INTRINSIC MANUFACTURE AND DESIGN OF POSITIVE LOCKING FIBRE REINFORCED THERMOPLASTIC METAL HOLLOW STRUCTURES

D. Barfuss[1], R. Grützner[2], C. Garthaus[1], M. Gude[1]

[1]Institute of lightweight Engineering and Polymer Technology, Technische Universität Dresden, Holbeinstr. 3, 01307 Dresden, Germany
Email: Daniel.barfuss@tu-dresden.de, Christian.garthaus@tu-dresden.de, maik.gude@tu-dresden.de
Web Page: http://www.tu-dresden.de/mw/ilk
[2]Fraunhofer-Institute for Machine Tools and Forming Technology, Reichenhainer Straße 88, 09126 Chemnitz, Germany
Email: raik.gruetzner@iwu.fraunhofer.de, Web Page: http://www.iwu.fraunhofer.de

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Abstract
In contrast to common and classical joining technologies for composite metal hybrid structures such as bonding and riveting, profile and contour joints offer promising potential for novel lightweight structures. First and foremost, joining systems with a form closure function enable to pass very high loads into rod- and tube-shaped fibre reinforced structures, whereby a high degree of material utilization for composite parts can be achieved. This paper presents an intrinsic manufacturing approach for the efficient production of carbon fibre reinforced thermoplastic hollow composite structures with multi scale structured metallic load introduction elements.

1. Introduction

Multi material design in general allows to utilize the advantageous of specific materials to meet local design requirements whereby additional challenges are induced in terms of joining, e.g. due to varying thermal expansion coefficients or corrosion. Especially for lightweight structures it is beneficial to combine the high specific mechanical properties of fibre reinforced plastics (FRP) with the isotropic characteristic of metals. Numerous techniques are known to join FRPs with metallic structures. In most cases joining takes place after the manufacturing of the single components in a subsequent process step like bonding, bolting, riveting or screwing [1, 2]. The common and classical joining technologies are often linked to machining processes, which may cause damage to the composite or require a surface treatment that adds extra costs and effort to the manufacturing process. In contrast the here pursued intrinsic manufacturing strategy destines to produce hybrid parts, which are joined and consolidated in the same process step to reduce cycle time and overall costs. This intrinsic manufactured hybrid systems are here in general named as intrinsic hybrids.

Known contour joints for hollow profiles such as tension-compression rods or driveshaft made from carbon fibre reinforced plastic (CFRP) show great potential to increase the material utilization by a fibre adapted load conduction design [3]. In [4] CFRP hydraulic cylinders are presented on basis of an interlocking joining strategy where the axial loads are transmitted from the metallic cylinder flange into the fibre reinforced tube structure by means of a contour joint. Comparable joining techniques and their specific design approach for drive shafts based on a positive locking principal are shown in [5]. In [6] rotational moulding concepts were utilized to intrinsic join and manufacture non rotational

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symmetric aluminium FRP hybrids. The necessary pressure to impregnate the carbon fibres with thermoset resin is applied by an expanding mandrel system from the inside.

The known applications with a contour connection utilizing thermoset resin systems are mostly limited to small- and medium-series production due to the manufacturing effort linked to processing the thermoset matrix system whereas thermoplastic matrix materials deliver structures characterized by outstanding thermoformability and weldability. Load introduction concepts using the advantageous of thermoplastics for hybridization of continuous fibre reinforced hollow structures by press- and welding processes are shown in [7]. There, economical manufactured, mainly pultruded, semi-finished FRP hollow profiles are used and funcionalized in a second manufacturing step.

In contrast to the aforementioned two stepped approach the integral blow moulding as a discontinuous, but intrinsic manufacturing process enables forming and consolidation at the same time. A braided preform made from commingled yarn was used in [3] and consolidated into metallic functional elements. Lightweight structures, such as hollow shafts made of textile reinforced plastic with integrated flanges, gears and wheel hubs constitute an initial stage of intrinsically manufactured hollow thermoplastic hybrids. However, the characteristics of presently known developments utilizing commingled yarn are limited in terms of consolidation quality in combination with the achievable fibre volume fraction, fibre alignment within the textile, greater fibre damage during processing and longer processing times due to the time consuming process step of impregnation. With regard to the form closure only interlocking on the macro level was investigated, but no additional strengthening due to micro or meso structuring.

