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Characterization of intrinsic interfaces between fibre-reinforced composites and additively manufactured metal for designing hybrid structures

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ABSTRACT

The combination of additively manufactured metal components with thermoset fibre-reinforced composites provides the possibility to produce hybrid structures with increased functionality and reduced mass. The application in the high-performance sector, for example the implementation of such a hybrid structure in electric drive units in aviation, provides the potential to achieve the high power densities required. The challenges in this regard are the manufacturing, design and dimensioning of the interface between the two components regarding the technical requirements, such as the high temperature range. In this publication, metal specimens are manufactured using selective laser melting (SLM) and then pre-treated. The joint with the composite is obtained in the subsequent infiltration process when the composite part is manufactured. For the experimental characterization of the interface different combinations of fibre-reinforced composites and metals are used. Within roughness measurement the surface of the different materials due to the treatment were analysed and the intrinsic interfaces were microscopically examined. The joint strength is investigated in double lap shear test at different temperatures and the results are discussed based on the fabrication process and the characteristics of the hybrid interface. The results provide the basis for the future design and numerical description of the interfaces.

Introduction

Electric drive systems with significantly increased power density offer the potential to make aviation compatible for the future in terms of ecological factors. The combination of additive manufacturing (AM) of metals with the use of fibre-reinforced plastics (FRP) enables hybrid structures with increased functionality and reduced mass. Regarding their anisotropic and adjustable behaviour with good mechanical properties, the FRP are predestined for areas of remote load transfer and parts of critical rotational inertia (Rayer et al., 2023). Due to complex loading conditions, metal structures are suitable for load transfer to adjacent structures.

The usage of hybrid FRP-metal structures presents promising opportunities in engineering, offering a blend of strength and versatility. However, traditional methods of connecting these materials, such as bolts or adhesives, often introduce drawbacks like added weight, complexity, and potential weak points in the structure. This has led to the exploration of alternative approaches, one of which is the utilization of intrinsic interfaces. An intrinsic hybrid involves integrating different materials during the primary or forming process, eliminating the need for any added adherents or additional joining processes. This results in seamless transitions between materials, enhancing structural integrity and reducing potential points of failure.

An intrinsic hybrid is an integral component in which the connection of the different materials occurs during the primary or forming process of the metallic or continuous fibre-reinforced component. Thus, no subsequent joining process is necessary (Fleischer et al., 2021), is referred to as Direct Assembly (DA) in the literature (Feistauer et al., 2018). Moreover, the incorporation of AM metals within the Resin Transfer Moulding (RTM) process opens up new avenues for enhancing hybrid structures. By integrating metal components directly into the RTM process, engineers can achieve precise geometries and tailored material properties. This approach offers advantages such as improved mechanical properties, enhanced corrosion resistance, and greater design flexibility. Explorations of AM metals within RTM processes have commenced (Borsellino et al., 2021), but to date, there has not been any research specifically focused on examining the compatibility of epoxy materials under aerospace conditions within the context of AM metals in

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RTM processes. This highlights the need for continued research and development to fully leverage the potential of hybrid structures in diverse engineering applications. The interface of the hybrid structure can be specifically adapted to the functions to be fulfilled, the resulting loads and the induced stresses by using the increased degrees of freedom of additive and composite manufacturing.

However, when integrating AM metal parts with FRP, several challenges arise:

Material Mismatch: AM metal materials possess distinct mechanical properties compared to composites, such as stiffness, strength, and thermal expansion. This disparity can lead to stress concentration and potential interface failure (Rajendran et al., 2023).

Thermal Considerations: The thermal history during AM can introduce residual stresses and distortions in metal parts, which must be considered when combining them with composites (Rajendran et al., 2023). Similarly, the curing process in RTM for composites also induces thermal stresses, underlining the need for comprehensive thermal observations in both processes and following applications.

Joining Techniques: Traditional joining methods, like bolts or adhesive bonding, may not be suitable due to the differing properties of AM metal parts and composites, particularly in aerospace engine applications. The alternative to manufacturing hybrid components is joining during component production via intrinsic interfaces. This is possible, for example, for moulding thermoplastic FRP and joining it to preformed metal sheets (Würfel et al., 2022). Whereas high rough surfaces can provide additional textured surface for the adhesive to enter creating locking mechanisms to bond, excessive roughness may also impede the ability of the adhesive to flow into the cracks and crevices, leading to increased voids, reduced strength or poor environmental protection of the bonds (van Dam et al., 2020). Developing effective and reliable joining techniques is a critical challenge.

Durability and Fatigue: The interface is vulnerable to long-term degradation, particularly under cyclic loading conditions and aging (Liu et al., 2020). Understanding the durability and fatigue behaviour of the interface is essential for ensuring the long-term performance of composite structures.

