and unrolled cylinder (right)

2. Process Chain

A process chain for a cost-efficient production of hybrid thermoset-thermoplastic robot-based 3d TowPreg winding structures is shown in Figure 2. In the first process step, the position and orientation of the continuous fibers and the thermoplastic injection molding material must be determined with the help of an adapted hybrid & anisotropic structural optimization based on a BESO (bi-directional evolutionary structural optimization) algorithm [10]. The winding paths can then be developed with the help of this optimization. For this purpose, the component is manually divided into individual sub-areas with individual winding patterns. The number of previously defined winding patterns required can then be determined in an automated computer-based process with the aid of a global mathematical optimization. Since winding paths are normally traversed more often than it is structurally necessary, it is possible to vary the number of TowPreg strands to be deposited (between one and two) during the winding process so that only as much CFRP material as required is deposited.

In the next step, the core geometry can be planned based on the structural optimization and winding paths. Three variants are usually possible as winding cores in robot-based 3d filament winding:

- the core remains in the component, which are usually temperature-resistant cores with low density
- a dismountable or soluble core is used, which leads to even lighter components
- the wound core can serve as a reusable tool, where the core is usually made from metal

The core will typically not remain in the part for the hybrid process with a subsequent overmolding of the CFRP skeleton structures. In all cases, it is possible/necessary to add additional deflection points to the existing core geometry or the existing load introduction elements. These are mainly pins, channels or steep turns, which allow an even stronger curvature of the TowPreg path (details are described in Chapter 3.2). The existing core is mounted on an external rotational axis in this example, but it can also be guided by the robot itself (Figure 3).

It is important to ensure a smooth movement of the robot with a large distance criterion (C_DIS) when manufacturing the winding structure in the robot-based 3d filament winding process. Only then, a very high winding speed with the TowPreg material can be achieved. The TowPreg must also be specially wound onto the carrier roll, so that it can be processed in the automated robot-based process. However, the winding speed is also defined by the core geometry, the tack of the TowPreg material and the winding paths which were developed in an earlier stage.

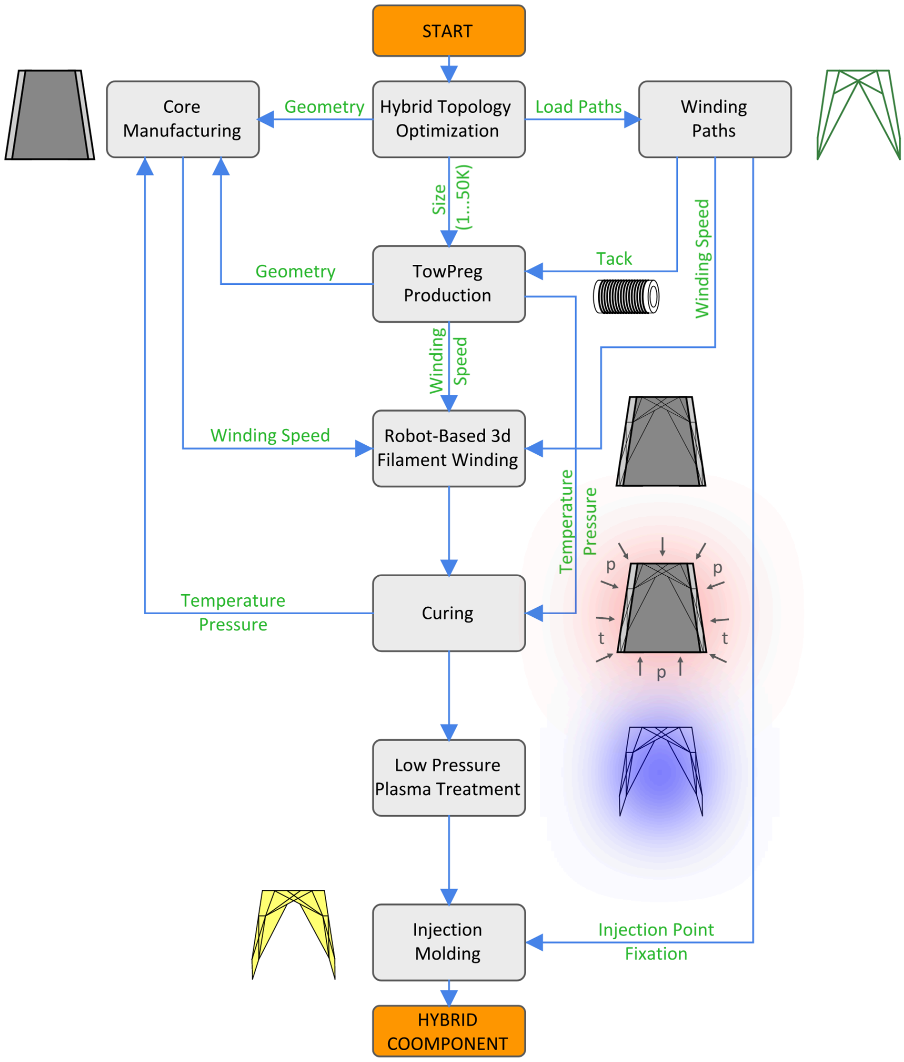


Figure 2. Single steps of the hybrid production process with different influences (green) on other steps

The wound component can now be cured by means of increased temperature and, if necessary, pressure, whereby the properties of the core material and the TowPreg must be considered. New possibilities arise when applying the pressure due to the hybridization. Normally there is increased pressure (vacuum or autoclave) applied to compact the laminate in CFRP structures. It may be possible to omit the compacting process in this new hybrid process. Here, the voids in the existing uncompacted CFRP skeleton structure can be filled with injection molding material to generate a high loadable component. This still has to be proven in future studies.

The CFRP skeleton structure must be pretreated after curing for a highly loadable interface. This can be done by low pressure plasma (for example air or oxygen as process gas) or by other pretreatment methods like a CO_2 laser [7, 11]. The aim here is to expose the top fiber layer and apply functional groups on the CFRP structure for a better coherent connection to the thermoplastic injection molding material. The cured CFRP structure is overmolded in the final process step in an injection molding process. Here, particular attention must be given to the placement in the injection mold so that the CFRP structure does not dislocate in the form. Ideally, existing load introduction elements are used for this purpose.

3. Robot-Based 3d Filament Winding Cell

Different configurations are possible for a robot-based 3d winding system. Figure 3 shows an overview of possible basic configurations of a winding system based on 6-axis industrial robots. Of course, industrial robots with fewer axes can also be used, but 6 axes have become the standard and are available in many different sizes.

Concept A shows a 7-axis configuration where the robot guides and deposits the TowPreg strand. The TowPreg itself is stored on an external rack and the fiber tension is also controlled at this point. The winding core is mounted on an external seventh axis. Concept B shows a 6-axis configuration where the winding core is mounted on the robot flange. The TowPreg material is located on an external rack together with the fiber tension control. In concept C, also a 7-axis configuration, the control for the fiber tension and the TowPreg material is located directly on the robot flange in form of a winding head. Concept D shows a configuration with two 6-axis robots. Here, the winding core is attached to one robot flange and a winding head with integrated fiber tension and material storage is located on the other robot flange.

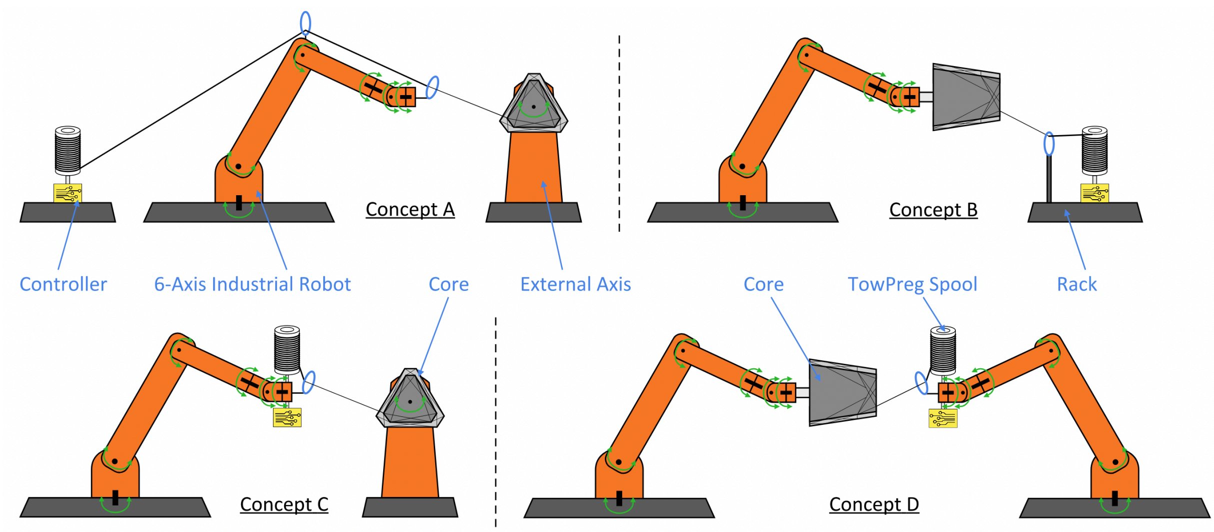


Figure 3. Four basic robot-based filament winding concepts

Table 1 provides an overview of the respective advantages and disadvantages of the four concepts shown in Figure 3. The main advantage of concept A is the almost unlimited amount of TowPreg, since this is stored on an external rack and independent of the robot. Also, by limiting the motion degree of the robot, parallelization can be achieved, where multiple cores (one above the other, each with an additional external axis) can be wound simultaneously. Another advantage is that a smaller robot can be used here, because it only guides the fiber and does not carry any additional loads. The main disadvantage of this concept is the limitation of the winding speed. Due to the external storage of the TowPreg coils, the TowPreg strand must overcome a very long distance (several meters) until it is deposited. This results in a complex control and slower traversing speeds so that the TowPreg does not vibrate or become tangled.

Concept B is as cost effective as concept A, since only one bigger industrial robot (it must carry the core) and no external axis is needed in addition to the external rack. However, this makes parallelization very difficult and the kinematics somewhat more limited. The programming effort is also somewhat lower and unlimited material can be provided due to the external storage. Also, the winding speed is relatively good because of the short distance between TowPreg coil and the winding core.
The same winding speed is also possible at concept C. The TowPreg is located on a winding head on the robot flange together with the control system. It also has the smallest cell size, like concept B. The

disadvantage here is the limited storage of material on the robot, which should nevertheless be enough for most processes & components (depending on the dimensions of the winding head).

Concept D promises a very high winding speed due to the use of two robots and can create the most complex winding patterns. However, this comes with the disadvantage of a much higher programming effort. In addition, parallelization is very difficult to implement. Furthermore, this would also involve the highest investment, since the industrial robot is the most expensive component in the system. Also, the space needed for this production concept is the biggest one.

Table 1. Comparison of different robot-based filament winding concepts

	Axis Setup	Code	Material	Speed	Kine-matics	Paralle-lization	Cell Size	Invest
A	Rack (Spool) + 6 (Guide) + 1 (Core)	o	+	-	o	+	o	+
B	Rack (Spool + Guide) + 6 (Core)	+	+	o	-	-	+	+
C	6 (Spool + Guide) + 1 (Core)	o	o	o	o	+	+	o
D	6 (Spool + Guide) + 6 (Core)	-	o	+	+	-	-	-

+ positive o neutral - negative

Code	Complexity of programming the robot code
Material	How much Material is stored at the cell / robot
Speed	How fast can TowPreg be applied to the Core
Kinematics	Degree of freedom to use for winding
Parallelization	Is a parallel production of serval components with one industrial robot possible
Cell Size	Size needed for the robotic cell
Invest	Investment costs for the robot production cell

The 7-axis winding system at Pforzheim University consists of a 6-axis industrial robot, an external axis and a self-developed winding head with associated PLC (Programmable Logic Controller). This corresponds to a system based on concept C in Figure 3 or Table 1.

A special characteristic of the robot-based 3D filament winding is the abrupt change of the winding head direction due to the complex geometries. Also, the winding head can move into the direction of the winding core, which is not required in the classic winding process. To prevent the fiber from sagging and thus a drop in the fiber tension, it must be possible to rewind the fiber back onto the carrier roll. This means that no simple brake (magnetic powder brake, hysteresis brake, etc.) can be used to generate the fiber tension (classic unwinder), but an electric motor is required. However, the use of an electric motor for generating the fiber tension results in a more complex control system, since it must work in both directions (unwind and rewind).

Figure 4 shows the robot system at Pforzheim University. The winding head is shown in the upper area. On the external axis an example of a wound, truss-like CFRP skeleton structure is shown. This is located on a reusable metal core with pins as deflection points. At the beginning of the winding process, the TowPreg strand gets placed around the winding axis. This small residual piece must be removed after winding and is not cured. After winding this whole structure, it can be compacted and cured in an oven using a vacuum bag or hot press curing.

