Materials Research Proceedings **25** (2023) 117-124 https://doi.org/10.21741/9781644902417-15

Influence of geometrical parameters of conic pin structures in thermoplastic composite/steel hybrid joining

Julian Popp[1, a *], Christoph Zirngibl[2,b], Benjamin Schleich[3,c], Sandro Wartzack[2,d] and Dietmar Drummer [1,e]

[1]Chair of Polymer Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Am Weichselgarten 10, 91058 Erlangen, Germany

[2]Engineering Design (KTmfk), Friedrich-Alexander-Universität Erlangen-Nürnberg, Martensstraße 9, 91058 Erlangen, Germany

[3]Product Life Cycle Management, Technical University of Darmstadt, Otto-Bernd Straße 2, 64287 Darmstadt, Germany

[a]julian.georg.popp@fau.de, [b]zirngibl@mfk.fau.de, [c]schleich@plcm.tu-darmstadt.de, [d]wartzack@mfk.fau.de, [e]dietmar.drummer@fau.de

Keywords: Composite, Joining, Hybrid Manufacturing

Abstract. Hybrid parts consisting of continuous fiber reinforced thermoplastic (CFRT) and steel components offer promising potential in lightweight construction. In this approach, the joining operation poses the major challenge due to different physical and chemical properties of both materials. This paper studies a joining method in which conical pin structures, protruding from the surface of the metal component, are inserted into the locally heated CFRT component to create a form fitting joint. The aim is to identify and quantify the influence of the parameters pin height and pin head diameter on the mechanical performance in single lab shear and cross head normal experiments. Based on the results it can be shown, that both an increased pin height and head diameter are beneficial under shear load in means of increased maximum load capacity while under normal load only an increased head diameter has clear benefits. Those effects are led back to the geometrical properties and the resulting stress distributions in the joining area.

Introduction

Lightweight construction is a widely applied approach in the transportation sector to achieve reductions in fuel consumption and consequent CO2 emissions. Thereby, a substitution of classic engineering materials, such as steel and aluminum alloys, with materials with superior weight related properties, such as fiber-reinforced polymers, is a common strategy to achieve substantial weight savings [1]. Thereby especially continuous fiber reinforced thermoplastics (CFRT) combine favorable weight related properties [2] with good processability and uncomplicated handling with unlimited shelf-live [3] and allow for functional integration through polymer welding and injection molding processes [4].

Despite these obvious advantages, CFRTs reach limitations under elevated temperatures in which the matrix begins to soften or melt and thus reduces the mechanical stability of the composite. Furthermore, under certain conditions like high abrasive wear [5] or under the influence of solvents and aggressive media CFRTs can be unsuitable. An approach to address these limitations is the use of intelligent hybrid structures where the lightweight CFRT component is combined with a metal component where the application exceeds the capabilities of the CFRT material. Thereby, the main challenge lies in a durable and cost-efficient joining technology [6]. Due to chemical incompatibilities, established joining methods like welding or brazing are not applicable [7] and while adhesive bonding is theoretically suitable and also leads to a fiber friendly force application into the composite, it oftentimes requires long curing cycles and specific surface pre-treatments [8]. Especially unpolar polymers with low surface energy, like polypropylene (PP) require elaborate surface modifications via e.g. plasma treatment to be adhesively joinable [9].

In the current industrial state of the art, typically mechanical joining via bolts or rivets is applied. Consequently, these joining methods are very well described in the literature and can be used to create durable joints [10]. However, these joining methods also come with disadvantages: first, an auxiliary element is needed which increases weight and costs of the structure. Second, a hole forming operation is required, which typically increases the process time and when realized via subtractive manufacturing, leads do destruction of load bearing fibers resulting in locally increased concentration of forces and weakens the composite. Consequently, a demand for a cost efficient, versatile and durable technology for joining CFRTs with metals is required.

A relatively new joining approach is the use of pin structures, that can be embedded into the locally heated CFRT composite as it is shown in [11] with cold formed pin structures while the fiber rearrange around the pin structures and thus avoids fiber breakage [12]. Other manufacturing technologies for pin structures are powder bed fusion [13], metal injection moulding [14], [15], and cold metal transfer welding (CMT) [16], [17]. Fig. 1 shows an example of a pin joint.