The large number of degrees of freedom of the material and geometry leads to major challenges for engineers in the development of such structures but also provides opportunities for force-flow compatible designs (Pohl et al., 2022). The interface between AM metal parts and FRP presents a complex set of challenges in the realms of advanced manufacturing and aerospace engineering. The industrial aerospace using thermoset FRP for even the biggest fan blades (Kellner, 2016) but metal shields are still common for impact sceneries (Gardiner, 2021). This junction, where two materials with differing properties meet, is critical for ensuring the structural integrity and performance of such hybrid composite structures (Hart-Smith, 1973). AM parts allow a large variety of geometric features, which can lead to a significant improvement in the joint strength (Whitehouse et al., 2023). Thus, AM has revolutionized the production of metal components, offering design flexibility and reduced waste (Attaran, 2017). The design of the joining zone in terms of pre-treatment, surface finish and geometric design has a significant influence on the properties of the joining zone in hybrid components and thus on the transferable loads. Studies have revealed that surface roughness plays a pivotal role in influencing the transferable shear strength (Bonpain and Stommel, 2018). From a structural perspective, not only does surface roughness contribute significantly, but the number and configuration of undercuts also emerge as decisive factors (Kleffel and Drummer, 2017). An alternative method involves perforating the metal structure to facilitate mechanical anchoring of the matrix (Berges et al., 2022). Moreover, the application of metallic pin structures, subjected to testing for anchoring in the Fibre-Reinforced Polymer (FRP), has been explored (Bianchi et al., 2023). Leveraging AM to deliberately modify geometric shapes in joint areas is posited as an avenue for augmenting joint strength through uniform stress transfer (Whitehouse et al., 2023). In tandem with diverse geometric considerations, the pre-treatment of joining partners constitutes a comprehensive and pivotal subject. A comparative analysis of various pre-treatments underscores sandblasting as a predominant process for achieving robust joint strength (van Dam et al., 2020). It is worth noting that there exist several different methods for the manufacturing of hybrid metal-FRP structures (Feistauer et al., 2018), adding complexity to the investigation, review and comparability of the hybrid interfaces. It necessitates specialized techniques for joining and analysing these distinct materials, with one key concept being the cohesive zone (Papanastasiou, 2017) in finite element modelling transferring the experimental data (Jimenez and Miravete, 2004). Thus, following the common specimen tests enables creating required data for perspective simulations of such joints.

Within this paper, the manufacturing process enabling an intrinsic joint between AM metals and thermoset carbon fibre-reinforced polymers (CFRP) is discussed, the created intrinsic interface is investigated and the transfer of forces within the joint is demonstrated in the Double Lap Shear (DLS) test with different materials and under a wide temperature range. Given the diverse parameters at play, the present research aims to establish an initial benchmark by investigating the intrinsic interface created through direct assembly using a one-step manufacturing procedure, involving both the composite layers and the metal part in the RTM-Tool. The behaviour under different curing cycles, employing two matrix hardeners, and encompassing a broad temperature range is examined. This inquiry seeks to ascertain the suitability of the proposed approach for further exploration in demanding environments. Specifically, the focus lies on the intrinsic interface, as the thermoset CFRP is bonded together in a singular curing cycle with the AM metallic surface. The examination of this intrinsic interface is pivotal for understanding the nuanced interplay of factors underpinning the joint strength in such a composite system.

Materials and methods

Materials

The research aims to investigate the intrinsically produced joining zone between AM metals and carbon fibre-reinforced polymers (CFRP). Both stainless steel (Inconel 718) and titanium (Ti6Al4) serve as metal joining partners. Stainless steel, especially Inconel 718 as well as Titanium alloys such as Ti6Al4 are commonly used in AM for aerospace applications due to their unique properties (Blakey-Milner et al., 2021). Inconel 718 provides a good durability, corrosion resistance, high strength and also a heat resistance due to the protective oxide layer (Blakey-Milner et al., 2021). Titanium also offers a high-temperature stability and its specific strength is decisive for aerospace and moreover cryogenic applications (Blakey-Milner et al., 2021). The AM metal parts were manufactured within the Selective Laser Melting Process. Due to their superior strength-to-weight ratio of CFRP they are highly beneficial in aerospace (Sekaran, 2019) as well and were used in this investigations as the composite joining partner with an IMS65 carbon fibre in unidirectional layers. In the future, hybrid metal-FRP components will be used in both the high and low temperature range. Based on this, the hardener Aradur 2954 for high temperature applications and the hardener Aradur 3486 for low temperature applications were used in addition to the resin system Araldite LY 3508 BD.

Manufacturing process

The metal samples were produced externally using the selective laser melting (SLM) process, which is why, unfortunately, no further statements on production parameters are possible. Roughness measurements were carried out to gain a better understanding of the material and surface properties of the AM process used. The intention is to test these components for compatibility and effectiveness in the given production environment in order to include them into subsequent processes.

Afterwards, the AM metal joining partners were pre-treated and then be processed into a hybrid component in the RTM mould by infiltration and consolidation of epoxy. The manufacturing chain is shown in Fig. 1. The surface pre-treatment of the metal joining partners was based on the standard DIN EN 13887, as well as ASTM-D2651. For prospective industrial use and applicability of the results, a process was chosen that allows a processing time of 4 h and promises realisation not only under laboratory conditions, which should make the results more comprehensible and reproducible. Hence, for produce the test specimens, the AM metal joining partners were cleaned for 10 min in a continuous ultrasonic bath, followed by sandblasting. The parameters of sandblasting are a spray distance of 7 – 10 cm, a 5 minute spray time and a compressed air pressure of 3.5 bar with 150 μm grain size corundum and then cleaning again for 10 min in an ultrasonic bath.