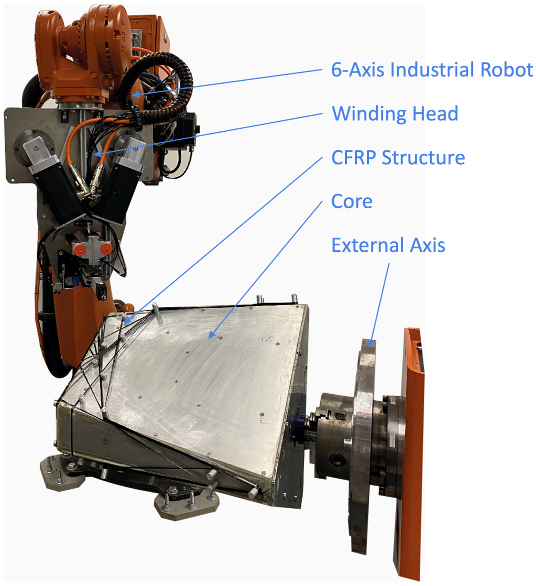


Figure 4. 3d robot-based filament winding cell at Pforzheim University with wound CFRP skeleton structure

3.1 Winding head

Figure 5 shows a schematic representation of the winding head shown in Figure 4. The TowPreg coil is mounted on a mechanical clamping unit, which allows quick changeovers. The TowPreg is then centered horizontally and vertically in the centering unit before entering the mechanical tensor. This consists of a compression spring which supports the control unit to maintain the fiber tension. The TowPreg is then deflected via the force sensor, which measures the fiber tension after all deflection points so that the friction in the system, which influences the fiber tension, is included in the final value of the fiber tension. The "Cut & Apply" unit for automated cutting and reattachment can be switched on if necessary to change between one or two TowPreg strands in the process. The TowPreg material can then be precisely deposited via a specially designed PTFE-based thread eye.

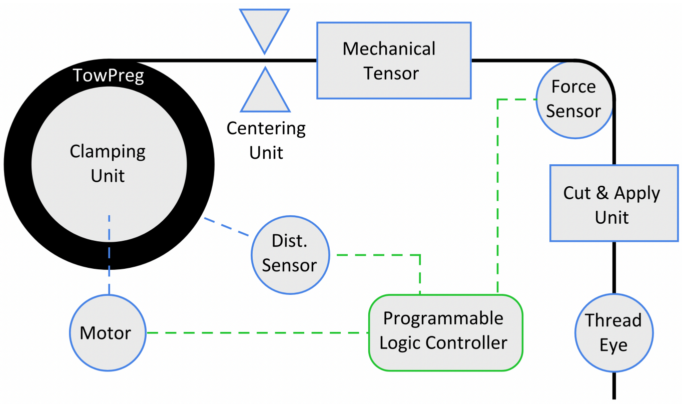


Figure 5. Schematic diagram of one half of the winding head at Pforzheim University

In addition to the mechanical tensor, the PLC is primarily used to control the fiber tension. This controls the torque in the asynchronous motor to which the clamping unit and thus the TowPreg is attached (up to 5kg CF TowPreg are possible per clamping unit). The fiber tension can be set at any time via a touch panel depending on the used TowPreg and CFRP skeleton structure. As input variables, the PLC uses a distance sensor, which measures the coil diameter and the force sensor for the current fiber tension. The electronic control must be supported by the mechanical tensor due to the large speed changes and the rapid transitions between winding and unwinding of the TowPreg strand. This mechanical tensor can react directly to a change in force in the TowPreg strand without a delay. The complete control system, sensors, motor and mechanical tensor can currently set a fiber tension of 25 - 100 N, which is sufficient for a broad variety of applications.

3.2 Fiber Deflection

The winding paths were defined in the first process step based on the hybrid topology optimization. For the design of the winding core, geometric adaptions must now be taken on the core for any strongly curved paths (with local bends) where the tack of the TowPreg is not sufficient for the deflection. For this purpose, four methods have proven to be effective, which can be applied due to the rectangular cross-section of the TowPreg strand. These are shown in Figure 6.

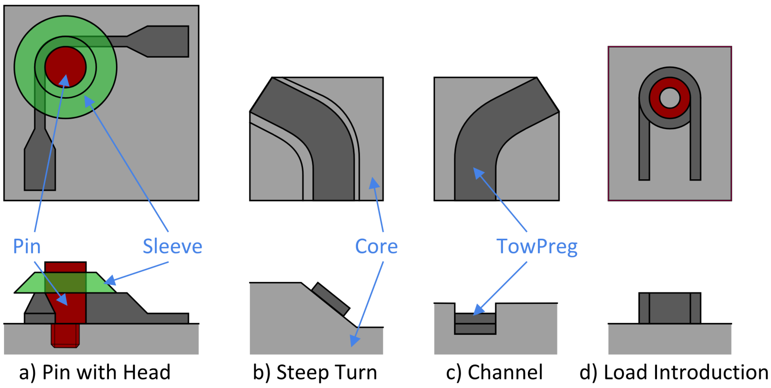


Figure 6. Geometries for strongly curved paths (with optional local bend)

The so-called pins (a) are very easy to implement. The winding path can be easily influenced with the help of pins, which can be placed on the core by screwing them into the core. As the TowPreg has a nearly rectangular cross-section, the material is set up vertically at the pin itself (as shown in Figure 6a). Angled sleeves are then used to compact the TowPreg during the curing process at the pin. These sleeves can slide along the pin and the vacuum bag presses neatly against them due to the bevel edges. This then compacts the TowPreg Material underneath.

Another possibility is the use of steep turns (b) or channels (c). Here, the TowPreg is guided on one or even two sides. Nearly all radii can be represented in this way. The steep turns are easier to wind, in contrast to the channels, as the TowPreg can be applied laterally from one side. Not too tight radii can be wound with channels as otherwise the strand can no longer be laid completely into the channel. The advantage of a channel is the defined geometry and the corresponding clear edges after curing.

Existing load introduction points can be used as a deflection point as the last and simplest option. These normally consist of cylindrical geometries, with which the final component can be connected to other parts. These can then easily be wound with TowPreg in the process and thus also used as deflection points. At the same time, as mentioned above, these load introduction elements can be used to fix the position of the CFRP structure in the injection mold.

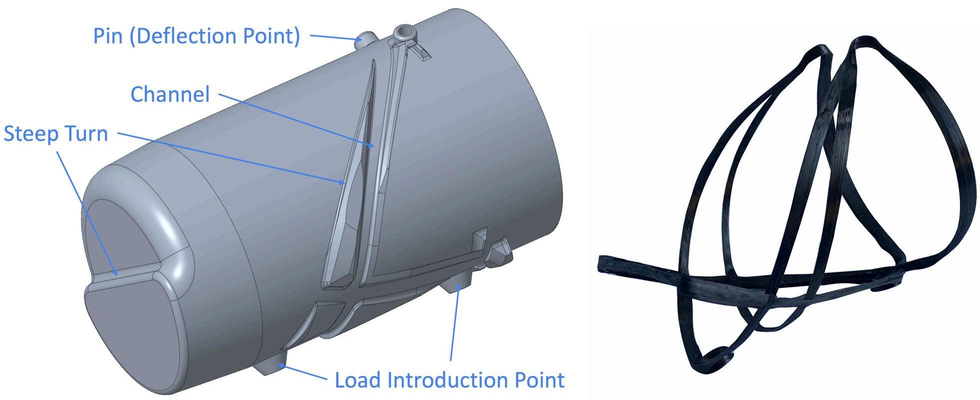


Figure 7. Core with geometric adaptions (channels, steep turns, pins and load introduction points) and resulting CFRP skeleton structure

Figure 7 shows a real-world application core for a winding structure with the above-mentioned channels, steep turns, pins and load introduction points as well as the resulting CFRP skeleton structure itself. The load introduction points in the resulting CFRP skeleton structure are wrapped several times and are used at the same time as a deflection point (like a pin). It is also shown that the TowPreg is set up vertically at the two pins, as described in Figure 6a. However, in the structure shown in Figure 7, no sleeves were used to compact the TowPreg material. The channel and steep turn at the lateral surface enable differently curved paths. The steep turn at the front surface generates a defined edge for this winding path and is used as a deflection point at the transition between lateral and front surface.

4. Conclusion

A hybrid thermoset-thermoplastic manufacturing process based on the robot-based 3d filament winding with TowPreg is demonstrated in this publication. It is shown that it is important to consider the complete process chain, starting with the hybrid topology optimization, the creation of the winding paths and the winding core, the TowPreg production, the winding of the truss-like CFRP structure as well as the curing, pretreatment and overmolding of the CFRP structure, since all individual decisions have an influence on the subsequent process steps. The TowPreg material can be deposited automatically at high speeds and nearly waste-free by using an industrial robot and a fiber tension control system on a specially developed winding head. It is also possible to switch between several TowPreg strands during the process, so that no unnecessary material is deposited. The TowPreg enables leaving the geodesic paths and thus to have greater design freedom in the geometry to be wound. With special geometry features in the winding core (pins, channels, and steep turns), the possibilities for the winding paths of the TowPreg increase even more.

5. References

[1] H. Friedrich (Ed.), Leichtbau in der Fahrzeugtechnik, Wiesbaden, Springer Fachmedien, 2013.

[2] AVK – Industrievereinigung Verstärkte Kunststoffe e.V. (Ed.), Handbuch Faserverbundwerkstoffe, Wiesbaden, Springer Fachmedien, 2013.

[3] N. Minsch, F.H. Herrmann, T. Gereke, A.Nocke, C. Cherif, Analysis of filament winding processes and potential equipment technologies, Procedia CIRP, Bd. 66, 2017, p. 125–130.

[4] I. Müller, M. Bürgmann, J. Heimann, A. Stieglitz, C. Sohl, V. Hörtdörfer, Method for producing a component and component, German Patent DE102017222579 (A1), 2017.

[5] M. Gutbrod, Towpregs zum fertigen Bauteil wickeln, K-EXTRA, 2017, S. 13.

[6] N. Karakaya, M. Papila, G. Özkoc, Overmolded hybrid composites of Pa6 on continuous carbon and glass fiber/epoxy composites: an assessment of the interface, Composites Part A, 131, 2020, S. 1–8.

[7] P. Bauer, Y.N. Becker, N. Motsch-Eichmann, K. Mehl, I. Müller, J. Hausmann, Hybrid Thermoset-Thermoplastic Structures: An Experimental Investigation on the Interface Strength of Continuous Fiber-Reinforced Epoxy and Short-Fiber Reinforced Polyamide 6. Composites Part C, 3, 2020.

[8] A. Forcellese, L. Greco, M. Pieraliisi, M. Simoncini, G. Trevisan, Mechanical Properties of carbon fiber reinforces plastic obtained by the automatic desposition of an innovatie towpreg, Procedia CIRP, Vol. 88, 2020, p. 451-456.

[9] S. Nagakalyan, B. Raghukumar, Preparation and characterization of carbon/epoxy towpreg composite material, Materialstoday: Proceedings, Vol. 23, 2020, p. 499-506.

[10] K. Mehl, S. Schmeer, N. Motsch-Eichmann, P. Bauer, I. Müller, J. Hausmann, Structural Optimization of Locally Continuous Fiber-Reinforcements for Short Fiber-Reinforced Plastics, J. Compos. Sci. 2021, 5(5), 118.

[11] Y. Ding, H. Tang, W. Shi, Q. He, Z. Zhai, Enhancement of interfacial strength of overmolded hybrid structures of short fiber reinforced polyamide 6 on continuous fiber reinforced epoxy composites under various surface pretreatments, Polymer Composites, 2021, p. 1-10.

Additive Manufacturing of Metal/Polymer Hybrid Parts – the AddJoining Technique

C. Belei[1], B. Meier[2,3], R. Falck[4], S. T. Amancio-Filho[1*]

[1] Graz University of Technology, Institute of Materials Science, Joining and Forming, BMK Endowed Professorship for Aviation, Graz (Austria)
[2] Graz University of Technology, Institute of Materials Science, Joining and Forming, Graz (Austria)
[3] Joanneum Research – Materials, Niklasdorf (Austria)
[4] Ariane Group, Bremen (Germany)
*sergio.amancio@tugraz.at

AddJoining is a novel additive manufacturing approach to produce metal-polymer hybrid structures. The technique was developed as an alternative to produce layered metal-polymer hybrid structures in substitution to the ones obtained by adhesive bonding and lamination process, such as co-curing and co-bonding, with higher manufacturing flexibility and shorter cycles, out of autoclave and without mechanical fasteners. The present work is aimed at presenting an overview of the AddJoining technique with respect to its principles, state of the art, material combinations, mechanical properties and possible application scenarios. In specific, two examples of material combinations are focused: the AA2024/CF-PA6 (continuous fibers) and the Ti-6Al-4V/PA-CF (short fibers).

On the aluminum-based hybrid joints, an ultimate lap-shear strength (ULSS) of 22.0 ± 1.2 MPa was achieved, which was 19% higher than adhesively-bonded joints using the same adherends. Under fatigue, those hybrid joints surpassed 30% of the ultimate lap-shear force at 10^5 cycles, which is a conventional aircraft certification benchmark. As for the titanium-based hybrid joints, the ULSS reached 23.9 ± 2.0 MPa, despite resorting to considerably lower substrate temperatures. Moreover, by applying a modified three-point bending test (ISO 14679:1997), a strong correlation between substrate roughness and joint strength was observed; this is a result of the polymer being able to flow around and penetrate into intricate surface irregularities, thereby enhancing the micro-mechanical interlocking. Finally, among the possible application scenarios, the examples of a hybrid skin-stringer and a topology-optimized hybrid floor beam were demonstrated, whereby a decrease in weight was achieved either via materials selection or material removal.