The here presented approach aims at increasing the load transmission capabilities by multi scale structuring as well as improving the manufacturing quality and reducing the overall cycle time by utilizing fibre reinforced thermoplastic tapes. Considering this the main objective is the development of an efficient manufacturing process for high performance CFRP hollow profiles with each production step being designed to minimize the overall cycle time. Focus in the investigation is a CFRP tension-compression rod with a metallic load introduction element. Its design principle is illustrated in Figure 1. In addition influences on the material properties due to the processing technology itself shall be reduced.

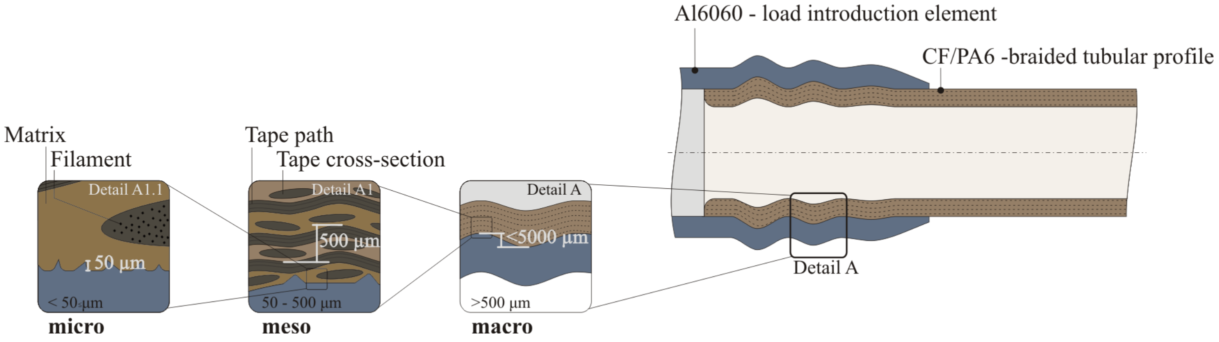

Figure 1: Contour joint concept with multi-scale structured interface

To design a reliable CFRP/metal hybrid contour joint several mechanical and physical aspects are to be taken into account. First and foremost the functional areas have to be tailored in a fibre appropriate design to transfer the targeted high loads homogeneously. In this approach surface structures on different scale levels from micro, to meso and to macro are applied. The discretization of the structuring levels for the contours main characteristic dimensions are defined as smaller than 50 µm for the micro level, 50 – 100 µm for the meso level and greater than 500 µm for the macro level (Figure 1). Second the laminate needs to be tailored to primary axial loads and minimal deviations in rigidity as well as differing thermal expansion coefficients of the composite to the aluminium part. The

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laminate is made out of Celanese, CF/PA6 Celstran® CFR-TP PA6 CF60-01 tape material and the load introduction element out of 6060T6 aluminum.

2. Intrinsic manufacturing approach

The general process chain (Figure 2) consist of two process paths producing semi-finished parts, one for the CFRP and one for metallic part, which are joined for the final hybrid part. The CFRP semi-finished part, the braided tape preform, is produced by an innovative tape braiding process [8]. The metallic semi-finished part, the load introduction (LI) element, is two-stepped hydroformed to create the necessary meso and macro structure. Both semi-finsihed parts are then intrinsically fused during an integral blowmoulding step as the fibre reinforced thermoplastic preform is simultaneously consolidated and formed into the load introduction element. The approach to combine hydroforming of metals with blowmoulding of fibre reinforced thermoplastic polymers enable a large scale production of tool-dropping composite metal structures without any need of further trimming or functionalization operations.