The metal joining partners pre-treated in this way were then be further processed as joining partners in the RTM process. The manufacturing process, seen in Fig. 1, was continued after the pre-treatment of the metal tool and the water jet cut adjustment plates twice with acetone and release agent Frekote 770-NC. Followed by inserting the adjustment plates into the 300×300 mm tool for the RTM process (Fig. 2a and b). In the first metal adjustment plate concept (Fig. 2a) had one complete metal plate per side and the modified concept was with a cut metal plate into two parts (Fig. 2b). The modification was necessary for a demoulding process preventing inertial damage to the specimens. The placed metal parts are among 8 layers of unidirectional carbon non-crimp fabric and a silicone strip in between (c). The next layer of metal parts are positioned above the carbon fibre layers. The adjustment metal plates providing the position of the metal joining partners and the geometry of the specimens needed. Subsequently, the process includes epoxy infiltration, using a gate with runners, which is joining the components, forming a cohesive structure. Depending on the hardener, corresponding curing cycles were carried out according to the data sheet seen in Table 1. Once the epoxy has set and consolidated the hybrid metal-FRP structure with an intrinsic interface is established.

The next step is to demould the hybrid metal-FRP component, carefully removing it from the mould. The removal of the metal plates in particular proved to be prone to errors during the manufacturing process, as the resin adhered to the metal plates despite the tool being pre-treated with release agent. During the demoulding of the first hybrid metal-FRP composites, this resulted in initial damage and partial removal of the metallic joining partners from the fibre reinforced composite. By adapting the metal plates (Fig. 2b), a significantly improved demoulding could be achieved. However, the modifications made to the metal plates posed new difficulties during the positioning process. Conversely, however, this led to a difficult positioning of the metallic joining partners above and below the FRP in relation to each other.

The demoulding is followed by cutting the hybrid composite creating individual specimens as shown in Fig. 4. The manufacturing process ends by cutting the demoulded hybrid metal-FRP plate to get the geometry seen in Fig. 3 needed for the double-lap-shear (DLS) experiments.

Testing

To investigate the influence of the pre-treatment on the surface appearance of the metal joining partners, the roughness of the metal parts were measured before and after pre-treatment using a NanoFocus μscan profilometer in accordance with the ISO 4287 standard. In Fig. 4 one DLS-specimen is shown with unidirectional composite layers and metal parts. To investigate the influence of the pre-treatment on the surface structure of the metal joining partners, in addition to the roughness measurements the joining zone between metal and FRP of the DLS-specimens is analysed microscopically. The model of microscope used is the Olympus BX53M and the section view applied is shown in Fig. 4 with an examined area of about 100 mm^2.

The DLS experiment (ASTM D3528 – 96) is a test method used to determine the shear strength of joints by reducing any additional peel stresses (Banea and da Silva, 2009) and was used for the metal-FRP specimens. The test specimen is loaded in shear by applying a force parallel to the overlap. This testing configuration offers several advantages, including essential data for simulation of bonded and joint materials and the ability to ensure a relatively uniform distribution of stress along the bonded area. The results of the DLS tests are generated on the Zwick Z100 tensile testing machine with testing parameters shown in Table 2.

The investigation of the strength behaviour of the intrinsic interface between the different metal materials and the FRP, with the influencing variables of temperature and the matrix material, resulted in a number of eight different variants as shown in Table 3.

Results and discussion

The first examination was carried out on the metal parts with regard to their surface roughness before and after pre-treatment by sandblasting. The intention was to investigate whether sandblasting has a significant influence on the surface roughness, as only an adequate pre-treatment of the joining process should be carried out, but not a change in the surface roughness in order to utilise the AM surface. Fig. 5 shows the examined surface area (a) and distribution of roughness after sandblasting for Ti6Al4 (b) and (c) and Inconel 718 (d) and (e).

The measuring range comprises 613 profile measurements over a length of 24.5 mm with a resolution rate of 92.1 μm per point over a width of 10 mm. The results in Table 4 show a slight decrease in the R_a values from titanium to stainless steel, as well as a decrease in the surface roughness of the samples before and after sandblasting.

