

ENHANCING THE SHEAR STRENGTH OF HYBRID TITANIUM-COMPOSITE JOINTS BY OUT-OF-PLANE PROTRUSIONS

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ABSTRACT

With the increasing usage of composite parts in aerospace, automotive and other sectors, there is a growing need for hybrid joining technologies. Innovation is desired in terms of joining methods to join metal and composite constituents. Traditional mechanical fastening methods, e.g. bolting and riveting, involve point contacts resulting in stress concentration, and labour and weight penalties. In this study, 3D-printed titanium is joined to unidirectional carbon fibre-reinforced thermoplastic composite. This type of joint is particularly challenging due to chemical incompatibility and mismatches of thermo-mechanical properties. The hybrid joint is constructed by hot press forming, as the heat and pressure control enable improved mechanical properties. Laser powder bed fusion is used to realize bespoke protrusions in the out-of-plane direction of the titanium faying surface that mechanically interlock with the composite material. Fabricated joints, with and without protrusions, are tensile tested in a single lap shear configuration. Results show that mechanical interlocking gives a 17x improvement compared to protrusion-free joints. The measured ultimate joint shear strength was on average 11.6 MPa. Moreover, this shear strength can be correlated to the feature size of the additively fabricated protrusions. Altogether, this gives valuable engineering insight for the design parameter optimisation of hybrid titanium-composite joints.

1. INTRODUCTION

Hybrid titanium-composite joints are increasingly integral to aerospace and high-performance engineering applications, in which structural efficiency, weight reduction, and durability are paramount. These joints combine the high strength, corrosion resistance, and fatigue performance of titanium alloys with the high specific stiffness and lightweight nature of Fibre-Reinforced Polymer (FRP) composites [1]. However, joining of these dissimilar materials poses significant challenges due to their contrasting mechanical properties, thermal expansion coefficients and surface chemistries. Traditional joining techniques, such as mechanical fastening and adhesive bonding, often result in suboptimal performance due to stress concentrations, delamination, fibre damage or insufficient load transfer across the interface [2]. Enhancing the bond strength between titanium and composite materials remains a central focus in this field. Mechanical fastening, although robust, introduces weight penalties and potential

damage to composite laminates. Adhesive bonding, while being lightweight and structurally efficient, suffers from reliability concerns, particularly under cyclic loading or harsh environmental conditions [3].

Hybrid joining methods that combine mechanical and adhesive approaches offer improved performance, yet they still encounter limitations related to interface durability and manufacturing complexity. Recent advances in Additive Manufacturing (AM), in particular Laser Powder Bed Fusion (LPBF) and Directed Energy Deposition (DED), offer promising pathways to engineer functionally graded or interlocking metal-composite interfaces with enhanced bonding characteristics [4]. By fabricating out-of-plane surface architectures on the metal adherend, AM enables mechanical interlocking and increased surface area for adhesion, thereby improving the joint strength. Moreover, AM allows for local tailoring of such features, such as hooks, pins or mesh structures, directly integrated onto the metal surface prior to welding or co-curing with the composite, effectively transcending the limitations of conventional joint geometries [5]. Figure 1 illustrates a schematic of such hybrid joint between a metal and an FRP adherend featuring out-of-plane protrusions to boost the strength of the welded joint.

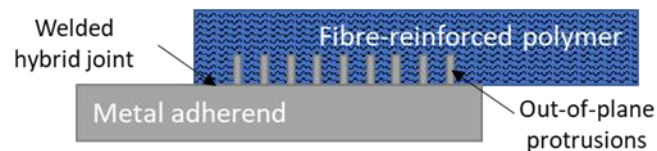


Figure 1: Schematic of an advanced hybrid single lap joint between fibre-reinforced polymer and metal.

Ongoing research continues to explore the synergy between AM and surface treatment methods (e.g., laser texturing, plasma treatment, and nano-coatings) to optimize interface adhesion and long-term durability [6]. These innovations mark a shift toward integrated, multifunctional joints that are lighter, stronger and more reliable under complex loading conditions, thereby unlocking new potential in hybrid structural design.

In this study, we study the development of a hybrid joint by thermoplastic welding via hot press forming of carbon FRP composite to additively manufactured titanium. To boost the joint strength, LPBF is exploited to fabricate out-of-plane reinforcement features on the titanium part, acting as anchors for fibre-friendly fixations points, as schematically illustrated in Figure 1.