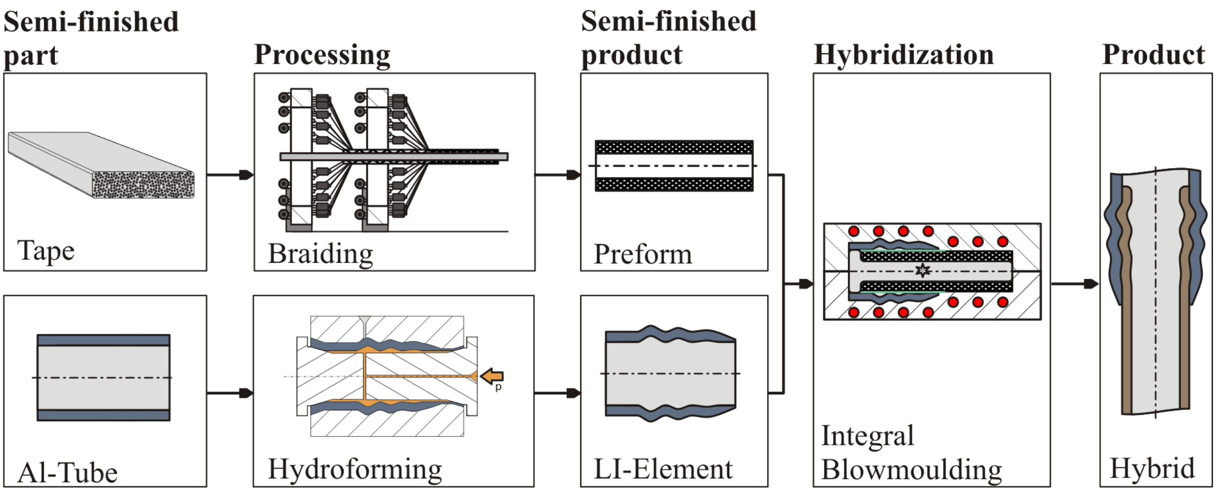

Figure 2: Integral blow moulding process chain for CFRP metal contour joints

2.1 Braiding of thermoplastic tape preform

Aiming at high performance applications pre-consolidated unidirectional fibre-reinforced thermoplastic tapes are used to reach the aforementioned development targets. Here in terms of automotive applications unidirectional carbon fibre reinforced Polyamid (PA) 6 tapes - Celanese, CF/PA6 Celstran® CFR-TP PA6 CF60-01- are used. Fully impregnated tapes enable to save the challenging and time-intensive process step of impregnating filaments with thermoplastic matrix material, which in return opens an enormous potential of significantly reducing processing time. Comparing available polymer and reinforcing fibre hybrid systems by prediction of the impregnation time conclusions for the additional effort during processing can be made. [9] used for the analysis of the necessary impregnation time Darcy's law and considered carbon fibres as reinforcing and PA6 as matrix material with a viscosity of 200 Pa s. The resulting impregnation times at 8 bar impregnation pressure varies from 0 s for tapes to 14,3 s for side-by-side hybrid yarn systems (Figure 3). This already shows the beneficial effect of using tape material to reduce cycle times. Furthermore the high impregnation quality of tapes, the straight fibre alignment within the tapes and high fiber volume contents have an additional positive impact on both the achievable level of composite quality and the mechanical properties of the resultant fibre thermoplastic composite structure.

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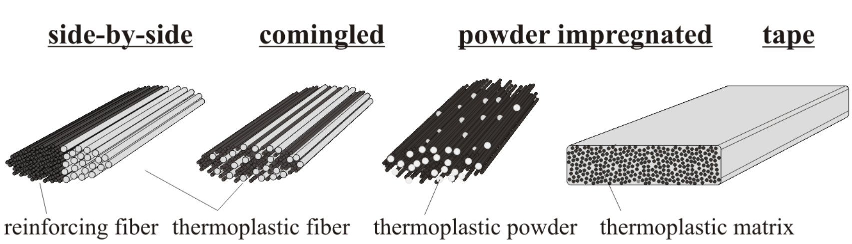

hybrid type	impregnation time [s]
side-by-side	14,3
comingled	0,9
powder	0,9
tape	0

Figure 3: Reinforced thermoplastic semi-finished parts (left) and their impregnation time (right) [9]

The process of tape braiding is characterized by high output rates as multiple tapes are simultaneously processed. In addition the high degree of automation predestines braiding well applicable for industrial application. Furthermore near-net-shape processing and varying off-axis reinforcing directions make braiding to a highly variable preforming technique. In general it is possible to braid straight, curved or complex preforms with variable cross-sections. In this investigation the preforms produced for the subsequent integral blowmoulding are straight with a of uniform diameter and biaxial as well as axial reinforcement. The manufactured braiding architecture with $\pm 30°_2 / 0°_7 / \pm 30°_2$ is designed to carry high axial loads and to avoid debonding by adjusting the themal expansion coefficient of the laminate to the aluminum load introduction element.