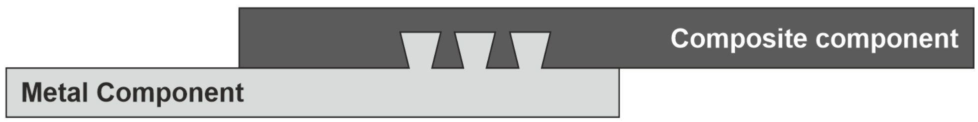

Fig. 1 Example of pin joint with pins embedded in composite component

The influence of the pin geometry on the joint characteristics has been investigated in several studies: In [12] the influence of different pin diameters and pin tip shapes on the fiber displacement and in [18] on the mechanical performance under shear load has been investigated, while the pins, due to a lack of an undercut failed through pin extraction. In [19] it could be shown that a joining with undercutting, conical pins is possible leading to good joint strengths under shear and especially normal load when compared to cylindrical reference pins. Thereby, the pins have been manufactured via a subtractive manufacturing process. That a manufacturing of undercutting, conical pin shapes is also possible via a cold forming processes could be shown in [20] which makes the conic pin shape a promising pin shape that combines good mechanical properties with easy manufacturing via cold forming.

Despite the above-described findings, a systematic and statistical investigation of different parameters of a conic pin shape and its influence on the joint characteristics has not yet been presented. Consequently, this study aims at creating an understanding of the influence of the parameters pin height and pin head diameter of conic shaped steep pins on the mechanical performance under shear and normal load of a CFRT-metal hybrid joint.

Material and Methods

Materials. The used CFRT material is a custom fabricated biaxial composite with an E-glass fiber reinforcement and a PP matrix. The matrix type is a BJ100HP from Borealis AG (Vienna, Austria) which is a special low-viscosity compound specifically for glass fiber reinforced applications. As glass fiber component a biaxial non crimp fabric from Saertex GmbH (Saerbeck, Germany) with an areal weight of 307 g/m^2 in 0° and 90° respectively and an aramide sewing thread with an aerial weight of 9 g/m^2 resulting in a total areal weight of 623 g/m^2. Thereby, the titer of both the 0° and 90° rovings is relatively low with 300 tex. The resulting thickness of the composite is 2 mm +/- 0.05 mm with a calculated fiber volume content of approximately 45 %. As a sheet metal a HCT590X steel type has been used. In order to be able to investigate a large variation of geometries the pins have been manufactured on a CNC lathe from a 42CrMo4 steel round. Subsequent of the turning process the pin structures have been joined with the steel component via welding. In future serial manufacturing, it is planned to manufacture the pins via cold forming as it is described in [20].

Definition of pin and sample geometry. In the scope of this study, two geometry parameters of the conical pin have been varied. First, the pin height *h* is varied between 1.7, 1.8 and 1.9 mm. Second the pin head diameter *D* is varied between 1.4, 1.5 and 1.6 mm. These parameters have been fully factorially combined for a total of nine combinations. Furthermore, pins with head diameter of 1.7 and 1.8 mm and a height of 1.8 have been manufactured, to determine, if a limitation of the head diameter is given above which adverse effects on the fiber reorientation occur that negatively impact the mechanical performance of the joint. The pin foot diameter *d* is constant at 1.25 mm as in previous studies, it's effect on the shear strength of the sample has already been investigated [21]. In total, eleven different pin geometries with a sample size of three have been investigated (compare Fig. 2 A and Table 1).

Table 1 Summary of investigated geometries

Name	*D* [mm]	*h* [mm]	*d* [mm]
D14_h17_d125	1.4	1.7	1.25
D14_h18_d125	1.4	1.8	1.25
D14_h19_d125	1.4	1.9	1.25
D15_h17_d125	1.5	1.7	1.25
D15_h18_d125	1.5	1.8	1.25
D15_h19_d125	1.5	1.9	1.25
D16_h17_d125	1.6	1.7	1.25
D16_h18_d125	1.6	1.8	1.25
D16_h19_d125	1.6	1.9	1.25
D17_h18_d125	1.7	1.8	1.25
D18_h18_d125	1.8	1.8	1.25

As samples single lap shear and cross head samples have been manufactured in order to investigate load capacity under both shear and normal loads. The samples are according to the technical bulletin DVS EFB 3480-1 and the sample dimension can be seen in Fig. 2 section B&C. The lap shear specimens have a length of 105 mm and the joining point is located 8 mm from the short edge of the sample, resulting in an overlap of 16 mm (compare Fig. 2 B). The width of the samples is 45 mm and the resulting length of the joined sample is 194 mm. The cross head specimens have a length of 150 mm and a width of 50 mm with clamping holes with a diameter of 20 mm placed symmetrically with a spacing of 100 mm (compare Fig. 2 C).