These specimens are then subjected to microscopic examination to assess their structural composition in the intrinsic interface area and to determine whether there are any defects such as air inclusions or areas without contact between the epoxy resin and the metallic surface. As seen in Figs. 6 and 7 the surface roughness is not leading to an increase of voids or an uninfiltrated area at the intrinsic interface, assuming a sufficient joining strength between the joining partners. Worth mentioning is that the fibres seemed to exhibit closer proximity to the titanium joining partners than to the stainless steel joining partner, warranting further investigation into the consistency of this phenomenon across the

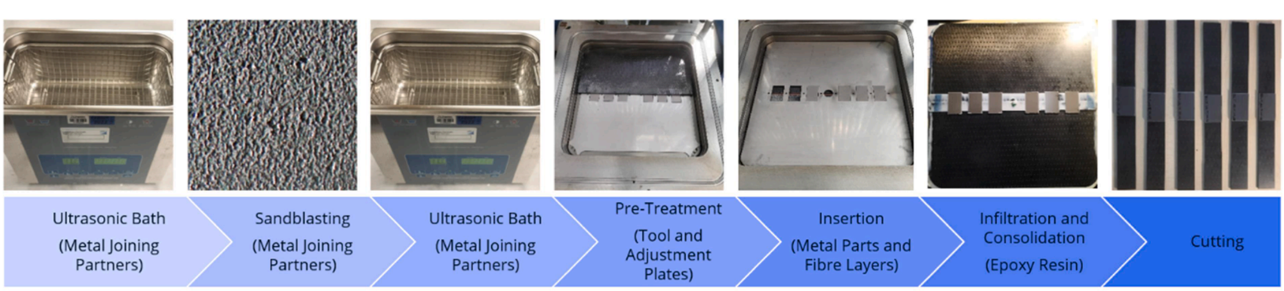

Fig. 1. Manufacturing process of hybrid metal-composite Double-Lap-Shear specimens.

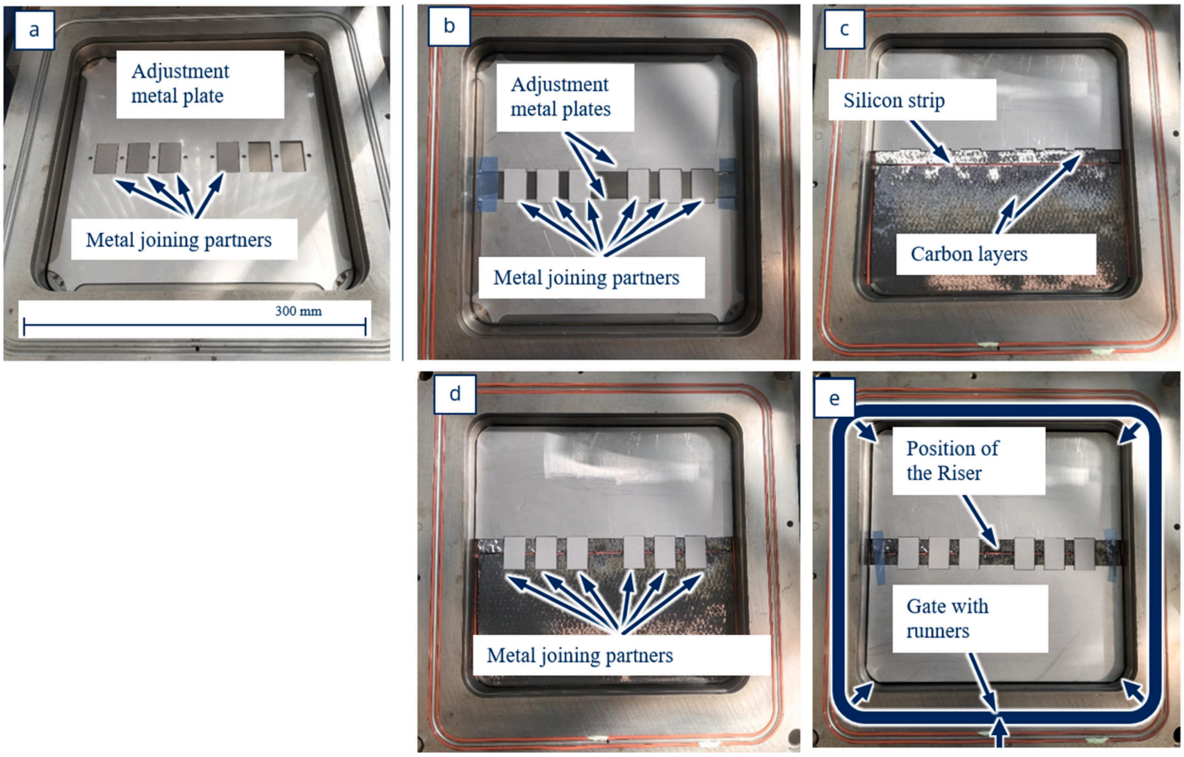

Fig. 2. Insertion process with the first concept (a) the modified concept with metal plate cut into two plates and inserted metal joining partners (b), inserted carbon fibre layers and one metal plate above (c), inserted metal joining partners above (d) and inserted last metal plate with sketched gate with runners and riser (e) inside the opened RTM-Tool.

Table 1
Curing Cycles for used hardeners.

Hardener	Aradur 3486	Aradur 2954
Glass transition temperature	70 °C	150 °C
Curing Cycle	16 h at 50 °C	1 h at 80 °C + 8 h at 160 °C

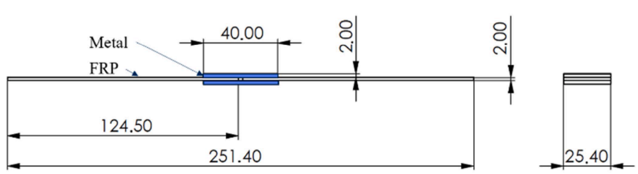

Fig. 3. Geometry and design of the hybrid metal-FRP DLS-specimens.

specimen set.