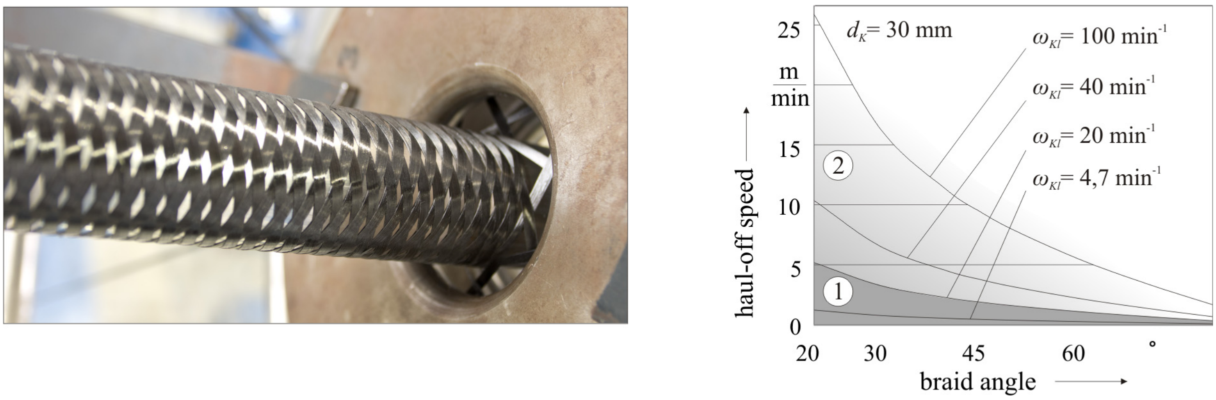

Figure 4: Thermoplastic tape braiding process (left) and haul-off speed according to braider type (right) [9]

Unlike hybrid yarn fully impregnated tapes are not limp and exhibit restricted, directional deformation properties. The braiding of semi-finished tapes therefore demands the availability of technological solutions featuring handling, braking, length compensation and spooling elements that are tailored to a processing and handling characteristics of the tape. Special in-house developed tape carriers enable the processing of semi-finished tapes of between 3 and 6 mm in width [8]. The embedding of the reinforcing filaments into the thermoplastic matrix enables braiding with increased take-off speed compared to todays standards. Figure 4 shows the achieavable haul-off speed according to the braiding angle of horn gear braiders, zone 1, compared to lever arm braiders, zone 2. It is demonstrated that in contrast to horn gear braiders already available lever arm braiders would quadruplicate at a 30° braiding angle the haul-off speed [9].

2.2 Two-stage forming process of load introduction element

Regarding serial production the manufacture of the metallic load introduction elements with a multi-scale structuring is performed by hydroforming. In general hydroforming is well established in terms

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of highly productive and low-cost forming processes for hollow profiles. Here first the meso scale and then the macro scale structuring is formed by internal pressure application. Different types of meso structuring patterns with shapes either interlocking with single fibres or complete tape yarns were designed. As low cost manufacturing alernative the fibre interlocking patterns were knurled and the yarn interlocking rhombic patterns were stamp formed. Both profile angles are adapted to the braiding angle of the CFRP component. The structuring depth varies between 0,15 and 0,8 mm [11]. In the subsequent hydroforming process step internal hydrostatic pressure is applied to form the preliminary meso structured tubes against the inner surface of a tool cavity. Thereby high plastic deformation as well as high accuracy of the manufactured parts can be achieved.

Numerical simulations of the hydroforming process (Figure 5 (left)) were performed to ensure the forming without failure of the macro contouring. The influence of surface deformation was investigated for the necessary hydroforming pressure to form the radiuses and failure limits. The deformation of the geometrically defined meso structuring by hydroforming of the macro structure is numerical determined and applied in the further design process. Numerical and experimental results show complete forming of the aluminum contour without failure at an internal pressure of 160 MPa. Diverse load introduction elements with varying meso and macro structuring as shown in Figure 5 (right) were produced.