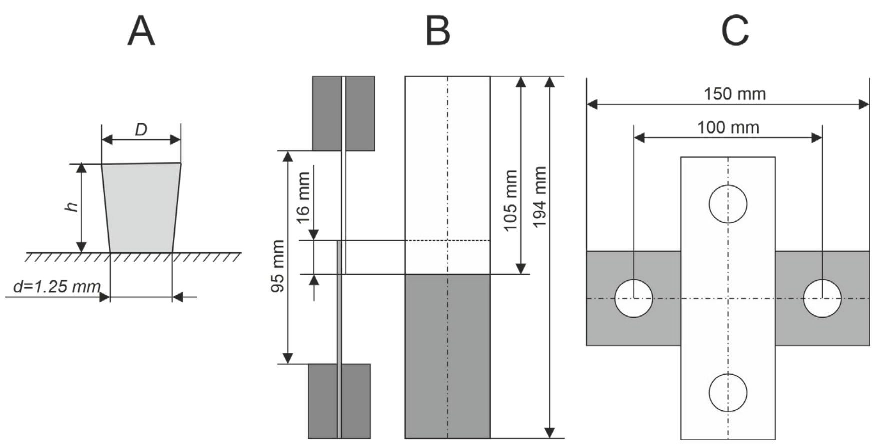

Fig. 2 Pin geometry and sample dimensions

Joining process. The samples have been joined on a custom multi-functional polymer welding machine manufactured by KLN Ultraschall AG (Heppenheim, Germany) using short wave infrared radiation emitted from an infrared spot from Optron GmbH (Garbsen, Germany). In order to define the irradiated area, a mask with a cylindrical opening with a diameter of 8 mm has been used. The heating parameters have been identified in pre trials to a power setting of 67.5 Watts and a heating time of 210 s. Thereby, special attention has been paid on avoiding overheating of the sample surface while ensuring a complete melting of the matrix through the thickness of the sample. After preheating the samples were joined with the pin being pressed into the CFRT concentrically with the radiated zone. The joining force is 3,000 N after which a consolidation and cooling phase of 30 s follows with applied pressure. Finally, the sample Is removed from the tool.

Mechnical characterization. The samples are tested on a universal testing machine type Z 1465 from Zwick&Roell AG (Ulm Germany) according to DVS EFB 3480-1 with a testing speed of 1 mm/min. Prior to testing, the samples are stored in normalized climate according to DIN EN ISO 139 of 23 °C and humidity 50 rel. %. For the lap shear test, the extension was measured via tactile extensometer with an initial measurement length of 50 mm. For the cross head test, the extension was measured via the machine traverse.

Results

When investigating the results from the single lap shear tests, it can be seen, that the maximum load capacity ranges between 325 ± 28.2 N and 448.7 ± 36.8 while the load capacity under normal load is lies significantly lower between 36.6 ± 3.9 N and 80.6 ± 8.0 N (compare Fig. 2 and Table 2). It is noticeable, that the standard deviation, especially for normal load results is comparably high and frequently exceeds 35 % of the base value. The highest individual measurements are 489 N (shear load) and 121 N (normal load) and can be interpreted as maximum achievable load capacities with single pin joints. Both measurements used a pin with a head diameter of 1.6 mm while the height is 1.8 mm (shear load) and 1.7 mm (normal load). Table 2 and Fig. 3 give an overview over the results. The failure mode for single lap shear specimens generally initially is a bearing failure of the CFRT component which is accompanied with a slight bending of the pin. One exception is a pin with D=1.7 mm and h=1.8 mm failed due to pin breakage at a force of 412N. A pin extraction like with non-undercutting structures [18] could not be observed. Under normal load, the samples failed due to elastic and plastic deformation of the CFRT component and subsequent pin extraction without pin deformation. It must be noted that of pins with a head diameter of 1.5 mm and height of 1.9 mm, only two lap shear and cross head samples could be tested because the pin structures were damage during the pin welding process.