The specimens using the low-temperature resin show a higher shear stress in the DLS test than the specimens using the resin for high-temperature applications.

Fig. 8 shows the entire results of the DLS tests. In some samples, a quite high standard deviation up to 3.4 MPa is evident within the experiment. The results show that the strength of the interface varies depending on the type of resin used. The test samples cured at a higher temperature failure at low force compared to those cured at only 50 °C. Surprisingly, the manufacturing method appears to exert a greater influence than temperature, as even specimens cured at 50 °C and subsequently tested at an extremely low temperature of −196.15 °C, they still exhibit increased strength. This leads to the assumption that, regardless of the subsequent temperature fluctuation, high residual stress is already introduced into the joint area during the manufacturing process.

In addition to the results three of the tested specimens are exemplary shown in Fig. 9. Within the examination, different failure modes became apparent in the interfaces as seen Fig. 9. Due to the lack of adhesive, the common failure modes (Omairey et al., 2021) cannot be transferred outright. The specimens exposed to 370 K (a) displayed mostly cohesive failure also with fibre pull-outs out of the FRP matrix but also substrate failure. Specimens exposed to room temperature (b) displayed substrate failure even with fibre pull-outs out of the FRP matrix and those subjected to low-temperature conditions (c) exhibited adhesive failure. This underscores the intricate interplay of factors influencing the results.

The considerable deviations in the DLS results can largely be attributed to the challenges faced during the demoulding process. The adjustment plates are cut with water jet and exhibit a very rough cutting

Table 2
Testing parameters.

Standard	ASTM D3528
Initial Force	10 N
Test Speed	0.15 MPa/s
Displacement measurement	Crosshead travel
Force measurement	100 kN Load cells
Temperatures	(77 | 296 | 370) K

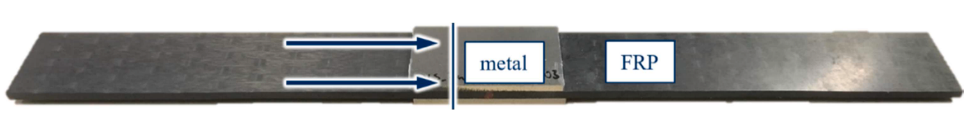

Fig. 4. DLS specimen including the section view for microscopy.

Table 3
List of test specimens, their material and test conditions.

Metal	Non-crimped-fabric	Matrix	Test Temperature in K	Specimen names
Ti6Al4	IMS65 unidirectional	Araldite LY 3508 BD Aradur 3486	77	DLS_Ti_UD_TT_77
			296	DLS_Ti_UD_TT_RT
		Araldite LY 3508 BD Aradur 2954	296	DLS_Ti_UD_HT_RT
			370	DLS_Ti_UD_HT_100
Inconel 718	IMS65 unidirectional	Araldite LY 3508 BD Aradur 3486	77	DLS_In_UD_TT_77
			296	DLS_In_UD_TT_RT
		Araldite LY 3508 BD Aradur 2954	296	DLS_In_UD_HT_RT
			370	DLS_In_UD_HT_100

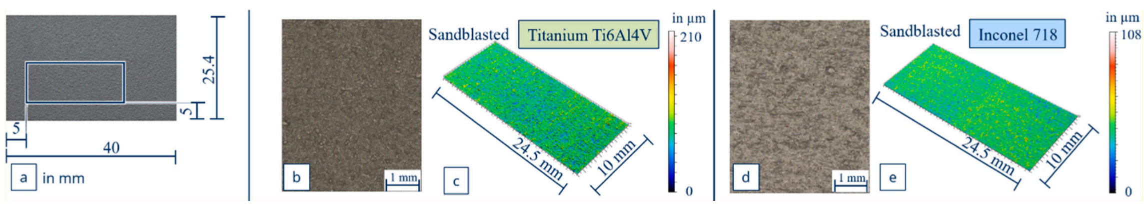

Fig. 5. Sandblasted metal specimen with definition of the examined surface (a) and distribution of roughness Ti6Al4 (b) and (c) and Inconel 718 (d) and (e).

Table 4
Surface roughness (according to ISO 4287) of the metal joining partners before and after sandblasting.