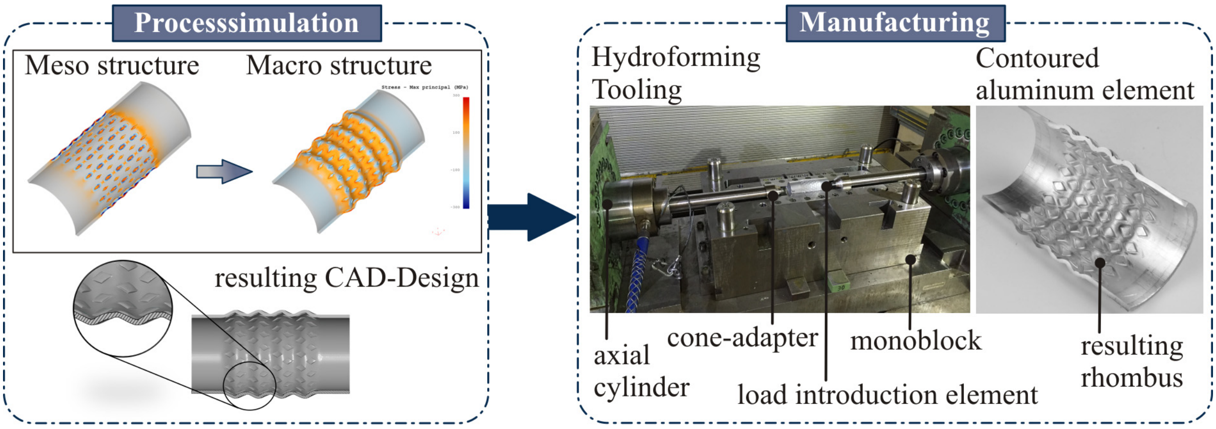

Figure 5: Simulation of the two-stepped meso-macro forming process (left) and the hydroforming tool with a manufactured load introduction element (right)

2.3 Intrinsic manufacture of hybrid system

The integral blowmoulding technology is utilized for the intrinsic manufacture of the hybrid system. In the integral blowmoulding process step the thermoplastic composite material is being moulded by an internal pressure bladder against an inner surface of a metallic tool and into the contours of the load introduction element. The developed tooling design separates the heating of the CFRP preform and the outer tooling to achieve a better individual temperature control of both the tooling and the preform. Especially with this overheating and material degradation of the polymer system is inhibited. The composite preform is heated in an infrared (IR) radiator oven and the tooling with an inductive heating technique wherby heating times below one minute are achieved. Furthermore the rotationally symmetric metallic load introduction element is used as the forming tool itself to minimize the bulge material, which otherwise unnecessarily needs to be heated and cooled, whereby the overall cycle time would be slowed down. The preform is positioned on an pressurized blowforming lance with additional guiding sleeves and transferred into the tooling for hybridization as the process temperature is reached. The blowforming lance itself is being moved by a pneumatic actuator system. For faster cooling cycles the blowforming lance enables air cooling from the inside of the tool. The assembled

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integral blowmoulding tool is illustrated in Figure 6 (right). To determine process boundaries numerical investigations of the reliance between the moulding quality and the process parameters were performed. First the textile architecture on the meso scale was modeled with the finite element method of the embedded elements [12] and with this the yarn moulding depth into the meso structure was analyzed. Figure 6 shows the process chain analysis cycle of design, process simulation and experiment. It appeared that the moulding quality is rather sensitive to the applied molding pressure, so that an minium moulding pressure of 7 bar was necessary to gain full moulding of the yarns into the meso structure.