*Table 2 Summary of single lap shear and normal tests; * indicates sample size of only 2*

Name	F max, shear [N]	F max, normal [N]
D14_h17_d125	346.7 ± 40.8	45.9 ± 12.4
D14_h18_d125	325.0 ± 28.2	36.6 ± 3.9
D14_h19_d125	394.3 ± 63.3	41.8 ± 8.2
D15_h17_d125	339.7 ± 58.7	61.2 ± 8.2
D15_h18_d125	416.7 ± 22.4	47.6 ± 18.5
D15_h19_d125	416.5 ± 38.5*	49.9 ± 7.9*
D16_h17_d125	350.7 ± 55.7	73.3 ± 33.9
D16_h18_d125	448.7 ± 36.8	72.0 ± 29.2
D16_h19_d125	422.0 ± 32.1	63.5 ± 22.6
D17_h18_d125	404.3 ± 61.2	53.9 ± 16.6
D18_h18_d125	410.3 ± 31.8	80.6 ± 8.0

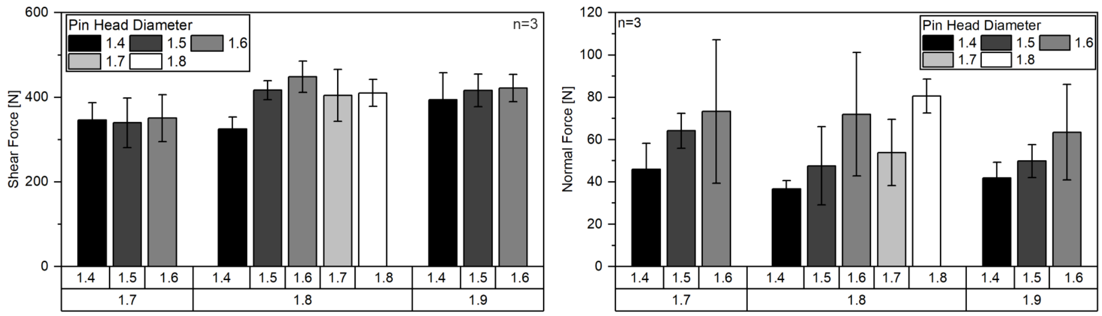

Fig. 3 Maximum shear (left) and normal (right) loads for different pin height and head diameter

Two different approaches can be used to explain the high standard deviation under normal load: first, the CFRT component on a macro scale is inhomogeneous with compact fiber rovings and matrix pockets (compare Fig. 4). Depending on the relative position, in which the pin is pressed into the composite, different joint morphologies can occur which are expected to influence the mechanical properties of the joint. Second, the manufacturing of the pin structures is complex and the repeatability is limited. A number of pins show residues of the welding process which partially fill the undercut of the pin structures presumably negatively influencing the joint properties. Fig. 3, right shows an example with very large welding residues. Typically, when residues could be observed, the phenomenon was less pronounced than it is shown in this image. In future Studies, it is planned to replace the combined turning and welding process with a two-step pin forming and caulking process, similar as it is shown in [22], which is expected to solve the repeatability issues.