Effect of different laser treatment strategies on the bonding properties of hybrid materials

In regard to the energy transition, lightweight construction of cars, aircrafts and ships is one of the main focuses of engineers and scientists at this time. Hybrid materials are an excellent complement to multi-material structures and offer high weight-saving potential while maintaining or even improving strength properties. The components of a hybrid material are mostly joined by adhesive bonding. Before joining, the removal of surface contamination such as grease or oil is a minimum requirement for a reliable bond. It is also possible to structure a surface of metallic component using processes such as sandblasting, anodizing or laser structuring to further improve the adhesive properties. Laser structuring offers the advantage that it is a low-wear and thus almost maintenance-free process. The process duration depends on the scanning speed of the laser and the area to be processed. A bonded joint subjected to shear loading has an uneven shear stress distribution: stress peaks are particularly present in the edge areas. This reveals a possibility to reduce the process time by laser structuring only the areas under shear stress peaks. In this study, partially laser-structured and bonded joints of a steel and a carbon fibre-reinforced plastic (CFRP) were investigated regarding their adhesion properties. They were determined by shear tensile tests according to DIN EN 1465. The surface morphology after the laser treatment was characterized by a scanning electron microscope. Subsequently, the fracture surfaces were analyzed following the DVS 3302 guideline. The investigations showed that the adhesion properties on partially laser-structured interfaces are comparable to those of fully laser-structured ones. This results in a high potential for time savings and thus improved cost efficiency of the process, which significantly enhanced the attractiveness of this sustainable surface pre-treatment for practical applications in the industry.

Friction stir welding of aluminum-copper lap joints: Challenges and future perspectives

Pascal Pöthig, Jörg Hildebrandt and Jean Pierre Bergmann

Department of Production Technology, Technical University Ilmenau, Ilmenau, Germany

Friction stir welding (FSW) is a suitable production technique for joining dissimilar materials such as aluminum and copper and gaining more and more interesting for engineering and design applications. Due to the fact, that there is no materials melting during the joining process of those materials, phenomena as they occur in fusion welding such as solidification and liquation cracking, porosity, and loss of volatile solutes can be avoided. These advantages of solid-state joining have been recognized by the industry due to the increasing demands for welding techniques in terms of battery applications and the electrification of the automotive industry. Because of this, the FSW sees widespread use in welding of aluminum or aluminum to copper and is utilized by a variety of industries, e.g. automotive industry. Nevertheless, there are still multiple challenges during friction stir welding of thin sheet applications, as the process control and the influence of tool wear. In particular, the tool wear is an influencing factor and can significantly reduce the quality of the weld.

Thus, the influence of FSW tool wear was investigated regarding the weld seam quality and process properties. The investigations were carried out with a force-controlled friction welding setup on 1.5 mm EN AW 1050 sheet and 1 mm CW004A sheet in lap joint formation. The resulting weld quality was characterized by different non-destructive and destructive methods e.g. tensile testing, optical inspections and in-situ temperature measurements. Furthermore, welding data was recorded during the process and subsequently analyzed with regard to tool wear. The data have been correlated with the joint quality regarding its suitability for predictive detection of process irregularities due to tool wear.

Friction-based mechanical fastening of hybrid metal-composite joints for industrial applications. Case studies and example of analyses for Friction Riveting

C.F. Rodrigues[1], L. Blaga[1], J.F. dos Santos[1] and B. Klusemann[1,2]

[1] Institute of Materials Mechanics, Department of Solid State Materials Processing, Helmholtz-Zentrum Hereon, Geesthacht, Germany, [2] Institute of Product and Process Innovation, Leuphana University of Lüneburg, Lüneburg.
*camila.rodrigues@hereon.de

This talk will cover the general principles of Friction Riveting, showing the investigation of material combinations relevant for industrial applications, from transportation and civil engineering to small-scale electronic components. Friction Riveting is based on mechanical fastening and friction welding principles, where a cylindrical metallic rivet is joined to polymer-metal multi-material layer structures through frictional heat and force [1]. Friction riveting feasibility studies have been conducted for various materials such as unreinforced and reinforced polymer, carbon, and fiberglass laminates joined with aluminium and titanium rivets [2-4]. Friction riveted joints characterization provided information on joint formation, anchoring efficiency, process temperature evolution, microstructural changes, mechanical performance, and aspects related to the materials' physical-chemical properties.

The process has been mainly investigated for featureless cylindrical 5 mm diameter rivets. Therefore, different geometrical aspects, such as rivet diameters and consequent effects on process energy input and rivet tip geometry, need a deeper understanding. Recent studies have shown Friction Riveting as an efficient alternative to the state-of-the-art joining techniques (traditional fasteners) with advantages such as no pre-drilling, reduced number of process steps, and rivet access from one side of the plate, and performance [1,3]. Successful joints were achieved with significant deformation at the rivet tip inserted into overlapped printed circuit boards laminates with thicknesses below 3.0 mm, considered the lowest achieved so far with Friction Riveting [5].

This talk covers case studies showing technology transfer aspects for industrial applications like suitable load combinations and environments, corrosion, and scalability aspects. The current knowledge in Friction Riveting asserts the process for increased TRLs in transportation and civil engineering. Nonetheless, even though it has been successfully proven that it can be applied even to thermosetting composites, interfaces have to be further characterized and optimized for sensitive applications like aeronautics or electronics.

References

[1] S.T Amancio-Filho, J.F dos Santos. Henry Granjon Prize Competition 2009, Winner Category A: “Joining and Fabrication Technology” FRICTION RIVETING: Development and Analysis of a New Joining Technique for Polymer-Metal Multi-Material Structures. Weld World, 2011, 55:13–24.
[2] C.F. Rodrigues, L.A. Blaga, J.F Santos dos, L.B. Canto, E. Hage Jr., S.T. Amancio-Filho. FricRiveting of aluminium 2024-T351 and polycarbonate: Temperature evolution, microstructure, and mechanical performance. Journal of Materials Processing Technology, 2014, 214(0):2029 – 2039.
[3] N.Z. Borba, C. Afonso, L.A Blaga et al. On the Process-Related Rivet Microstructural Evolution, Material Flow and Mechanical Properties of Ti 6Al4V/GFRP Friction-Riveted Joints. Materials (Basel), 2017, 10:184.
[4] S.T. Amancio-Filho, L.A. Blaga. Joining of polymer-metal hybrid structures: principles and applications. John Wiley & Sons, Inc, Hoboken, NJ, 2018.
[5] M.C.F. Antunes Vilas Boas, C.F. Rodrigues, L.A.Blaga, J. F. dos Santos, B. Klusemann, Deformation and anchoring of AA2024-T3 rivets within thin printed circuit boards, 24th Intl. Conf. on Material Forming ESAFORM 2021, 14-16 Apr 2021, Liège, Belgium.

Functionally graded ceramic-based components (FGC) manufactured by Multi Material Jetting technology

S. Weingarten[1*], L. Gollmer[1], R. Johne[1], P. Horn[1], U. Scheithauer[1]

[1] Fraunhofer Institute for Ceramic Technologies and Systems IKTS
*steven.weingarten@ikts.fraunhofer.de

Ceramic-based functionally graded Components (FGC) are ceramic parts with a variety of different properties, which change gradually throughout their dimensions by realizing a graded microstructure or material gradients. As a result, innovative, multi-functional property combinations, such as hard and ductile, electrically or thermally conductive and insulating or magnetic and nonmagnetic combinations can be created. Applications are conceivable in a variety of industrial and medical fields - for example, as cutting tools, wear resistant components, ceramic heaters, energy and fuel cell components or as bipolar surgical tools.[1][2]

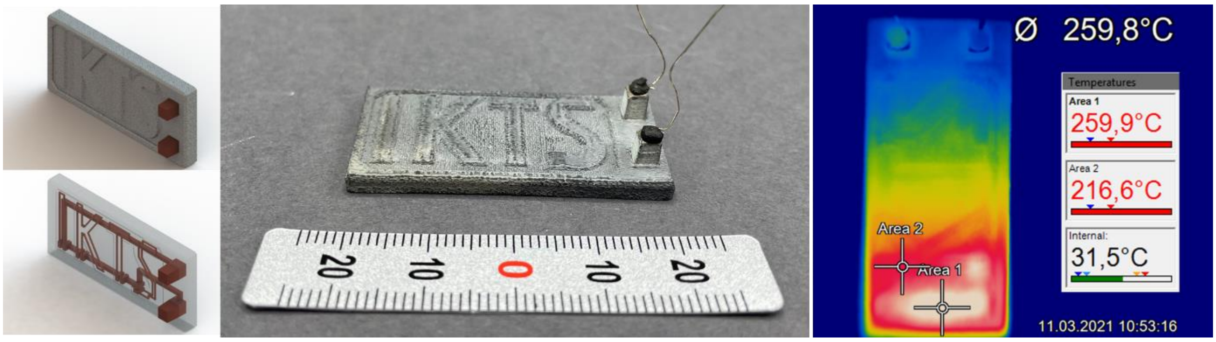


Figure 1. Ceramic heater based on electrically conductive and insulating silicon nitride molybdenum disilicide

Multi Material Jetting was specially developed for the manufacturing of ceramic-based functionally graded and multi material components. In our study, we investigated the AM of ceramic-based Functionally Graded Components (FGC) by CerAM MMJ, like zirconia components with a varying microstructure as well as Si3N4 -based components, which combine an electrically conductive phase and a non-conductive phase.

The Multi Material Jetting technology is currently in the commercialization phase. The project is being launched as part of the EXIST research transfer programme "EXIST: CerAM MMJ" (funded by the BMWi, project management organization PTJ, funding code: 03EFQSN180). The presentation will give an overview of the current state of the technology development, the available material portfolio, some applications and the progress of the commercialization activities.

References

[1] U. Scheithauer; S. Weingarten; R. Johne; E. Schwarzer; J. Abel; H.-J. Richter; T. Moritz; A. Michaelis, *Ceramic-Based 4D Components: Additive Manufacturing (AM) of Ceramic-Based Functionally Graded Materials (FGM) by Thermoplastic 3D Printing (T3DP)*
Materials: Open Access Materials Science Journal. - Multidisciplinary Digital Publishing Institute MDPI. - Basel, Switzerland: *MDPI. - 1996-1944 (E-ISSN). - 10* (2017) 12

[2] S. Weingarten, U. Scheithauer, R. Johne, J. Abel, E. Schwarzer, T. Moritz, A. Michaelis, *Multi-material Ceramic-Based Components - Additive Manufacturing of Black-and-white Zirconia Components by Thermoplastic 3D-Printing (CerAM - T3DP), Journal of visualized experiments* : JoVE, 7 January 2019, Issue 143

In-line quality assurance and process control in fully automated welding processes

S. Weidmann[1*], P. Mitschang[1]

[1] Leibniz-Institut für Verbundwerkstoffe GmbH, Erwin Schrödinger Straße 58, 67633 Kaiserslautern
*stefan.weidmann@ivw.uni-kl.de

The increasing use of composite structures made of thermoplastic fiber reinforced polymer composites (TP-FRPC) requires the development of suitable joining processes. Induction welding is particularly suitable as a thermal joining process due to the efficient and contact-free energy input. Especially for hybrid metal-composite structures the metallic joining partner can be efficiently heated by induction. When the metal is heated above the melting temperature of the TP-FRPC, the matrix polymer melts to the metal at the interface. Due to a simultaneously applied consolidation force, the metallic joining partner is pressed into the molten TP-FRPC. When using physical surface pre-treatments - such as laser structuring - the matrix polymer flows into the cavities of the structuring and solidifies after cooling, resulting in a hybrid bond. Using chemical surface pre-treatments, e. g. by bonding agents, bonding mechanisms act on a molecular level.
Hybrid induction welding has a number of advantages, but at the same time possesses major challenges when implementing in-line quality assurance and process control. Process control by contactless measurement of the surface temperature is usually not possible, because the joining zone is covered by the components. A new approach for in-line quality assurance is based on the thickness change (TC) of the hybrid structure before and after welding. This approach is implemented in the fully automated FlexHyJoin production cell (www.flexhyjoin.eu) for hybrid welding. It has shown that an increasing TC reduces the number of voids in the joining zone and can be correlated with tensile-shear strength. Therefore, TC can be used as criteria for in-line quality control.

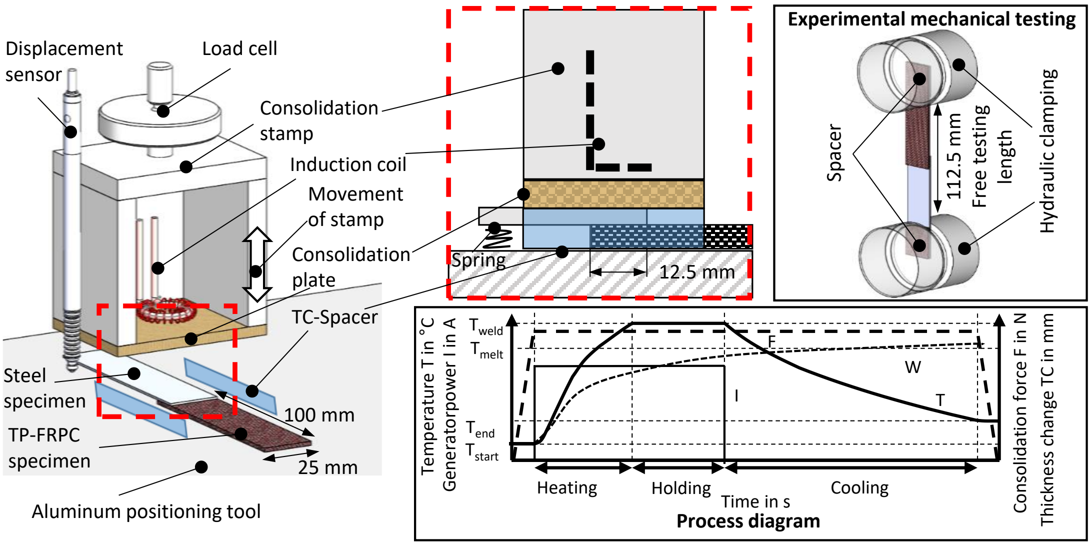


Figure 1. Experimental specimen manufacturing, mechanical testing and process diagram

The course of the TC as a function of joining temperature (JT) during hybrid welding of TP-FRPC with laser structured steel or with adhesion promoter coated steel show correlation with joint quality. It was found that both, the welding temperature and the surface pre-treatment, have not only an influence on the course of the TC curves, but also on the bond strength. The interdependencies of the mentioned parameters will be explained.
The fully automated production cell, which was developed in the FlexHyJoin project, will be used to demonstrate, how an in-line quality assurance based on TC can be integrated in an industrial process chain.