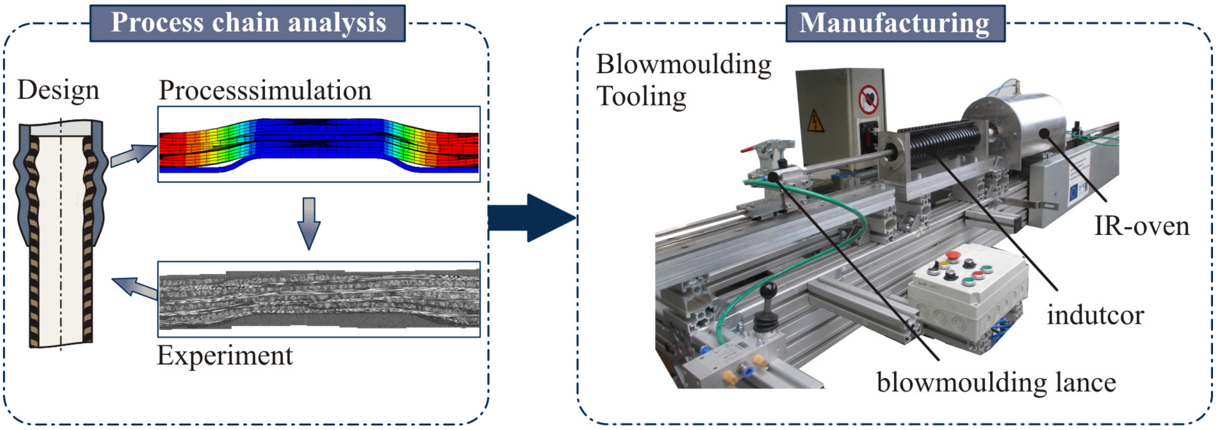

Figure 6: Holistic process analysis of the blow moulding process (left) and integral blowmoulding tooling (right)

Several CF-PA6 tension-compression rods with diverse structured load introduction elements as shown in Figure 6 (right) have been manufactured. As the anisotropic thermal expansion coefficients of the CFRP laminate can only be adjusted in one direction to the aluminium material, the circumferential one was adapted to avoid additional pressure loads in thickness direction on the laminate. Thus first non destructive inspections (NDI) with computer tomographic (CT) scanners showed debonding at the very top of the contour undercuts as the aluminium load introduction element shrinks stronger in axial direction than the CFRP part (Figure 7). To reduce this effect an appropriate steered cooling cycle needs to be applied. The consolidation quality was determined with the porosity level below 0,5 % at a measuring accuracy of 45 µm and the wallthickness with 1,39 mm showing a tolerance of ±0,03 mm. This laminate quality states a very high level of manufacturing quality making the shown intrinsic manufacturing approach well applicable to produce high performance hybrid systems for example in aviation industry.

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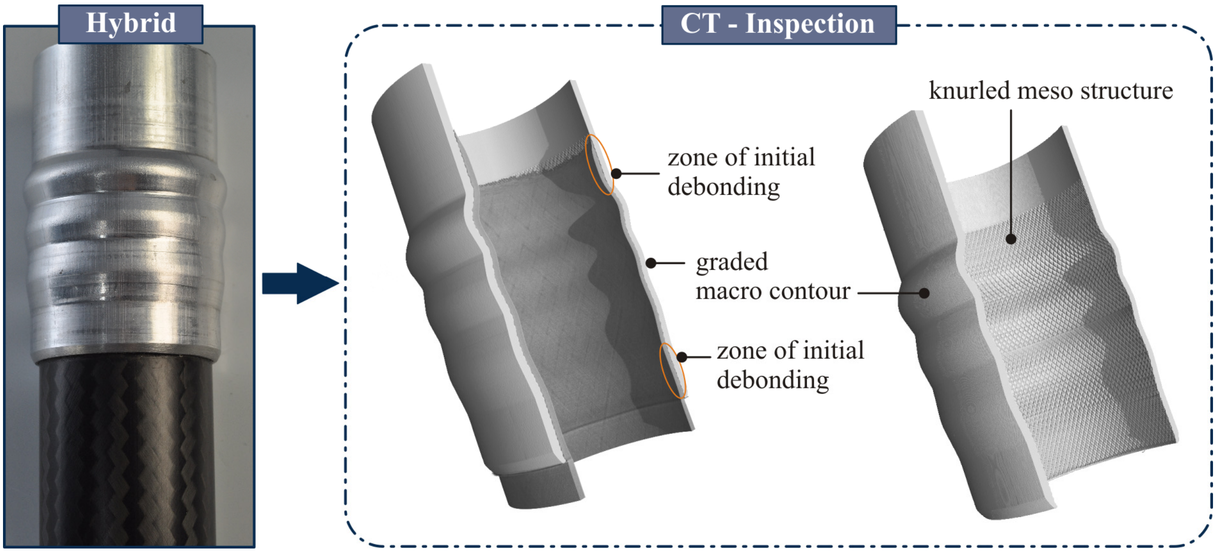