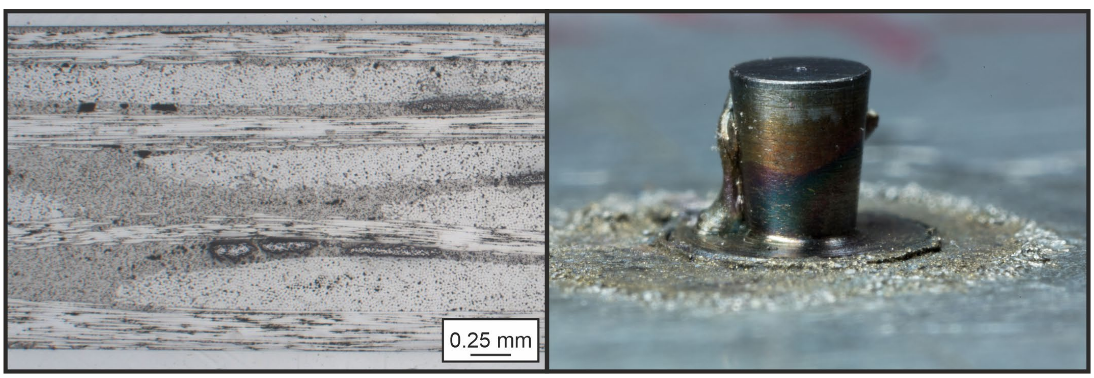

Fig. 4 Microsection of undisturbed CFRT laminate (left) and photography of welded pin structure with large welding residues (right)

When comparing the results with a study, in which cold extruded pins are used [20], the standard deviation with cold formed pins is significantly lower which in part is led back to the high repeatability of the cold forming process. In [21] undercutting pin geometries where joined with unidirectionally reinforced CFRT components. When comparing the results of pins with a head diameter of 1.25 mm and a hight of 1.8 mm, the results in [21] are lower with 347 ± 57.4 N in comparison to 416.7 ± 22.4 N under shear and load and higher with 85.2 ± 5.6 N in comparison to 47.6 ± 18.5 N und normal load. In [21] the shear samples failed due brittle breakage of the pin which explains the comparable high standard deviation and the reduced load capacity while the normal load samples have a comparably low standard deviation. Since in this study, no welding residues could be detected, this is seen as the reason for higher repeatability. The increased load capacity in [21] however, can be caused by the different CFRT material which potentially is more suitable under normal loads.

Statistical analysis using Pearson's correlation coefficients. For the statistical analysis of the results, the calculation of Pearson's correlation coefficients (r) provide the opportunity to investigate the linear relationships between input and target variables and thus gain a deeper understanding of the joining process. Furthermore, the results offer an evaluation of which parameter variations indicate to have a significant effect on individual quality-relevant joint properties and which are less important. In this context, an r-value of -1 implies a strongly negative correlation at which the increase of one parameter results in the decrease of another parameter. In contrast, an r-value of +1 means a strong positive correlation and can be interpreted that the change in one parameter leads to a change of the other parameter in the identical direction. An r-value of 0 indicates that there is no relationship between the input and target variables. [30] As an overview, Fig. 5 shows the calculated Pearson's correlation coefficients.

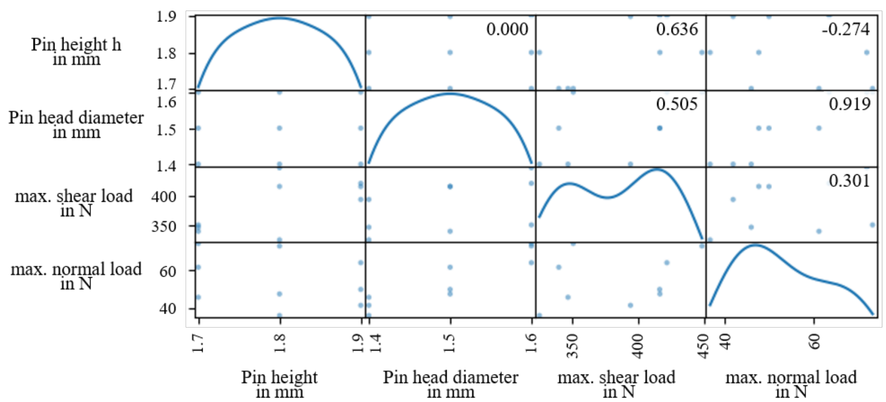

Fig. 5 Overview of the calculated Pearson's correlation coefficients

Focusing on the maximum shear load capacity, one can see that both input parameters show a positive correlation ($r = 0.505$ and $r = 0.636$) where the pin height tends to have a slightly stronger impact on the target variable. In this context, the increase of the pin height and to a lesser degree also of the pin head diameter result in an increase of the projection area of the pin structure. The increased projection area consequently leads to a decrease of the contact pressure between pin and CFRT laminate at a given load leading to a higher load capacity of the joint. In contrast, the Pearson's correlation coefficients of the maximum normal load capacity indicate a very strong positive linear relationship ($r = +0.919$) between the pin head diameter and the output variable. This bases on the increased necessary deformation in the CFRT component during the pin extraction with a larger pin head diameter in comparison to a smaller head diameter. This increased deformation leads to larger contact pressure between CFRT and pin flanks which due to the incline of the pin flank results in a counter force which is consequently measured as the load capacity. Compared to this effect, changes in the pin height result only in a weak modification of the resulting maximum normal load capacity showing a negative correlation value of -0.274. In summary, if the increase of both target variables is targeted, the selection of generally higher values of the pin head diameter is recommended.