Parameter investigation regarding the adhesion properties of the hybrid composite made of laser-structured aluminum EN AW 6082 and CFRP produced by prepreg pressing process

Shuang Wu[1*] (S. Wu), Alexander Delp[2] (A. Delp), Jonathan Freund[3] (J. Freund), Jan Haubrich[3] (J. Haubrich), Thomas Tröster[1] (T. Tröster), Frank Walther[2] (F. Walther),

[1] Paderborn University, Chair of Automotive Lightweight Design (LiA), Mersinweg 7, 33100 Paderborn
[2] TU Dortmund University, Chair of Materials Test Engineering (WPT), Baroper Str. 303, D-44227 Dortmund
[3] German Aerospace Centre, Institute for Material Research, Linder Höhe, 51147 Köln
*shuang.wu@upb.de

With increasing demands on environmental protection and the reduction of CO2 emissions in the automotive sector, developing innovative lightweight design strategies for vehicles is a significant research focus. Therefore, fibre-reinforced plastics (FRP) are increasingly being used because of their high lightweight potential. Furthermore, FRP is often applied on metal structures according to the load cases for enhanced material utilisation and cost reduction. To produce such hybrid structures, the prepreg pressing process was investigated at the Chair of Automotive Lightweight Design at the University of Paderborn. It is an intrinsic manufacturing process in which the joining and shaping of the metal and FRP components will take place simultaneously, and therefore reduce cycle times.

As part of a DFG-funded collaborative research project, "HerKoLas", the process parameters of the prepreg pressing process are further narrowed down and optimised so that a component-like structure such as a hat profile made of laser-structured aluminium sheets and a thermoset CFRP prepreg can be formed simultaneously. The results of the basic investigations are presented and discussed in this presentation. To determine the bond strength between the laser-structured aluminium sheet and the CFRP-laminate, the Shear Edge test was used. The influence of various factors such as laser parameters, curing temperature, curing time, and pressing pressure were investigated. Then, 3-point bending tests were carried out to analyse the influence of the consolidation parameters (temperature, pressure, and time) on the mechanical properties of the CFRP-laminate. Results so far show that the flexural strength increases with the increased pressure, and the laminate quality is improved. The test results are evaluated based on statistical methods to determine the optimum curing parameter for good bonding and laminate properties.

Investigation on the joining of an inner organic sheet with an outer metal sheet by hemming

H. Deutges[1*], M. Mannig[1], K. Dilger[1], S. Hartwig[1]

[1] Technische Universität Braunschweig
*h.deutges@tu-braunschweig.de

Folding or hemming is a technique to join two metal sheets and is commonly used in automotive industry for the production of doors and flaps. The outer sheet is folded around the inner sheet, while the outer provides a nice surface and the inner sheet creates the stability of the part. While using additional adhesive in the fold and a fine seam sealing it also provides a corrosion resistant joint. The problem with using an adhesive is the need of an additional process.
In this work the inner metal sheet is replaced by an organic sheet. Thermally assisted press joining is used to join the sheets. Here, the adhesive and the fine seam sealing are not needed anymore and the process can be simplified. Furthermore, the organic sheet increases the lightweight potential of the joined part. The aim of this study is to find the best process parameters and folding fillings. In figure 1 you can see the crosssections of a folded metal before and after the inductive heating showing that the fold can be fully filled by the "lofting" expansion of the organic sheet.

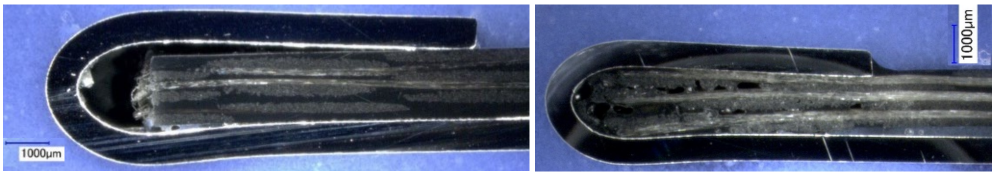


Figure 1: Crosssections of folds before (left) and after (right) the heating

In this systematic investigation, different samples are analysed with respect to the appearance and the pull-out properties of the folds. It has been observed that especially the force during folding, the heating time and the pretreatment of the metal have an influence on the maximum pull-out force and the work during pull-out.
We thank the Federal Ministry for Economic Affairs and Energy and the AiF for the funding of this project.

Joining of steel/CFRT-hybrid parts via non-rotational symmetric cold formed pin structures

J. Popp[1*], D. Drummer[1]

[1] Institute of Polymer Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

Hybrid parts, consisting of a steel and continuous fiber reinforced thermoplastic (CFRT) component offer new possibilities such as the combination of good weight related mechanical properties and high temperature resistance that can exceed the potential of single material parts. This study investigates the direct pin pressing process with single cold formed, non-rotational symmetric pins into a quasi-unidirectional CFRT component. In the current state of the art, primarily rotational symmetric cross sections of the pins are investigated [1,2], although non-rotational symmetric cross sections as investigated with three different geometrien for metal/metal joints in [3] could offer potential in means of material and load appropriate joining and introduction of forces into the reinforcing fibers: Depending on the failure mode of the joint, the orientation of the non symmetric pin strucuture is expected to influence the joint characteristic.
On the example of an oval pin, in [3] the metal-metal joints failed with pin breakage at higher loads when the pin was oriented with the long side in load direction. However, for metal/CFRT joints, where a failure of the composite is more likely, it is possible that a pin orientation with the long side in 90° to the load direction is more beneficial due to a more even load introduction into the composite. Thereby, another factor that has to considered is the pin orientation in relation to the fiber orientation in means of fiber displacement: It is expected, that with unidirectional CFRT samples, a pin orientation with the long side along the fiber orientation is beneficial.
On the example of a three sided polygon, it can be assumed that the joint characteristics are dependend on the orientation of the pin in relation to the load direction: It is assumed, that a load introduction with the "triangle side" is more beneficial than with the "triangle corner".
Summarizing, the approach to use non-rotational symmetric pin geometries to create metal/CFRT joints offers high potential to tailor the joining process to the joint requirement for a versatile joining method but still requires extensive research and thus is to be investigated in the present study. Figure 1 shows examplaric pin geometries as investigated in this publication:

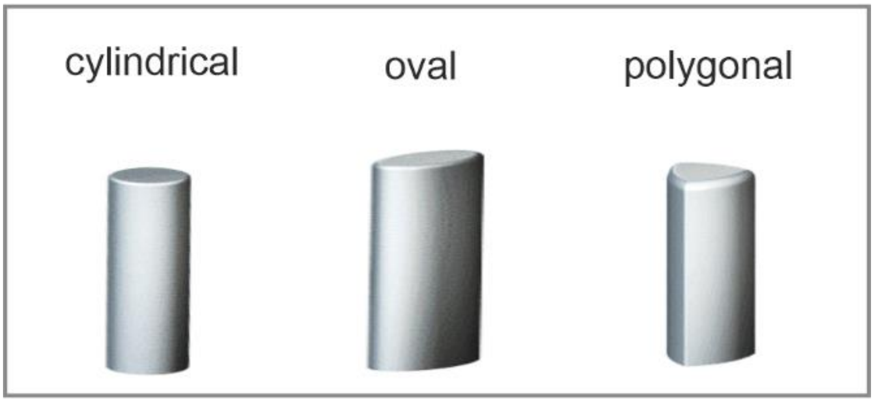


Figure 1. Examplary CAD models of investigated pin geometries.

Consequently, in the scope of this study, three different geometries are investigated: As a baseline geometry, a cylindrical pin with a diameter of 1 mm is used, which is utilized to compare the results of the non-rotational symmetric pins. The second geometry is an oval shaped pin with an aspect ratio of 1:2 and length of the short side of 1 mm aiming at a more gently fiber displacement in the quasi unidirectional composite and also increased bending resistance of the pin structure. The third geometry is a polygon, which is based on a triangular shape with rounded corners and sides and an in circle diameter of 1 mm aiming at an increased, load direction dependent, joint strength. Thereby, the fiber component is a custom-manufactured quasi-unidirectional CFRT glass fiber/polypropylene composite with a fiber volume content of approximately 45 %.

In a first step, the joints are characterized via imaging methods in order to create a thorough understanding of the geometries' influence on fiber displacement mechanisms. Thereby the structures are joined with the CFRT in different orientations in relation to the fiber orientation in order to investigate the resulting anisotropic fiber orientations.

In a second step, the joints are characterized in quasi-static single lap shear tests in 0° and 90° to the fiber orientation in order to determine the mechanical performance and the results of the different geometry types. Besides the fiber orientation, the orientation of the non-symmetric pin structures is also varied in relation to the load direction resulting in a total of six tested combinations.

References

[1] Kraus, M.; Frey, P.; Kleffel, T.; Drummer, D.; Merklein, M.: Mechanical Joining Without Auxiliary Element by Cold Formed Pins for Multi-Material-Systems., *AIP Conference Proceedings*, 2020, 1-6

[2] Popp, J.; Kleffel, T.; Römisch, D.; Papke, T.; Merklein, M.; Drummer, D.: Fiber orientation mechanism of fiber reinforced thermoplastics hybrid parts joined with metallic pins.
Applied Composite Materials, 2021, *28*, 951-972

[3] Römisch, D.; Kraus, M.; Merklein, M.: Investigation of the Influence of Formed, Non-rotationally Symmetrical Pin Geometries and their Effect on the Joint Quality of Steel and Aluminium Sheets by Direct Pin Pressing, *2nd International Conference on Advanced Joining Processes AJP 2021*, 2021

Laser Welding for the Production of Hybrid Textile Composites

M. Brosda[1*], M. Seidenberg[2], P. Nguyen[1], Prof. Dr. A. Gillner[1], Prof. Dr. T. Gries[2]
[1] Fraunhofer Institute for Laser Technology ILT, [2] Institute for Textile Technology of RWTH Aachen University
*Maximilian.brosda@ilt.fraunhofer.de

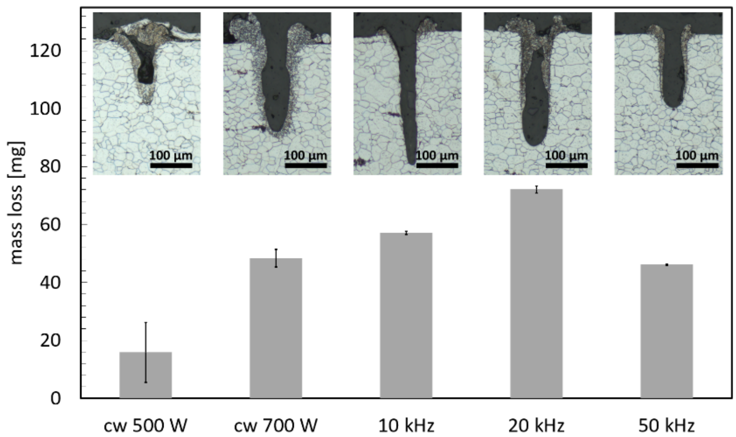
Finishing processes for textiles are also increasingly used in the personalization of sportswear and workwear as well as in the production of smart textiles. While textile finishing focuses on the high-quality look and feel of the applied ornaments, applied ornaments for smart textiles must serve a functional purpose. The aim is to integrate electronic components such as sensors, lighting or circuits into the textiles. Also suitable textile-compatible flexible connections must be created for data transfer and power supply. This is currently achieved by stitching in cables and conductive yarns or by printing the conductor paths. However, these two process approaches have key deficiencies that prevent their use in numerous fields of application in the field of smart textiles. These are, in particular, the complex and costly application of the conductive structures and the damage to the base textile. Laser welding of metals onto flexible textiles represents an alternative approach. The desired metallization can be applied by locally precise controllable energy deposition using laser radiation. The process can be used to weld precious metals in foil form directly onto thermoplastic textiles without pretreatment. The produced microstructures are extremely resistant to abrasion and kinking due to a strong bond between the joining partners. If metals such as copper and silver are welded, high conductivities can be achieved. Another advantage of the process is the high resolution of the structures that can thus be created on the textile substrate. To investigate the potential of the process, commercially available textiles are locally finished with various precious metals. An evaluation is made with regard to conductivity and abrasion resistance. By varying the laser power and the feed rate, the influence of the deposited energy on the finishing is investigated. Supplementary spectral and microscopic examinations provide information on the dimensioning of the applied finishing.