Material	Titanium Ti6Al4 Untreated	Titanium Ti6Al4 Sandblasted	Inconel 718 Untreated	Inconel 718 Sandblasted
R_a in µm	7.77	6.58	4.85	3.70

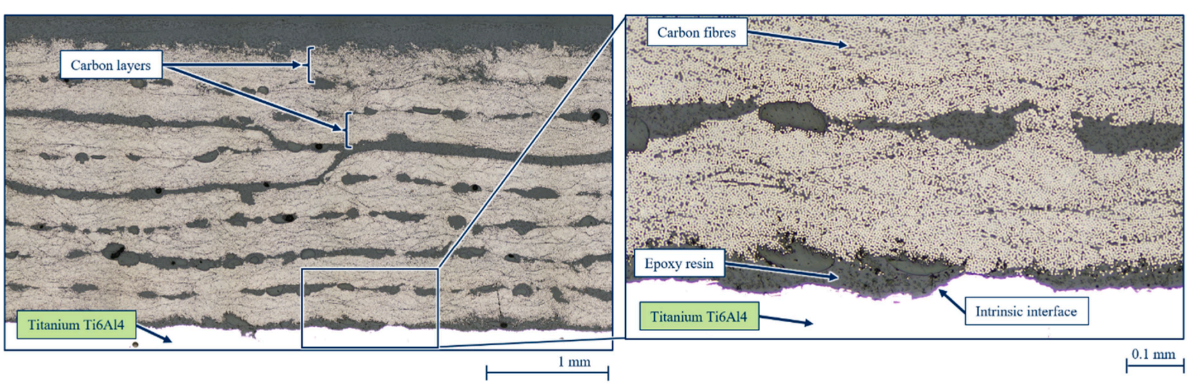

Fig. 6. Microscopic views of the specimens focussed to the intrinsic interface at DLS-specimen with Ti6Al4.

edge. There is a high potential for improvement in the application of laser-cut metal sheets. These setbacks highlight the necessity for methodological enhancements in future experiments to enhance the reliability of our results and gain a more comprehensive understanding of the underlying phenomena. Nevertheless the results showing that it is possible to create a robust joint with the intrinsic interface method.

Summary and conclusion

In conclusion, this research presents a novel approach for manufacturing hybrid structures with additive manufacturing (AM) metals and carbon fibre-reinforced polymers (CFRP), creating an intrinsic interface through a resin transfer moulding (RTM) process. The materials chosen for this study, including stainless steel (Inconel 718) and titanium (Ti6Al4), are commonly utilized in aerospace applications due to their exceptional properties. The AM metal parts were manufactured using selective laser melting (SLM), while CFRP was employed as the composite joining partner.

The manufacturing process involved thorough surface pre-treatment of the metal joining partners followed by infiltration and consolidation of epoxy resin in the RTM mould. Various hardeners were used to accommodate both high and low-temperature applications. Despite initial challenges in the demoulding process, modifications to the metal plates improved the overall manufacturing process. Testing of the hybrid metal-FRP specimens included roughness measurements, microscopic analysis of the intrinsic interface, and double-lap-shear (DLS) experiments. Results indicated a slight decrease in surface roughness after sandblasting, with no significant impact on the intrinsic

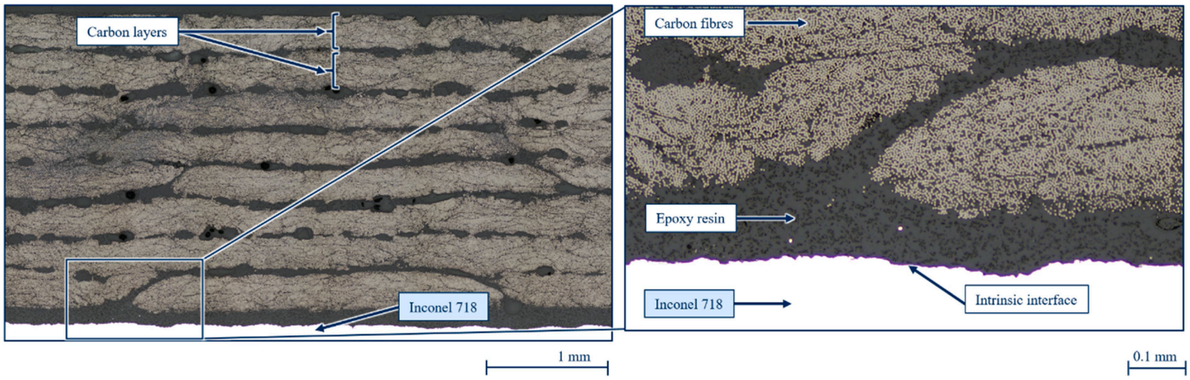

Fig. 7. Microscopic views of the specimens focussed to the intrinsic interface at DLS-specimen with Inconel 718.

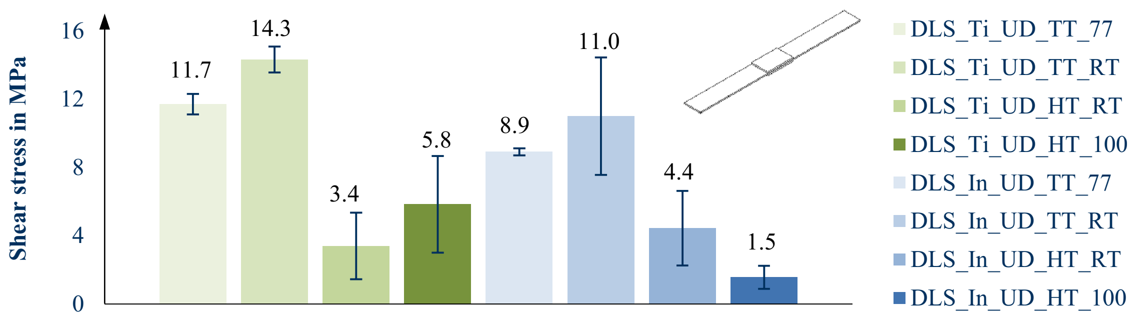

Fig. 8. Test results of the DLS testing.