Summary

In the present study, it could be shown that conical pins are suitable to create joints with biaxial CFRT sheets that can be loaded under both shear and normal load. Maximum load capacities for single pins were 489 N under shear and 121 N under normal load while maximum average values were 448.7 N (shear) and 80.6 N (normal) for series of 3 samples.

The high standard deviations in the measurments are explained with the morphology of the CFRT sample as well as the manufacturing process of the pin sample. It is expected, that with cold formed pins, the joining process will be more repeatable. The calculation of Pearson's correlation coefficients indicated a high impact of the selected pin head diameter on both the maximum achievable shear and normal load. An increase of this parameter leads to a larger contact zone with reduced contact pressure and thus to an increased load capacity. In contrast to this, the correlation indices of the pin height showed a positive effect on the shear load while simultaneously leading to slightly decreased maximum normal loads. Based on this, it is recommended to choose rather higher pin head diameters instead of a changed pin height. However, the parameter selections have to be in accordance with the permissible pin manufacturing and joining process limits.

In future studies, it is planned to investigate cold formed, undercutting pin structures where an increase in the load capacity under shear load is expected due to work hardening effects as well as an decrease of the standard deviation, due to the more repeatable forming process, is expected especially under normal loads. Furthermore, multi-pin arrays have to be investigated, both to increase the overall joint strength as well as to average effects of the inhomogeneous CFRT component which presumably leads to further increased repeatability. Finally, the findings of this study should also be verified for other material systems such as quasi-isotropic and unidirectional reinforcements as well as other reinforcement fibers, such as carbon or aramid fibers and for other mechanical tests, such as peel tests, to increase the overall understanding on this particular joining technique.

Fundings

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German ResearchFoundation)-TRR 285 C01-Project-ID 418701707.

References

[1] W. Siebenpfeiffer, Leichtbau-Technologien im Automobilbau, ATZ/MTZ-Fachbuch, SpringerVieweg, 2014. https://doi.org/10.1007/978-3-658-04025-3

[2] B.D. Agarwal, L.J. Broutman, K. Chandrashekhara, Analysis and Performance of Fiber Composites. 4th Edition, John Wiley & Sons, Inc., Hoboken, 2017.

[3] M. Sommer, K. Edelmann, A. Wöginger, M. Christmann, J. Mack, L. Medina, Thermoplastische Prepregs und Halbzeuge, in: M. Neitzel, P. Mitschang, U. Breuer, (Eds.), Handbuch Verbundwerkstoffe, Carl Hanser Verlag, Munich, 2014, pp. 147–199.

[4] A. Yousefpour, M. Hojjati, J.-P. Immarigeon, Fusion Bonding/Welding of Thermoplastic Composites. Journal of Thermoplastic Composite Materials 17 (2004) 303–341. https://doi.org/10.1177/0892705704045187

[5] N.-M. Barkoula, J. Karger-Kocsis, Effects of fibre content and relative fibre-orientation on the solid particle erosion of GF/PP composites, Wear 252 (2002) 80-87. https://doi.org/10.1016/S0043-1648(01)00855-9

[6] K. Martinsen, S.J. Hu, B.E. Carlson, Joining of dissimilar materials, CIRP annals – Manufacturing Technology 64 (2015) 696-699. https://doi.org/10.1016/j.cirp.2015.05.006

[7] Z. Dawai, Z. Qi, F. Xiaoguang, Z. Shengdung, Review on Joining Process of Carbon Fiber Reinforced Polymer and Metal: Methods and Joining Process, Rare Metal Materials and Engineering 47/12 (2018) 3686-3696. https://doi.org/10.1016/S1875-5372(19)30018-9