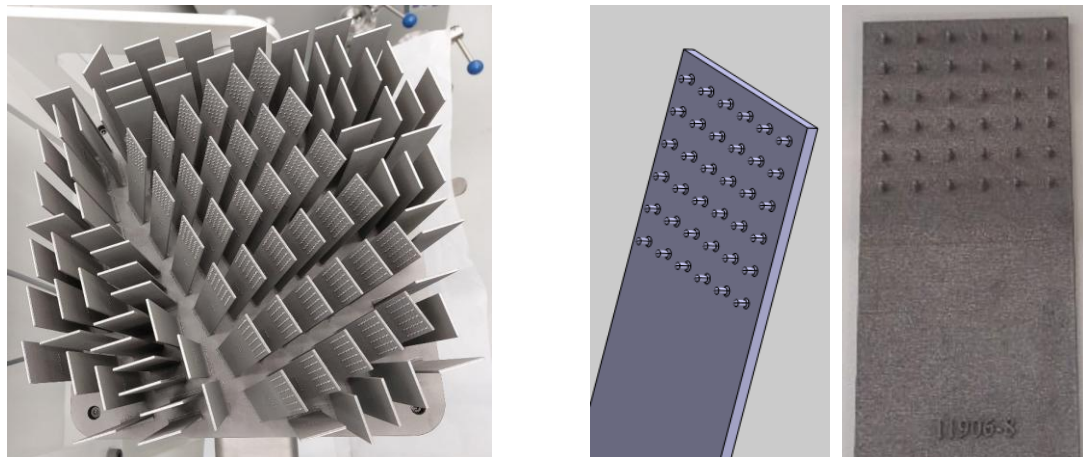
2. METHODOLOGY

2.1 Metal additive manufacturing

Metal AM is an advanced manufacturing process that builds metal parts layer by layer directly from a digital model. Unlike traditional subtractive methods, which remove material from a solid block, metal AM allows for the creation of complex geometries, reduced material waste and shorter production cycles [7]. It is widely used across industries such as aerospace, automotive, medical and tooling, where high-performance, custom or lightweight components are essential [8]. The process supports a range of metals, including titanium, aluminium, stainless steel and nickel-based alloys [9], enabling the production of functional parts with excellent mechanical properties. LPBF is one of the most widely used and most industrialised techniques within metal AM. In LPBF, a high-powered laser selectively fuses thin layers of

metal powder spread across a build platform. The part geometry directly comes from a (sliced) 3D CAD model. Each layer is melted and solidified after which the recoater deposits a new powder layer, building the part from the bottom up. The process takes place in a controlled environment, often filled with inert gas, to prevent oxidation and ensure material integrity. LPBF offers high resolution, fine detail and strong mechanical properties, making it ideal for producing intricate, high-performance components in aerospace and other demanding applications [10], [11].

For this study, parts were fabricated on a Nikon SLM Solutions 280HL. Titanium alloy Ti-6Al-4V (Grade 5), a common α - β titanium alloy exhibiting high strength, low density and good corrosion resistance, was used as feedstock material. Figure 2(a) shows the build plate after LPBF production with both pinned and regular (unpinned) specimens still attached to the build plate. The specimens were removed from the build plate via Electrical Discharge Machining (EDM) and received a stress relief heat treatment at 790°C for 2 hours under vacuum conditions. Figure 2(b) shows a close-up of the modelled and fabricated pin lay-out of the pinned specimens. 36 pins ($\text{Ø}0.8 \times 1.8 \text{ mm}$) were fabricated in a 6-by-6 matrix on the specimen. Although being one monolithic titanium part, the pins act as out-of-plane protrusions beneficial to the joint strength. As the surface roughness also plays an important role in the joint strength, the surface roughness of the specimens was determined using a Mahr MarSurf PS1. An average surface roughness (Ra) of five 2.5 mm sections per sample was measured both in length and width directions.



a) fabricated build plate with 105 pinned and regular specimens b) pin geometry of $\text{Ø}0.8 \times 1.8 \text{ mm}$ in a 6-by-6 matrix

Figure 2: LPBF of titanium adherends ($101.6 \times 25.4 \times 1.5 \text{ mm}$) for single lap shear specimens.

2.2 Thermoplastic composite manufacturing

Vacuum autoclave consolidation was used to prepare the polymer composite specimens used in this study. To enable welding of the hybrid joint, the composite was fabricated using unidirectional carbon fibre-reinforced thermoplastic material. A panel was made of 16 plies using TC1225 LMPAEK T700 145gsm fabric prepreg with a layup of $([+45; 90; -45; 0]_2)_s$. The low-melt PAEK resin is semi-crystalline and well processable with a specified melting temperature of 305°C and processing temperature range of 340°C to 385°C. Autoclave consolidation was performed at an 8 bar overpressure with a maximum temperature of 365°C for about 40 min. Ultrasonic C-scan inspection was performed to check the quality of the consolidated panel. Lastly, before hot press forming the thermoplastic composite was dried for 4 h at 250°C.