Laser surface structuring for metal-polymer hybrid connections using fast modulated cw-laser radiation

A. Schkutow[1*], T. Frick[1]

[1] Technische Hochschule Nürnberg Georg Simon Ohm
*andreas.schkutow@th-nuernberg.de

Laser direct joining of metals and plastics is a promising process for producing hybrid material joints without the need for adhesives, fasteners or additional materials [1,2]. In this process, a metallic part is structured by laser radiation to increase the surface roughness and to create undercuts. A thermoplastic or thermoplastic composite material is then brought into contact with the metal component and melted in the contact zone. The melt flows into the structures and, after cooling, a stable joint is formed.
The properties of such joints strongly depend on the properties of these structures. So far, two main approaches have been used for the structuring process: By repeated irradiation with continuous laser radiation, linear grooves or grid structures can be introduced at high removal rates [3]. More complex structures with high aspect ratios can be generated with short and ultra-short pulsed laser radiation [2]. Such structures can lead to higher bond strengths, but due to the limited average power and high cost per watt of those laser systems, the process is usually much slower than with cw beam sources [2]. Modern high-power and comparatively inexpensive cw-fiber lasers feature fast optical modulation capability with modulation frequencies in the range of up to 100 kHz [4], enabling increased temporal control of the laser-material interaction by using pulses in the µs range and temporal pulse shaping.



Processing conditions:

Laser beam source: nlight CFL-700
Wavelength: 1070 nm
Beam quality: M² ≤ 1.1
F-Theta focal length: 163 mm
Focal spot diameter: 24 µm
Scanning speed: 4.0 m/s
Scan path length: 1.4 m
Number of irradiations: 4
Duty cycle in pulsed mode: 71.4 %
(corresponding to an average power of 500 W and a peak power of 700W)

Figure 1. Ablated mass and corresponding metallographic cross sections using continuous and modulated laser radiation.

As shown in Fig. 1, surface structuring using fast modulated laser radiation was found to lead to increased melt expulsion and therefore higher removal rates compared to remote ablation cutting with continuous wave laser radiation at the same average and peak power levels. Therefore, shorter processing times and in some cases a single irradiation can be sufficient to achieve the desired structuring depth. In addition, the lower overall heat input reduces distortion in thin-walled specimens.

References

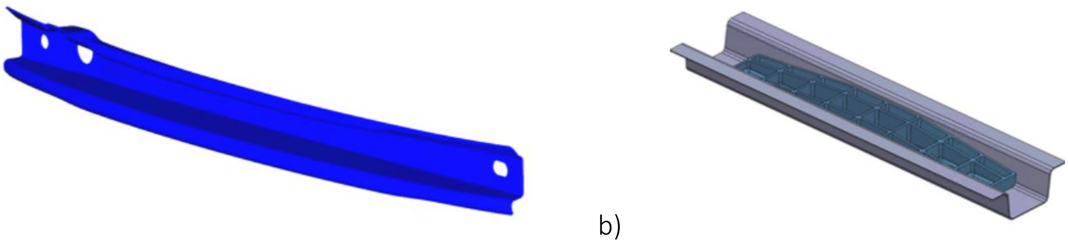
[1] A. Klotzbach; M. Langer; R. Pautzsch; J. Standfuß; E. Beyer; Thermal direct joining of metal to fiber reinforced thermoplastic components. J. Laser Appl. **2017**, 29, 22421.
[2] K. van der Straeten; C. Engelmann; A. Olowinsky; A. Gillner; Comparison of laser-based joining approaches for plastic-metal-hybrids - Strength vs. process speed. In Proceedings of the 3rd Hybrid Conference, Bremen, Germany, **2018**, pp. 203–309.
[3] C. Engelmann, D. Meier, A. Olowinsky; M. Kielwasser, Metal meets Composite - Hybrid Joining for Automotive Applications, Lasers in Manufacturing Conference 2015, **2015**.
[4] D. A. V. Kliner et al.; Next-generation industrial fiber lasers enabled by high-performance components, Proc. SPIE 10513, Components and Packaging for Laser Systems IV, **2018**, 105130S.

Technology comparison of a novel SMC pressing process with the thermoplastic back injection moulding process for hybrid metal/fibre-composite lightweight structures

D.R. Haider[1*], T. Weber[1], R. Thomas[2], S. Wehler[2], F. Aljouda[2], M. Gude[1]

[1] Institute of Lightweight Engineering and Polymer Technology (ILK), Technical University Dresden
[2] Volkswagen AG – Group Innovation
*daniel.haider@tu-dresden.de

The development of body structures for battery electric vehicles (BEV) constantly requires new approaches to optimise crash behaviour and component costs as a result of increasing requirements. Crash structures in the body-in-white that are focused on bending loads are constructed as several parts in conventional sheet metal design in such a way that the cross-section is optimised with regard to an adapted bending moment of resistance. When these structures are loaded locally in a vehicle crash, the profile cross-section fails under increased loads and the structure only transmits a fraction of the loads. Previous studies have already shown that a significant increase in performance can be achieved by using hybrid structures made of a combination of metal sheets, fibre-reinforced plastics (FRP) and a local hybridisation by generating a rib structure [1,2]. To realise such a hybrid crash structure, thermoplastic as well as thermoset processing technologies are available.
Within this, a novel sheet moulding compound (SMC) pressing process is developed. In this process, two different SMC semi-finished products are used in a one-step pressing process to create a rib structure inside a formed steel structure. One SMC semi-finished product is used as a bonding layer between metal and plastic, while the second SMC semi-finished product shapes the final rib structure. The joining of metal and plastic is generated intrinsically during component manufacture. To demonstrate the novel technology, a bumper cross member was selected for local plastic hybridisation, which is loaded in bending during a vehicle crash (Fig. a). From this, a simplified generic test specimen structure in the shape of a ribbed hat profile was derived for technology development and large-scale studies (Fig. b).



a) b)

Figure 1. Automobile use case of local plastic hybridisation: a) bumper cross member; b) ribbed hat profile as test specimen.

In this study, the results of a technology comparison of the described SMC pressing process and a thermoplastic back injection moulding process on the example of the ribbed hat profile is shown. To produce the test specimens, a manufacturing process chain with a uniform mould system for both the thermoset and the thermoplastic matrix system was developed. Furthermore, extrinsic joining, by subsequent joining of the plastic ribbing to the steel sheet, was compared to intrinsically joined profiles, for both the thermoplastic and thermoset processes. The mechanical properties of the manufactured variants of the hat profiles were determined in a 3-point bending test.

References
[1] D.R. Haider *Plastics in Automotive Engineering*, 2018.
[2] M. Gude *Plattform FOREL Abschlussbericht Q-Pro*, 2018.

[Hybrid] O: Design

A study of the rivet and die design impact on the feasibility and quality of self-piercing riveted joints of aluminum and steel sheets

N. Karathanasopoulos[1*]

[1] New York University, Department of Engineering, Abu Dhabi, United Arab Emirates
*n.karathanasopoulos@nyu.com

Self-piercing riveting is one of the most prominent techniques in the mechanical joining of metallic sheets. Its successful application is highly dependent on the use of appropriate rivet and die materials, with each joining case to require a specific range of rivet materials and die configurations [1]. In the current contribution, the successful joining of a set of aluminum-to-aluminum and aluminum-to-steel stacks is analysed both numerically and experimentally. It is observed that a certain range of rivet length and die depth parameters needs to be employed for joining to be feasible, avoiding bottom sheet penetrations while enhancing the creation of substantial interlocks.

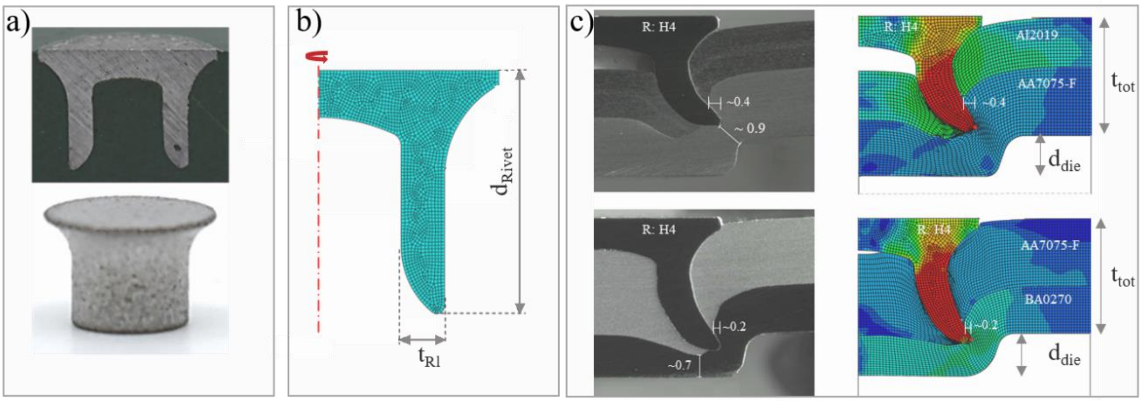


Figure 1. Rivet geometry (a) and finite element axisymmetric representation (b). Experimental and numerical joining results are provided in (c) for an aluminum-to-aluminum and an aluminum-to-steel joining case.

For each of the investigated designs a characteristic die depth to rivet depth design limit is identified, along with an upper rivet material strength [2]. Moreover, the effect of different design parameters on the Von Mises stresses induced during the piercing process is numerically evaluated, providing relevant conclusions for the selection of optimal riveting parameters.

References

[1] N. Karathanasopoulos, K. S. Pandya, D. Mohr; Self-piercing riveting process: Prediction of joint characteristics through finite element and neural network modelling, *Journal of Advanced Joining Processes*, **2021**, *3*, 100040
[2] N. Karathanasopoulos, K. S. Pandya, D. Mohr; An experimental and numerical investigation of the role of rivet and die design on the self-piercing riveting joint characteristics of aluminum and steel sheets, Journal of Manufacturing Processes, **2021**, *69*, 290-302

Computational study of a ceramic-titanium material compound for hybrid knee endoprosthesis

J.-O. Sass[1*], D. Vogel[1], C. Ganz[2], U. Lembke[3], R. Bader[1]
[1] Department of Orthopaedics, Rostock University Medical Center, Rostock, Germany, [2] ZM Präzisionsdental-technik GmbH, Rostock, Germany, [3] DOT GmbH, Rostock, Germany
*jan-oliver.sass@med.uni-rostock.de

Introduction

Aseptic loosening remains the major cause for long-time revisions of total knee endoprosthesis.[1,2] Recent studies are focussing on material innovations to decrease wear propagation [3] and the stress-shielding around the femoral component.[1,2] Novel approaches for joining ceramic and titanium materials could lead to improved biomechanical behaviour, but the feasibility for knee endoprothesis has not been investigated in any study to date.[4,5,6]
The aim of this computational study was to analyse the capability of such hybrid knee endoprosthesis with respect to their biomechanical properties in terms of fracture risk, primary fixation and stress-shielding.

Materials and Methods

A simplified model (Figure 1-A) was constructed with respect to established total knee designs.[6] Finite element models of the intraoperative press fit implantation and postoperative load during two leg stance.[1,2,7] were generated. Different material configurations were investigated: monolithic alumina-toughened-zirconia (ATZ) as well as hybrid material compound of ATZ and Ti-6Al-4V or Ti-42Nb, respectively. The Young`s moduli of the materials were: 230 GPa (ATZ), Ti-6Al-4V (114 GPa), and 60.5 GPa (Ti-42Nb).

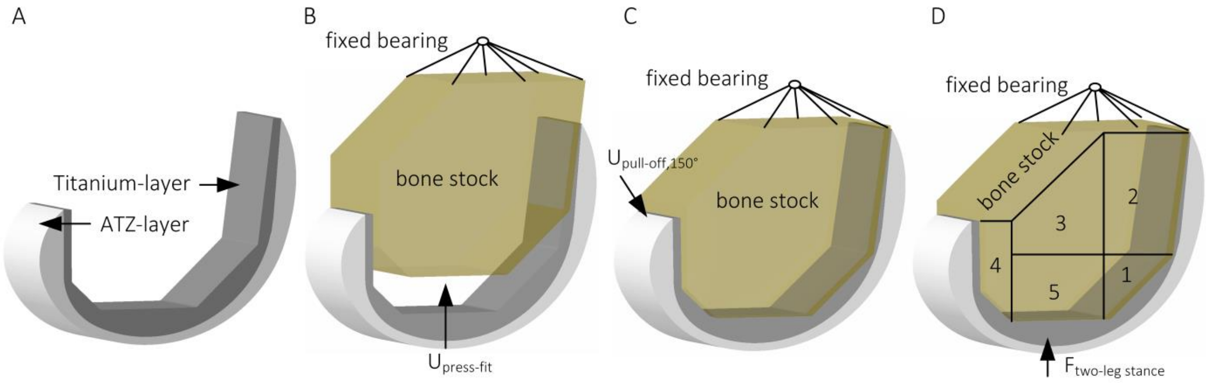


Figure 1. A) Simplified design construct of a hybrid total knee prosthesis made of ATZ-titanium material compound and boundary conditions of the finite element models: B) intraoperative press-fit, C) postoperative pull-off during deep flexion of 150°, and C) postoperative axial load during two-leg stance and defined regions of interest 1 - 5.