Figure 7: Manufactured contour joint demonstrator part (left) and NDI via CT analyzis (right)

3. Conclusion

An efficient and intrinsic manufacturing approach has been developed and presented for hollow fibre reinforced thermoplastic metal hybrid structures. Subject of investigation is enhacing the load transfer capabilities of contour joints by multi-scale structuring, producing high quality products and development of a serial production process. For the load introduction element manufacturing an effiecient two stepped forming approach creating the meso and macro scale structures is shown. To ensure manufacturability process simulations have been performed to determine the process limitations of the hydroforming of the metallic load introduction element as well as the integral blowmoulding of the hybrid part. Finally an intrinsic blowmoulding process is demonstrated and conducted to consolidate the composite and form it into the multi-scale structures of an aluminium load introduction element.

Acknowledgments

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References

[1] Hahn, O.; Hufenbach, W.; Gude, M.; Kläger, O.: *Entwicklung eines Auslegungskonzepts für geklebte und genietete CFK/Al-Karosseriestrukturen auf Basis experimenteller und numerischer Untersuchungen.* Paderborner Symposium Fügetechnik, 11 (2004) S. 144-161

[2] Fischer, T.; Schürmann, H.: *Der Pressverband als Krafteinleitungs-Element in Faser-Kunststoff-Verbund-Wellen.* 11. Nationales Symposium SAMPE Deutschland e.V. (2005)

[3] Helms, O.: *Konstruktion und technologische Umsetzung von hochbeanspruchten Lasteinleitungssystemen für neuartige Leichtbaustrukturen in Faserverbundbauweise.* Dissertation, TU Dresden (2006)

Excerpt from ISBN 978-3-00-053387-7

[4] W. Hufenbach, L. Kroll, M. Gude, O. Helms, T. Seung, *Beanspruchungsgerechte Krafteinleitungen für Luftfahrt-Hydraulikaktuatoren in Faserverbund-Leichtbauweise*. In: Konstruktion 58 (2006), S. 71 - 74.

[5] M. Gude, F. Lenz, A. Gruhl, B. Witschel, A. Ulbricht, W. Hufenbach, *Design and automated manufacturing of profiled composite driveshafts*, in: , Science and Engineering of Composite materials (2014), Vol. 22 issue 2, p.p 187-197

[6] J. Fleischer, S. Koch, S. Coutandin. *Manufacturing of polygon fiber reinforced plastic profiles by rotational molding and intrinsic hybridization*, In: Production Engineering (2015) 9, pp.317-328

[7] Töpker, J.; Schulz, J.; Haberstroh, E.; Michaeli, W.; *Krafteinleitungselemente und Verbindungstechniken bei endlosfaserverstärkten thermoplastischen Hohlprofilen*, 3. AVK-TV Tagung Baden-Baden, September 2000

[8] Garthaus, Barfuss, Witschel, Gude; *Tape braiding: high-performance fibre reinforced thermoplastic profile structures*, In: JEC Composites Magazine No 96 April 2015, S.62-64

[9] C. Garthaus, B. Witschel. *Pultrusion of braided thermoplastic tapes*, Proceedings in 13th World pultrusion conference, Prague, Czech Republic, March 3rd - 4th 2016

[10] D. Barfuss, C. Garthaus, M. Gude; *Advanced waviness modelling of thermoplastic tape braids*, Proceedings 20th International Conference on Composite Materials, Copenhagen, 19-24th July 2015

[11] D. Barfuss, R. Grützner, C. Garthaus, M. Gude, R. Müller, D. Landgrebe; *Intrinsic manufacture of hollow thermoplastic composite/metal structures*, Proceedings 19th ESAFORM, 27th – 29th April 2016, AIP Publishing

[12] Freund, A.: *Numerische Untersuchung zum visuellen Eindruck von presstechnisch hergestellten Textil-Thermoplastverbunden.* Dresden, Techn. Univ., Fak. Maschinenwesen, Diss., 2014

Excerpt from ISBN 978-3-00-053387-7