[8] H. Schürmann, Klebeverbindungen, in: H. Schürmann, Konstruieren mit Faser-Kunststoff-Verbunden, Springer Verlang, Berlin-Heidelberg, 2005, pp. 569-604. https://doi.org/10.1007/b137636

[9] W. Brockmann, Adhesive Bonding of Polypropylene, in: J. Karger-Kocsis, Polypropylene: An A-Z Reference, Kluwer, London, 1999, pp. 1-6. https://doi.org/10.1007/978-94-011-4421-6_1

[10] P. Mitschang, R. Velthuis, R. Rudolf, Fügeverfahren für FKV, in: Neitzel M., Mitschang P., Handbuch Verbundwerkstoffe, 2nd Edition, Carl Hanser, Munich-Vienna, 2014. pp. 469-482. https://doi.org/10.3139/9783446436978.015

[11] M. Kraus, P. Frey, T. Kleffe, D Drummer, M. Merklein, Mechnical joining without auxiliary element by cold formed pins for multi-material-systems, AIP Converence Proceedings 2113, 2019. https://doi.org/10.1063/1.5112570

[12] J. Popp, T. Kleffel, D. Römisch, T. Papke, M. Merklein, D. Drummer, Fiber orientation Mechanism of Continuous Fiber Reinforced Thermoplastic Hybrid Parts Joined with Metallic Pins, Applied Composite Materials 28 (2021) 951-972. https://doi.org/10.1007/s10443-021-09892-0

[13] R. Plettke, A. Schaub, C. Gröschel, C. Scheitler, M. Vetter, O. Hentschel, F. Ranft, M. Merklein, M. Schmidt, D. Drummer, A new process chain for joining sheet metal to fiber composite sheets, Key engineering material 611-612 (2014) 1468-1475. https://doi.org/10.4028/www.scientific.net/KEM.611-612.1468

[14] E.E. Feistauer, S.T. Amancio-Filho, Ultrasonic joining of Lightweight Alloy/Fiber-Reinforced Polymer Hybrid Structures, Joining of Polymer-Metal Hybrid Structures: Principles and Applications, (2018) 307-333. https://doi.org/10.1002/9781119429807.ch11

[15] E.E. Feistauer, E. Ebel, J.M. Santos, S.T. Amancio-Filho, Ultrasonic joining of through-the-thickness reinforced Ti-4 Al-6 V and polyetherimide hybrid joints, Society of Plastics Engineers: SPE ANTEC Anaheim (2017) 1718-1724.

[16] S. Ucsnik, M. Scheerer, S. Zaremba, D.H. Pahr, Experimental investigation of a novel hybrid metal-composite joining technology, Composites Part A 41 (2010) 369-374. https://doi.org/10.1016/j.compositesa.2009.11.003

[17] R. Thakkar, S. Ucsnik, Cost Efficient Metal to Fibre Composite Joining, 16th European Conference on Composite Materials (2014).

[18] J. Popp, T. Kleffel, D. Drummer, Influence of pin geometry on the joint strength of CFRT-metal hybrid parts with metallic pins, Joining plastics/Fügen von Kunststoffen 3 (2021) 177-183.

[19] J. Popp, D. Römisch, M. Merklein, D. Drummer, Joining of CFRT/Steel Hybrid Parts via Direct Pin Pressing of Cold Formed Non-Rotational Symmetric Pin Structures, Applied Sciences (2022) 12. https://doi.org/10.3390/app12104962

[20] D. Römisch, J. Popp, D. Drummer, M. Merklein, Joining of CFRT-steel hybrid parts via hole-forming and subsequent pin caulking, Production Engineering 16 (2022) 339-352. https://doi.org/10.1007/s11740-021-01093-9

[21] J. Popp, D. Drummer, Joining of continous fiber reinforced thermoplastic/steel hybrid parts via undercutting pin structures and infrared heating, Journal of advanced joining processes, 5, (2022). https://doi.org/10.1016/j.jajp.2021.100084

[22] R.J.S. Baptista, J.P.M. Pragana, I.M.F. Bragança, C.M.A. Silva, L.M. Alves, P.A.F. Martins: Joining aluminium profiles to composite sheets by additive manufacturing and forming, Journal of Materials Processing Technology 279 (2020). https://doi.org/10.1016/j.jmatprotec.2019.116587