Within the finite element analysis the simplified implant design was pressed on a bone substitute material (Sawbones Europe AB, Malmo, Sweden) and then pulled-off under high knee flexion of 150°.[7] The friction coefficient between the bone stock and implant was set to 0.5.[8] In an additional model, axial loading of 1 kN was applied based on the two leg stance and a fully integrated bone-implant-interface was assumed.[1,2] Furthermore, strain energy density (SED) in predefined regions of interest (ROI) was used as indicator for stress-shielding.[1,2] The general boundary conditions are presented in Figure 1-B to –C.
All materials were modelled with homogenous, linear-elastic mechanical properties according to other studies.[9-11] The bone substitute material was modelled with a crushable foam property for a density of 40 pcf.[9]

Results and Discussion

Implantation procedure demonstrated highest mechanical stresses within construct. However, within the ATZ component normal stresses during intraoperative insertion amounted 1641.0 MPa in the monolithic construct, in contrast to 161.6 MPa in the ATZ - Ti-6Al-4V compound) and 236.8 MPa in the

ATZ - Ti-42Nb compound. The stress in the components is determined by their structural stiffness. The stiffer component takes a higher stress. Therefore, the less stiff material Ti-42Nb leads to a higher stress in the ATZ. Accordingly, the hybrid material construct seems suitable for cementless knee endoprosthesis, whereas the monolithic one experiences high stresses above the ultimate flexural strength (755 – 1163 MPa [12]).

Pull-off force of the hybrid implant construct (ATZ – Ti-42Nb: 1826.0 N) decreased compared to the monolithic design (3576.6 N) due decreased stiffness and accordingly lower contact area. The impact on the primary stability should be investigated in future studies.

However, the SED increased, in particular, in the area of the distal resection cut (ROI 5) of 13.3% with the ATZ – Ti-42Nb compound compared to monolithic ATZ construct.

Our presented data are limited by the simplified design construct and lack of experimental validation.

Conclusion

The hybrid implant concept was proven within this computational study. The simplified construct of a hybrid knee endoprosthesis showed highest mechanical stresses within the ATZ component during cementless fiaxation. However, the hybrid design can reduce stress-shielding in the bone stock and wear propagation due to the advantageous combination of ATZ and titanium-alloy. Pull-off forces may be increased by taking advantage of the manufacturing capabilities of additive manufacturing and creating an open-porous structure. Future studies have to address the biomechanical capability of the hybrid ceramic-titanium material compound using standard implant designs.

References

[1] L. de Ruiter et al; *J Biomech*, 2021, *118*,110270.
[2] KE. Rankin et al, *Clin Orthop Relat Res*, **2016**, *474*, 2405–2413.
[3] S. Affatato et al; *Materials*, **2021**, *14*, 2112.
[4] E. Mick et al; *Materials*, **2015**, *8*, 4287–4298.
[5] M. Mitrovic; Knieendoprothese, DE 10 2015 016 895 B3.
[6] C. Zietz et al; *J Orthop Surg*, **2012**, *6*, 20-32.
[7] S. Berahmani et al; *J Arthroplasty*, **2015**, *30*, 300–307.
[8] X. Gao et al; *J R Soc Interface*, **2019**, *16*, 02-59.
[9] C. Schulze et al; *Comput Methods Biomech Biomed Eng*, **2019**, *22*, 25–37.
[10] D. Vogel et al; *Mech Behav Biomed Mater*, **2021**, *113*, 104-115.
[11] C. Schulze et al; *Materials*, **2018**, *11*, 124.
[12] McEntire et al; *J Eur Ceram Soc,* **2016**, *16*, 4327-4369.

Acknowledgements

We thankfully acknowledge the contribution of R. Hauschild. This work was funded by the German Federal Ministry of Education and Research (BMBF) (funding reference: 03XP0279D).

Experimental investigation and numerical modelling of effects of overmoulded rib foot shape, boundary conditions and residual stresses on the apparent joint strength

Robert R. Enderle[1*], Mathias Mühlbacher[2], Christian Cornejo-Runge[2], Thomas Neumeyer[2], Axel S. Herrmann[3]

[1] Faserinstitut Bremen e. V., [2] Neue Materialien Bayreuth GmbH, [3] Universität Bremen
*enderle@faserinstitut.de

1 Introduction

The overmoulding process for thermoplastic fibre composites combines the excellent mechanical properties of continuous fibre reinforced laminates with the high degrees of geometric freedom and short process times of injection moulding. Flat or thermoformed continuous fibre composites can be stiffened and functionalized by overmoulding with a short fibre reinforced thermoplastic.

While composite overmoulding has been widely adapted in the automotive industry, there is no structural component known yet in the aerospace sector. This may be, on the one hand, due to longer development cycles compared to the automotive sector. On the other hand, carbon fibre-reinforced high performance thermoplastics such as polyetheretherketone (PEEK) and poly(p-phenylene sulfide) (PPS) are required which are harder to process. Possible applications of overmoulding in aircraft structures could be stiffened panels for instance in the fuselage perimeter. In order to avoid riveting through the outer skin to attach frames and other structural components, the injection moulded section could not only serve as a stiffener but also as load transferring feature. In such configuration, the predominant load case becomes tensile perpendicular to the overmoulded interface, given that the cabin pressure is higher than that outside. Since the interface is a weak spot in such hybrid material structures, particular attention must be paid to the optimal design of the rib foot.

However, there are no justified recommendations for rib foot shapes given in the literature for PAEK-based overmoulded composites. Consequently, this study aims at quantifying the joint strength for different rib foot dimensions in a parametric study. As the mechanical boundary conditions and significant residual stresses do also affect the apparent joint strength, the parametric study is extended to these.

2 Experiments

For characterisation of the overmoulded bond strength under tensile load, single-rib test coupons as shown in figure 1 are manufactured, as described in more detail in [1]. The coupon consists of a rib moulded onto a 240 x 50 x 2.5 mm flat laminate made of Toray TenCate Cetex® TC1225 RTL, a polyaryletherketone (PAEK) reinforced with a 5 harness satin fabric of T300JB 3K carbon fibre [2]. The layup is $[0,90]_8$. The injection moulding compound is VICTREX® PEEK 90HMF40, a polyetheretherketone (PEEK) filled with 40 wt.% short carbon fibres [3]. In order to induce failure at the interface, the transition between rib and insert is designed as a butt joint, with sharp corners and without distinct foot geometry.

For coupon manufacture, the laminated inserts are preheated in a convection oven to 220°C and transferred manually into the opened injection mould which is kept also at 220°C. The moulding compound is injected at 400°C with a packing pressure of 50 MPa. After sufficient cooling time, the coupon is ejected and cools down to ambient temperature.

For rib-pull-testing, 25 mm long sections are carefully cut from the coupon using a circular saw. The sections are then mounted in a custom-made fixture within the Zwick Z250 universal testing machine equipped with a 200 kN load cell. The fixture clamps the laminate leaving a 10 mm wide gap in the centre through which the rib protrudes. The rib is clamped using wedge grippers and pulled off the insert with a constant crosshead velocity of 2 mm/min until a brittle fracture occurs at maximum pull-off-force.

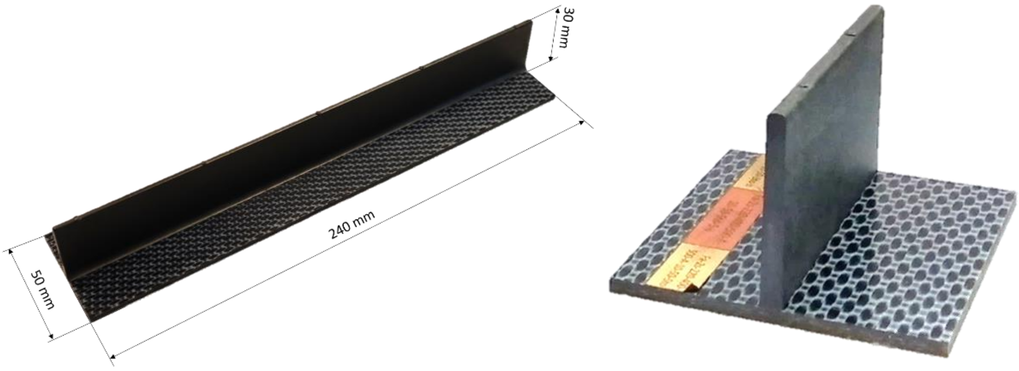


Figure 1. Overmoulded single-rib test coupon (left) with butt joint interface for interface strength characterisation (right).

3 Numerical modelling

In order to conduct a parametric study on the rib foot geometry and its effect on joint strength, a non-linear finite elements analysis (FEA) approach is developed using ABAQUS, version 6.14. It comprises modelling the injection moulded and laminate insert section using continuum elements with linear elastic material models, i. e. Young's Modulus and Poisson's ratio. The injection moulded section is assumed as isotropic, while the laminate section is modelled assuming orthotropic behaviour. Bulk section failure is assumed to possibly occur only in the moulded section. Therefore, a maximum principal strain criterion is applied. The material constants are derived from material datasheets. The overmoulded interface is modelled using a cohesive contact interaction with a traction-separation-law (TSL) describing the initiation and progression of a crack in the interface. The TSL requires values for critical tractions, fracture toughness of the bond and elasticity of the bonded surface. These are calibrated using the force-displacement data from the rib-pull-off tests. A fitting routine is therefore implemented in Python, capable of varying the TSL model parameters, running a non-linear simulation of the rib-pull-off-test, post processing the results and comparing the force-displacement curves of test and simulation. In order to minimise the computational effort for each run, the model is reduced to two dimensions including a symmetry about the vertical rib axis. Comparing the force-displacement curves of the reduced model with a full three-dimensional shows very good agreement although neglecting edge effects at the front end of the specimen.

4 Parametric studies

From a structural mechanical point of view, a fillet in the corner between rib and insert would be preferrable to smooth out stress concentrations in the moulded part and reduce stiffness jumps. However, from literature [4,5] and own preliminary experiments it is known that for overmoulded ribs, subjected to tensile load acting perpendicular to the interface, a wider rib foot is more beneficial. As during the filling phase, the interface must experience sufficiently high temperature to allow formation of a strong weld, the an infinitely thin end of the rib foot will most probably induce weak bonds and initial cracks in the interface. This is due to the rapid heat transfer from the preheated insert and the compound into the much cooler mould. Both materials must bring sufficient heat into the border triangle of cavity, insert and mould steel to ensure the insert surface is molten when it makes contact with the compound. Hence, a step-like rib foot is considered as a generally preferable shape of the rib foot. However, there are no justified recommendations given in the literature on specific dimensions for PAEK-based overmoulded composites. Hence, this study aims at quantifying the joint strength for different rib foot dimensions in a parametric study. As the mechanical boundary conditions and significant residual stresses do also affect the apparent joint strength, the parametric study is extended to these too.

4.1 Rib foot shapes

For the parametric study, the two-dimensional, half-symmetric model of the rib-pull-off-test is parameterised using the Python-based application programming interface (API) of Abaqus. As depicted in figure 2, four dimensions are varied determining the shape of the rib foot.

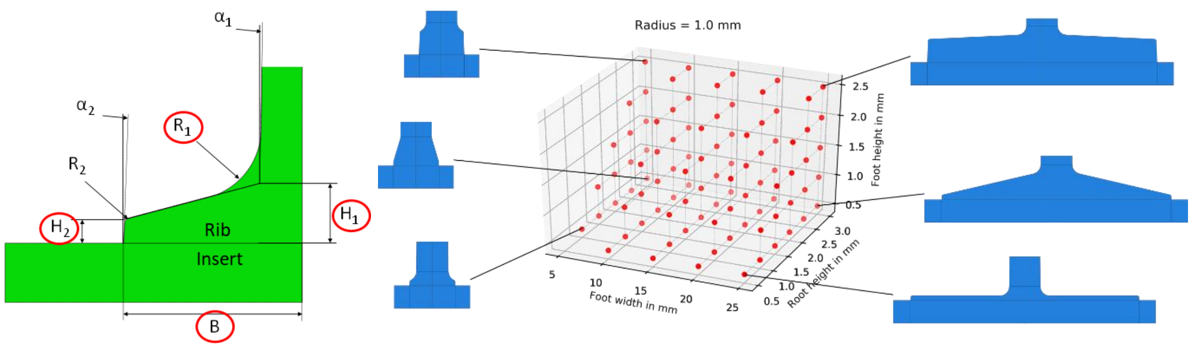


Figure 2. Parameterised half-symmetric, two-dimensional FEA model (left) and visualised part of the parameter space, here for R_1 = 1 mm (right).

The results for the four dimensions in figure 3 clearly show that, within the studied parameter range, the foot width has the largest effect on the maximum attainable pull-off-force. The height of the foot end should be chosen rather small. There is an interaction between the fillet radius and the height of the root, as indicated by tending higher force to smaller root height for higher radii.