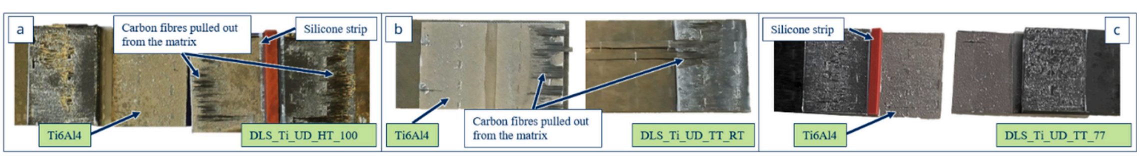

Fig. 9. Tested specimens at 370 K (a), in room temperature (b) and tested specimen at 77 K (c).

interface quality. Microscopic examination revealed no voids or areas lacking resin-metal contact, suggesting adequate joining strength between the partners. DLS testing showed variations in interface strength depending on the type of resin used, with specimens cured at higher temperatures exhibiting cohesive failure, while those cured at lower temperatures displayed adhesive failure. The manufacturing method appeared to exert a greater influence on strength than temperature fluctuations, indicating the introduction of high residual stress during the manufacturing process.

The research aimed to investigate the generated intrinsic interface between fibre-reinforced-plastic and additively manufactured metals to determine initial characteristic values necessary for finite element method descriptions. Achievements in the manufacturing process included identifying defects such as air inclusions or areas without contact and generating robust joints with notable successes utilizing the intrinsic interface method. However, certain intricacies of the manufacturing process remain unresolved, necessitating ongoing efforts to ensure future specimen production remains free from initial damage. In the microscopic evaluations, it becomes evident that a larger pool of specimens is required for comparative analysis. Expanding the dataset allows to perform more robust statistical analyses and better understand how the configuration in the mould might affect the generated interfaces. This is of particular significance when examining the placement of fibres in relation to the metal surfaces, as it can offer valuable insights into the mechanical properties of these materials at a microscale level.

Furthermore, the research can benefit from diversifying the scope of materials and geometries explored. The inclusion of more complex geometries and the incorporation of aluminium materials alongside the current investigations would enable drawing valuable comparisons. These comparative studies would provide insights into the material-specific behaviour of the intrinsic interface method and its interaction with different substrates. Additionally, conducting comparative analyses with results obtained from conventional metal sheet materials used in metal joining partners will provide a richer perspective on the potential advantages and limitations of the actual approach, thereby contributing to a more comprehensive understanding of the factors influencing the study and emphasizing the importance of further advancements in hybrid metal-FRP component manufacturing especially for aerospace applications.

CRediT authorship contribution statement

R. Grothe: Writing – original draft, Visualization, Validation, Resources, Investigation, Conceptualization. **M. Pohl:** Supervision. **J. Troschitz:** Writing – review & editing. **Ch. Weidermann:** Writing – review & editing. **K.-P. Weiss:** Writing – review & editing. **M. Gude:** Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Attaran, M., 2017. The rise of 3-D printing: the advantages of additive manufacturing over traditional manufacturing. Bus. Horiz. 60 (5), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011. VolumeIssuePagesISSN 0007-6813.

Banea, M.D., da Silva, L.F.M., 2009. Adhesively bonded joints in composite materials: an overview. Proceed. Instit. Mech. Eng., Part L: J. Mater.: Des. Applic. 223 (1), 1–18. https://doi.org/10.1243/14644207JMDA219.

Berges, J.M., Jacobs, G., Berroth, J., 2022. A numerical approach for the efficient concept design of laser-based hybrid joints. Appl. Sci. 12, 10649. https://doi.org/10.3390/app122010649.

Bianchi, F., Liu, Y., Joesbury, A.M., Ayre, D., Zhang, X., 2023. A finite element model for predicting the static strength of a composite hybrid joint with reinforcement pins. Mater. (Basel) 16 (9), 3297. https://doi.org/10.3390/ma16093297.

Blakey-Milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., Leary, M., Berto, F., Plessis, A.du, 2021. Metal additive manufacturing in aerospace: a review. Mater. Des. 209, 110008 https://doi.org/10.1016/j.matdes.2021.110008. VolumeISSN 0264-1275.

Bonpain, B., Stommel, M., 2018. Influence of surface roughness on the shear strength of direct injection molded plastic-aluminum hybrid-parts. Int. J. Adhes. Adhes. 82, 290–298. VolumePagesISSN 0143-7496.

Borsellino, C., Urso, S., Alderucci, T., Chiappini, G., Rossi, M., Munafò, P., 2021. Temperature effects on failure mode of double lap glass-aluminum and glass-GFRP joints with epoxy and acrylic adhesive. Int. J. Adhes. Adhes. 105, 102788 https://doi.org/10.1016/j.ijadhadh.2020.102788. VolumeISSN 0143-7496.