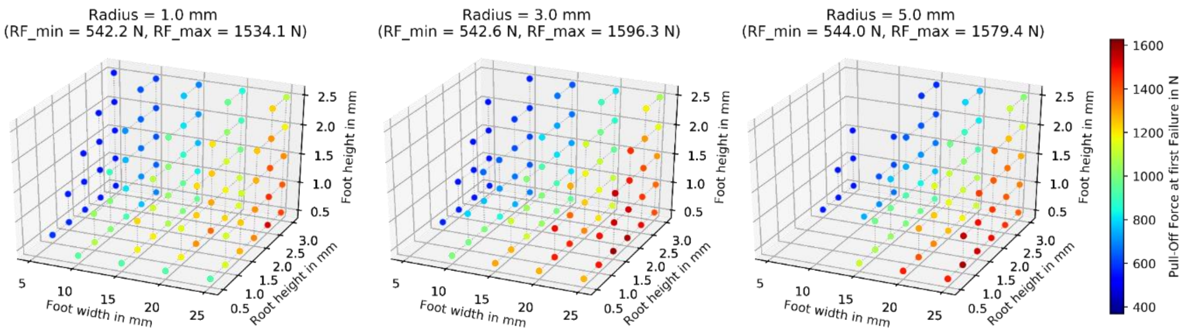


Figure 3. Results of the parametric study on rib foot dimensions

4.2 Insert clamping boundary conditions

A major difference from the common pull-off-test setups and real components is that the laminate will be more tightly fixed in the test. In real components, the next stiffening feature will be farer away from the rib foot, allowing the laminate to bend more under tensile loads. Therefore, the parametric study is extended by a varied distance of the laminate fixture to the rib. As can be seen in figure 4, the optimum depends largely on the boundary conditions. This must be taken into account during design.

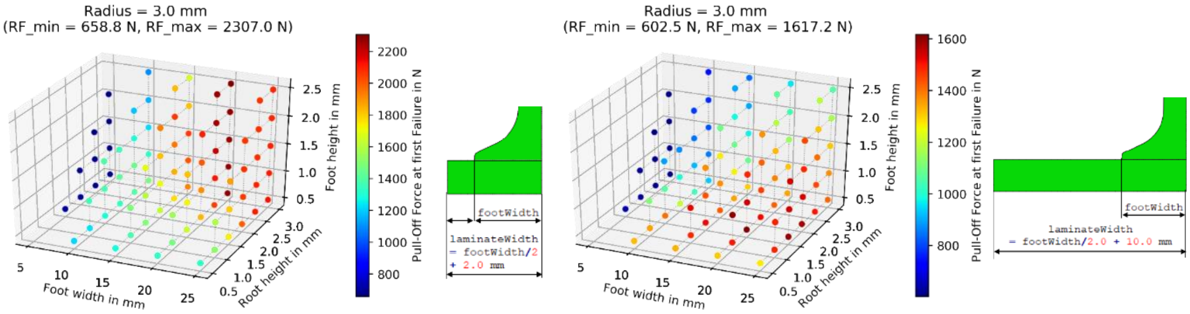


Figure 4. Results of the parametric study on rib foot dimensions with varied laminate clamping distance.

4.3 Simplified residual (thermal) stresses

In overmoulded composites, especially when using high-performance thermoplastics and carbon fibres, there may develop significant residual stresses during manufacture. In a worst-case scenario, these can deteriorate the usable strength of the structure. Residual stresses result for example from differences in coefficients of thermal expansion (CTE) and the large temperature difference between bond formation and in-service-conditions, crystallinity-related density variations, frozen-in and later relaxing flow-induced stresses, flow-induced short fibre orientation and insert deformations. Here, thermal stresses due to different CTEs of compound and insert material are additionally applied to the model in order to study their effect on the overall joint strength.

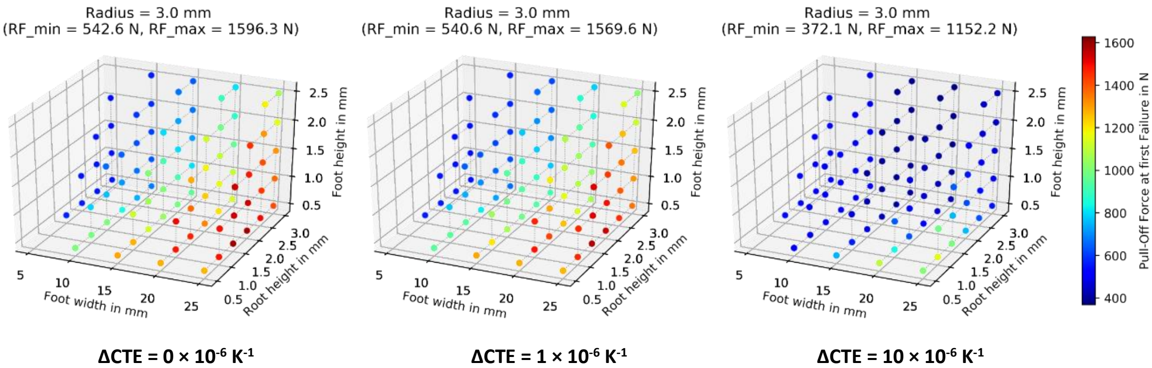


Figure 5. Results of the parametric study on rib foot dimensions with varied differential thermal stresses between rib and insert.

As can be seen in figure 5, thermal stresses very much influence the apparent joint strength, as CTE differences in the range of 1×10^{-6} K^{-1} to 10×10^{-6} K^{-1} are considered realistic for the studied material system. It seems that this particular value range is the transition region towards significant effects.

5 Experimental validation

From the parametric studies one geometry is selected for experimental validation. An injection mould is built for manufacturing single-rib-coupons. Coupons are manufactured using varied processing parameters in an automated one-step overmoulding process. Final processing parameters are mould temperature: 210 °C, IR preheating temperature laminate: 400°C, melt temperature: 400 °C. Before processing the laminates are dried in a convection oven for 3 hours at 200°C. Similar to those used for calibration of the model, shorter (30 mm long) sections are cut from the single-rib-coupon and tested accordingly in rib-pull-off-configuration as depicted in figure 6.

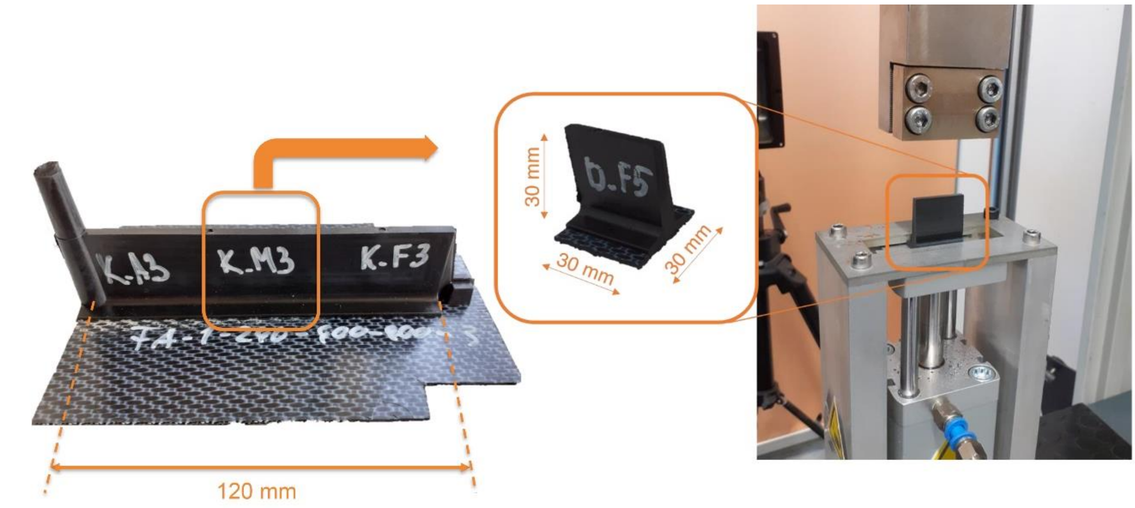


Figure 6. Single-rib-coupon with selected rib foot geometry for validation of model prediction through rib-pull-off tests.

From the recorded force-displacement data the maximum value before the first drop in force of more than 10 % is considered as the maximum bearable load without failure. From the different processing conditions, the highest average maximum force value is 2967 N. Other configurations lead lower values, often accompanied by visible quality issues. As the simulation does not assume any defects, the highest average experimentally determined value of 2967 N is considered as most suitable for comparison with the model predictions. Therefore, the maximum force value is divided by the interface area of 600 mm², resulting in 4.95 MPa.

A re-run of the pull-off-test model from the parametric study is performed, but now with interface failure progression being active. There, failure is predicted to occur at 2524 N for a 25 mm long section of the coupon. Dividing that by the interface area of 500 mm² results in an apparent joint strength of 5.05 N. Although this is a first result and other geometries are to be manufactured with optimised processing parameters and tested, the agreement of prediction and test within 2% difference provides confidence into validity of the approach.

6 Conclusion

The present study quantifies the apparent joint strength of ribs overmoulded onto continuous fibre-reinforced composite laminates as a function of the rib foot geometry. Furthermore, the effects of assumptions for boundary conditions and residual stresses are investigated. Although the study is mainly based on a simulation model, a first experimental validation with one specific rib foot geometry indicates excellent agreement of the model and reality. It is shown that there is not a single optimum rib foot shape. In fact, it depends very much on the load case, the boundary conditions and manufacturing-related residual stresses. Consequently, all these factors should be taken into account when designing overmoulded structural components, not only, but particularly for PAEK-based aircraft applications. In a future work, such optimisation could be coupled to more elaborated predictions of residual stresses, e. g. obtained from numerical processing simulations.

References

[1] R. R. Gaitzsch, M. Koerdt, H. Bertling, S. Scholl, T. Schäfer and A. S. Herrmann "Characterisation of bond strength in overmoulded high-performance thermoplastic composites". *Proceedings of ICCM22*, Melbourne, Australia, VIC: Engineers Australia, **2019**, pp 3675-3686.
[2] Toray Advanced Composites "Toray Cetex TC1225 ® Product Data Sheet", **2020**
[3] Victrex PLC "VICTREX® PEEK 90HMF40 Technical Data Sheet", **2014**
[4] LANXESS Deutschland GmbH "LANXESS Tepex® Fibel", **2017**
[5] S. Hummel; L. Knorr; P. Karlinger; M. Schemme *Kunststoffe*, **2017**, vol. 07, pp 42-46

Hybrid Components realised by Additive Manufacturing of Metallic Inserts and Fibre Reinforced Plastics Processing Technologies

M. Ley[1*], A. Al-Zuhairi[1], T. Rupp[1], V. Nagaraj[2], T. Pfaff[2], M. Werling[3], N. Motsch[2], R. Teutsch[1]

[1] Institute for Mechanical and Automotive Design (iMAD), TU Kaiserslautern (TUK), Germany;
[2] Leibniz-Institut für Verbundwerkstoffe GmbH (IVW), Kaiserslautern, Germany;
[3] mawe presstec GmbH, Hatzenbühl, Germany;
*ley@mv.uni-kl.de

Hybridisation is a major topic in mechanical engineering due to the limitations of individual technologies. Drawbacks are substituted and benefits enhanced by the combination of different technologies. Furthermore, hybridisation serves as a bridging technology till a single technology is fully developed. Hence, various types of hybridisation can be found in literature, like processes [1], machines [2], materials and structures [3,4].
According to the definition and classification in [5], the integration of an additively manufactured (AM) metallic insert while fibre reinforced plastic processing is a hybrid component in terms of the material as well as manufacturing process. To face the challenges of different material characteristics, like stiffness, and the bonding in between the two material classes the characteristics resulting from the additive manufacturing and its post processing are analysed. At the same time the requirements of fibre reinforced plastic processing technologies need to be considered. Both is done by the help of methodical, simulative and experimental approaches. In a first step AM "thin"-metal parts were bonded with woven carbon fibre by vacuum assisted resin transfer moulding and tested for tensile-shear performance (Fig. 1). This is the starting point to develop more complex, load adapted metallic inserts.

Figure 1. Left: Adapted VARTM mould, Middle: Tensile-shear specimens, Right: Tensile-shear testing.

Due to the novelty and variability of AM, design engineers need to be supported even more. This can be done by sufficiently provided design guidelines [5]. The results of the simulations and experiments mentioned above will serve to develop this kind of guidelines.

References

[1] B. Lauwers et al. Hybrid processes in manufacturing. *CIRP Ann Manuf Technol* 2014; *63(2)*:561-583.
[2] M. Cortina et al. Latest Developments in Industrial Hybrid Machine Tools that Combine Additive and Subtractive Operations. *Materials* 2018;*11*:2583.
[3] M. P. Sealy et al. Hybrid Processes in Additive Manufacturing. *J Manuf Scie E-T ASME* 2018;*140(6)*:060801.
[4] D. Lehmhus et al. New Materials and Processes for Transport Applications: Going Hybrid and Beyond. *Adv Eng Mater* 2019;*21*:1900056.
[5] M. Ley, A. Al-Zuhairi, R. Teutsch. Classification Approach for Hybrid Components in Mechanical Engineering with a Focus on Additive Manufacturing. *Procedia CIRP* 2021;*10*:738-743.

Virtual Design and physical validation of a graded CFRP-Titanium-structure at the example of a lightweight strut for aircraft applications

M. Birke[1*], J. Luft[1], S. Spitzer[1], R. Gottwald[1], M. Gude[1]
[1] Technische Universität Dresden, [2] Action Composite Technology Limited
*michael.birke@tu-dresden.de

Especially in aerospace applications, the right material substitutions in the right places can significantly increase performance and reduce environmental impact and costs through lower kerosene consumption. Using the example of large monolithic high-performance structures, such as tension-compression struts in the landing gear area, novel fiber composite-based hybrid designs were developed [1].
Such hybrid designs increase the complexity of the development process, so that compared to conventional designs, anisotropic material properties, material interfaces and other resulting parameters must be taken into account. Multi-axial loads in conjunction with anisotropic material behavior lead to a correspondingly demanding task for the stress-appropriate design. In addition, there is no known procedure and little experience for the development of such hybrid designs.

The paper shows that the use of high-strength carbon fibers in combination with titanium leads to efficient lightweight hybrid structures through graded material transitions [cf. 2], load-oriented functional separations and optimized load introduction areas. The systematically structured development process is characterized by the networking of virtual and physical methods.

The authors present a methodical construction method using the example of a highly loaded tension-compression strut. At the concept level, partial solutions are synthesized from known ones, such as fiber composite loops for tensile force transmission [3] and compression supports for compressive force transmission, supported by a numerical evaluation (Figure 1, left side). The design detailing of the preferred variant is carried out in further in-depth comprehensive FE calculations. In addition, the use of shape optimization methods further increases the lightweight quality of the structure.
At the same time, material and structural properties are determined at coupon level (e.g. titanium-CFRP interface) and partial concept validations are carried out on the basis of substructure tests. The findings obtained from these tests provide information and are used directly in concept development and detailing (Figure 1, right side).

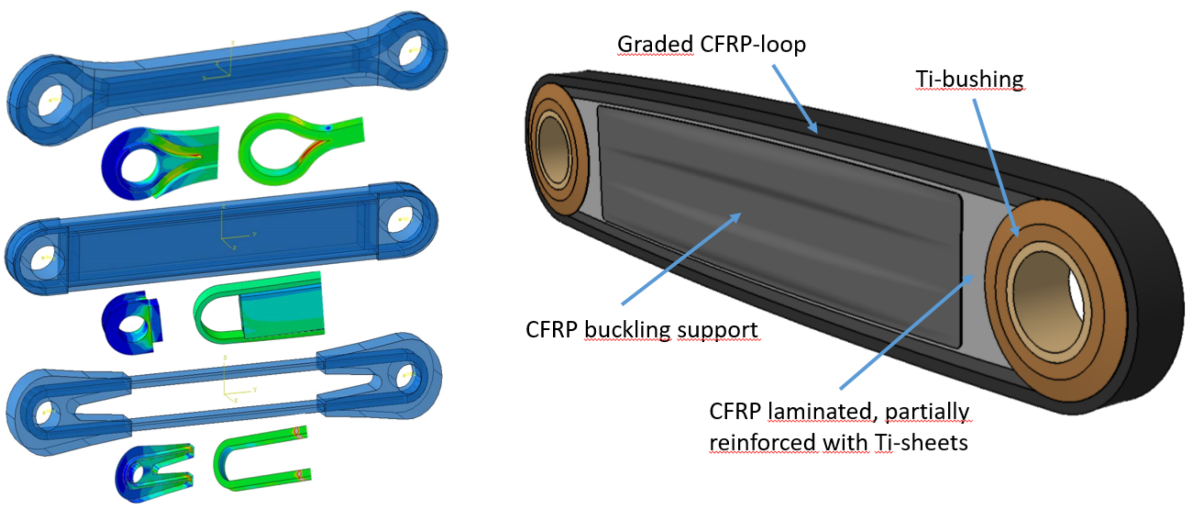


Figure 1. left: FEM-assisted concepts, right: detailed concept for a lightweight strut at the example of a lower drag brace (modified after [1])

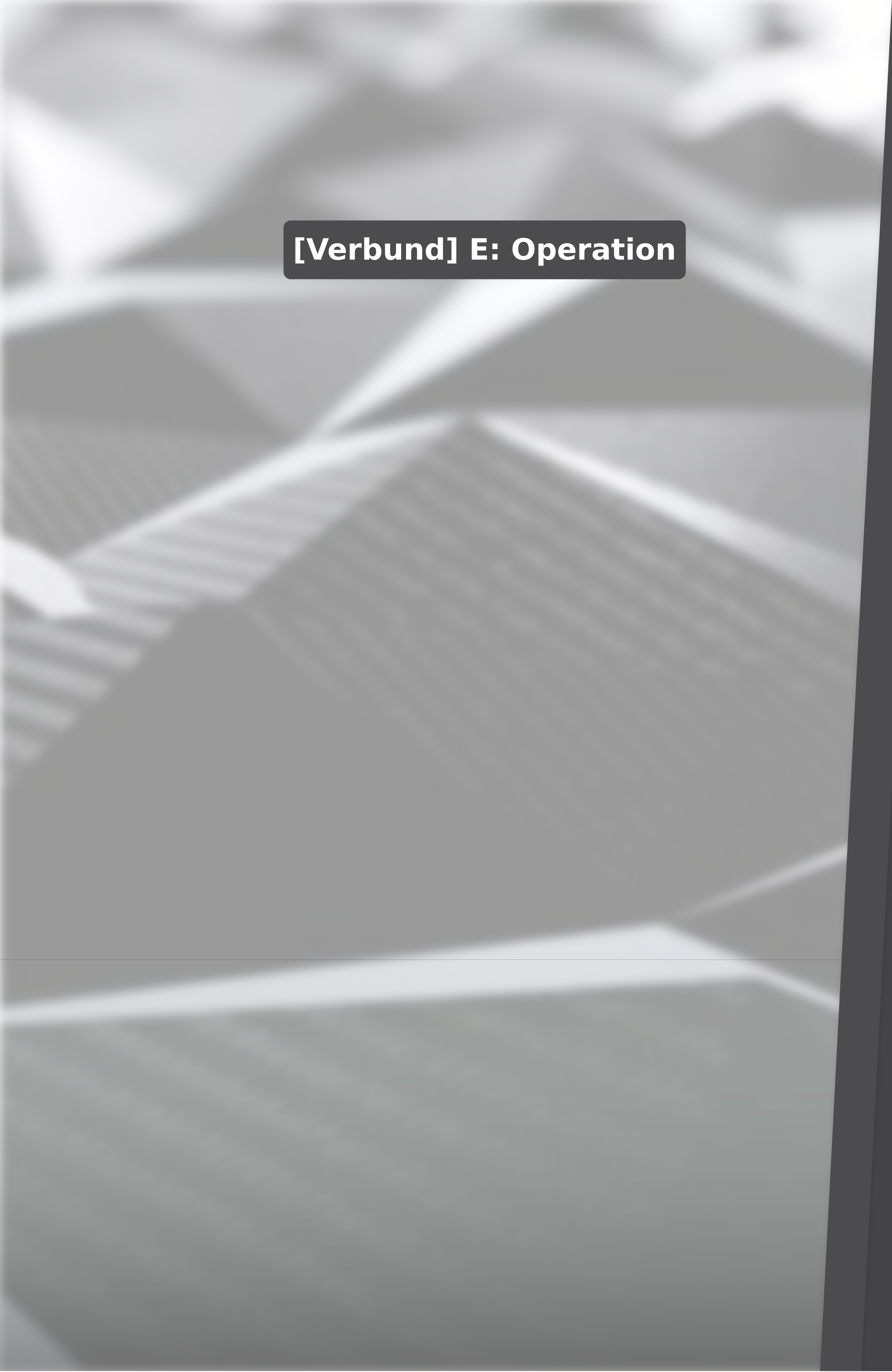
Taking into account the use of established aerospace technologies and with the knowledge gained from coupon and substructure manufacturing, a suitable manufacturing process is developed. This is used to physically implement the developed concept for tension-compression struts as scaled testable structures (Figure 2, left and middle). These are loaded in static-mechanical tests up to test forces analogous to ultimate load. The test structures are monitored in tension and compression tests by optical strain measurement. Furthermore, after loading, the structures are subjected to non-destructive testing using CT to analyze any damage that has occurred and to assess the structural integrity that still exists (Figure 2, right).

Figure2. left: infiltrated CFRP-Ti structure in the RTM mold, middle: final scaled drag brace, right: CT picture of a tested specimen (modified after [1])

The work presented focuses on the methodical procedure for developing high-performance tension-compression struts in CFRP-Ti hybrid design using the example of an aerospace structure. In order to achieve the highest performance, the load and boundary conditions for the particular application are of decisive importance and must be taken into account individually for the material and structural design. For the fundamental approach to the development of struts in hybrid construction, the present presentation is intended to make a significant contribution to improved understanding in the design finding process.

Acknowledgment
The project on which this work is based was funded by the German Federal Ministry for Economic Affairs and Energy under the funding code 20Y1505B. The authors are responsible for the content of this publication.

References
[1] M. Gude et. al.: *Joint project FAWIBO: landing gear system for wide-body aircraft of the next generation: subproject: development of a modular design methodology for hybrid stuctures in highly loaded landing gear components*. Abschlussbericht, **2020**
[2] B. Kolesnikov; L. Herbeck; A. Fink: *Fortschrittliche Verbindungstechniken von Faserverbundwerkstoffen. Institut für Strukturmechanik des DLR*, Braunschweig, **2004**
[3] H. Schürmann: *Konstruieren mit Faser-Kunststoff-Verbunden*. Deutschland: Springer, **2007**



[Verbund] E: Operation

Fatigue and fracture of ultrasonically welded aluminium alloys to carbon fiber reinforced thermoplastics

F. Balle[1,2,3*], F. Staab[1]

[1] Walter-and-Ingeborg-Herrmann-Chair for Power Ultrasonics and Engineering of Functional Materials (EFM), Department of Sustainable Systems Engineering (INATECH), Faculty of Engineering, University of Freiburg, Freiburg i. Br. (Germany), [2] Freiburg Materials Research Center (FMF), Freiburg i. Br. (Germany), [3] Fraunhofer-Institute for High-Speed Dynamics (EMI), Freiburg i. Br. (Germany)

*efm@inatech.uni-freiburg.de

The paper covers the fatigue behavior of ultrasonically welded aluminum (AA5024) to fiber reinforced thermoplastic (CF-PEEK) joints at a stress ratio of R>0 [1]. Ultrasonic metal weld-ing itself is a sustainable technology for joining light metals with fiber reinforced plastics (FRP) to hybrid engineering structures [2]. This low-temperature joining technique permits an efficient design of multi-material structures, offering superior mechanical properties while maintaining the material's lightweight potential [3, 4]. Besides promising monotonic properties also the cyclic deformation behavior of welded hybrid joints are of high relevance for future applications. So first, initial so called load increase tests were carried out and, based on a de-tected material reaction caused by fa-tigue damage, the load horizon for subsequent constant amplitude tests was derived. After identifying characteristic stress levels, microscopic investi-gations of hybrid fracture surfaces were carried out. For a fatigue limit of 2 mil-lion loading cycles, the applied maximum force corresponds to 35% of the maximum lap shear force for monotonic testing. The findings were confirmed by supplementary experiments at higher test-ing frequency. In addition to this, an interpretation of the stiffness degradation of the hybrid joints under cyclic loading over the lifetime took place. A drop in stiffness to 88% close to failure was observed. Here, two significantly different degradation mechanisms could be identified and their differences could be assigned microstructurally. A pronounced decrease in joint stiffness was observed, which can serve as an indication of progressive dam-age for later application and maintenance criteria. Finally, the fracture surfaces of both the metallic and the polymeric joining partner were evaluated and a distinctive fatigue failure mechanism was identified. In addition, striking differences compared to the failure pattern under monotonic load have been determined and will also be discussed at the conference.

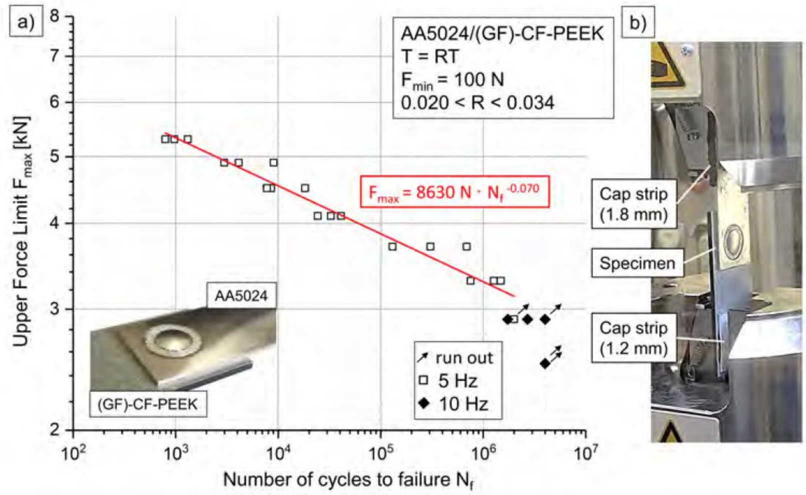


Figure 1. a) S-N-curve of ultrasonically welded AA5024/(GF)-CF-PEEK joints; b) Experimental setup, acc. to [1]

References

[1] F. Staab, F. Balle, *Fatigue and Fracture of Engineering Materials and Structures*, **2022**, 45
[2] F. Lambiase, F. Balle, L. Blaga, F. Liu, S. Amancio-Filho, *Composite Structures*, **2021**, 266, 113828
[3] F. Staab, F. Balle, *Ultrasonics*, **2019**, 93, p. 139-144
[4] F. Staab, M. Liesegang, F. Balle, *Composite Structures*, **2020**, 248, 112481

Authors

IMPRINT – IMPRESSUM
5th Hybrid Materials and Structures 2022 - International Conference on Hybrid Materials
Editor: Prof. Dr. Joachim M. Hausmann, Leibniz-Institut für Verbundwerkstoffe GmbH

Postanschrift:
DGM - Deutsche Gesellschaft für Materialkunde e.V.
Marie-Curie-Straße 11-17
53757 Sankt Augustin

T +49 (0) 69 75306 750
F +49 (0) 69 75306 733
E-Mail: dgm@dgm.de
Web: www.dgm.de

ISBN 978-3-88355-426-6