Feistauer, E., dos Santos, J., Amancio-Filho, S., 2018. A review on direct assembly of through-the-thickness reinforced metal-polymer composite hybrid structures. Polym. Eng. Sci. 59 https://doi.org/10.1002/pen.25022.

Fleischer, J., Coutandin, S., Nieschlag, J., 2021. Einführung in Intrinsische Hybridverbunde, Intrinsische Hybridverbunde Für Leichtbautragstrukturen. Springer Vieweg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-62833-1_1.

Gardiner, G., 2021. Developing next-gen, smart engine composite fan blades. CompositeWorld News. https://www.compositesworld.com/news/developing-next-gen-smart-engine-composite-fan-blades.

Hart-Smith, L., 1973. Adhesive-Bonded Single-Lap Joints. (No. NASA-CR-112236). https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.461.4731&rep=rep1&type=pdf.

Jimenez, M., Miravete, A., 2004. Application of the finite-element method to predict the onset of delamination growth. J. Compos. Mater. 38, 1309–1335. https://doi.org/10.1177/0021998304042734. https://journals.sagepub.com/doi/full/10.1177/0021998304042734.

Kellner, T., 2016. The art of engineering: the world's largest jet engine shows off composite curves. GE News. https://www.ge.com/news/reports/theart-of-engineering-the-worlds-largest-jet-engine-shows-off-composite-curves.

Kleffel, T., Drummer, D., 2017. Investigating the suitability of roughness parameters to assess the bond strength of polymer-metal hybrid structures with mechanical adhesion. Compos. Part B: Eng. 117, 20–25. https://doi.org/10.1016/j.compositesb.2017.02.042. VolumePagesISSN 1359-8368.

Liu, J., Guo, T., Hebdon, M.H., Yu, X., Wang, L., 2020. Behaviors of GFRP-steel bonded joints under cyclic loading after hygrothermal aging. Construct. Build. Mater. 242, 118106 https://doi.org/10.1016/j.conbuildmat.2020.118106. VolumeISSN 0950-0618.

Omairey, S., Nithin, A.J., Kazilas, M., 2021. Defects and uncertainties of adhesively bonded composite joints. SN Appl. Sci. 3 https://doi.org/10.1007/s42452-021-04753-8.

Editor(s) Papanastasiou, P., 2017. Ernestos Sarris, 6 - Cohesive zone models. In: Amir, K, Shojaei, Jianfu Shao (Eds.), Porous Rock Fracture Mechanics. Woodhead Publishing, pp. 119–144. https://doi.org/10.1016/B978-0-08-100781-5.00006-3. PagesISBN 9780081007815.

Pohl, M., Spitzer, S., Grothe, R., Weidermann, C., Gude, M., 2022. Intrinsic interfaces between additively manufactured metal and composite structures for use in electric propulsion engines. In: 11th EASN International Conference. https://doi.org/10.1088/1757-899X/1226/1/012077.

Rajendran, S., Palani, G., Kanakaraj, A., Shanmugam, V., Veerasimman, A., Gądek, S., Korniejenko, K., Marimuthu, U., 2023. Metal and polymer based composites manufactured using additive manufacturing—a brief review. Polym. (Basel) 15, 2564. https://doi.org/10.3390/polym15112564.

Rayer, M., Wilkowski, M., Schiffers, R., et al., 2023. Entwicklung von innovativen Faserverbundantriebswellen in Hybridbauweise – Funktionsintegration und Leichtbau über neuartige Materialkombinationen. Forsch Ingenieurwes 87, 581–591. https://doi.org/10.1007/s10010-023-00672-9.

Sekaran, S.C., et al., 2019. 7 - Haptic-based virtual reality system to enhance actual aerospace composite panel drilling training, Structural Health Monitoring of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites. Woodhead Publish. 113–128. https://doi.org/10.1016/B978-0-08-102291-7.00007-1. PagesISBN 9780081022917.

van Dam, J.P.B., Abrahami, S.T., Yilmaz, A., Gonzalez-Garcia, Y., Terryn, H., Mol, J.M.C., 2020. Effect of surface roughness and chemistry on the adhesion and durability of a steel-epoxy adhesive interface. Int. J. Adhes. Adhes. 96, 102450 https://doi.org/10.1016/j.ijadhadh.2019.102450. VolumeISSN 0143-7496.

Whitehouse, A.D., Médeau, V., Mencattelli, L., Blackman, B., Pinho, S.T., 2023. A novel profiling concept leading to a significant increase in the mechanical performance of metal to composite adhesive joints. Compos. Part B: Eng. 261, 110791 https://doi.org/10.1016/j.compositesb.2023.110791. VolumeISSN 1359-8368.

Würfel, V., Grützner, R., Hirsch, F., Barfuss, D., Gude, M., Müller, R., Kästner, M., 2022. Hybrid Fibre Reinforced Thermoplastic Hollow Structures with a Multi-Scale Structured Metal Load Introduction Element.