2.3 Hot press forming of hybrid joints

Hybrid Single Lap Shear (SLS) joints were welded by hot press forming. Hybrid joints were welded in batches of ten SLS specimens in one hot-press cycle. Ten titanium LPBF-specimens were placed next to each other in a holder frame mounted to the bottom tooling block of the press, see Figure 3(a). To alleviate the temperature difference, and hence minimise residual thermal stresses, between the composite in molten state and the titanium, the press was preheated to 270°C. The carbon fibre-reinforced composite was heated to the maximum processing temperature of 385°C using an infrared oven. The composite was then transported to the hot press by a robotic arm and placed on top of the titanium with an overlap of approximately 32 mm. Subsequently, the hot press was automatically closed and the hybrid joints were welded at a pressure of 20 bar for 2 min. Transport of the laminate from the oven to the closing time of the hot press was performed within 5 s, guaranteeing that the composite was in molten state when the weld was formed. After hot press forming, the thermoplastic composite was machined to obtain SLS test specimens following the geometry of Figure 3(b).

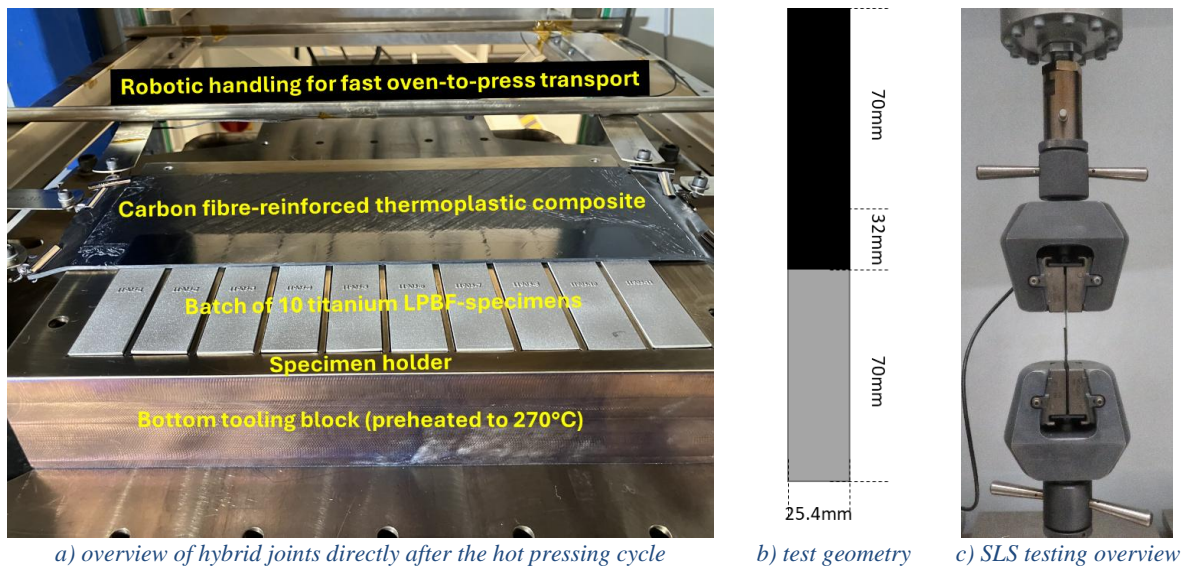


Figure 3: Hot press forming and SLS testing of hybrid titanium-composite joints.

2.4 Single lap shear testing of hybrid joints

SLS testing of the hybrid joints was performed on an Instron universal testing machine equipped with a 50 kN load cell to monitor the shear load. Testing was done with a speed of 1 mm/min following the ASTM D5868 norm at room temperature and 49.4% relative humidity. Prior to tensile testing, tabs were bonded to both ends of the SLS specimens to ensure that the load path is aligned with the welded surface and bending at the joined surfaces is avoided. Both the force and displacement were recorded for each SLS specimen.

3. MODELLING OF HYBRID JOINT STRENGTH

The joint strength between titanium and PAEK is governed by three principle bonding mechanisms: *i*) mechanical interlocking, *ii*) physical attraction and *iii*) chemical bonding [12]. For chemical bonding to occur covalent bonds between the metal and thermoplastic atoms need to be present. Similarly, physical attraction relies on secondary bonds, e.g. van der Waals forces and hydrogen bonds, between the metal and thermoplastic constituents. Finally, mechanical

interlocking relies on anchoring of PAEK by irregularities on the titanium surface, e.g. surface roughness or asperities.

In this study, the aim is to promote mechanical interlocking by designing out-of-plane protrusions, i.e. pins, on the titanium surface. During hot press forming, the carbon fibres and PAEK matrix are forced around the pins. At the faying surfaces, physical attraction and chemical bonding may occur; however, for this study it is assumed that mechanical interlocking is the dominant bonding mechanism. During SLS testing of the hybrid joints, either shearing failure of the pins or pin pull-out leads to joint failure. To model joint failure, shearing is assumed to be the dominant factor for determining the joint strength. Shearing is presumed to occur at the base of the pins without bending. Hence, the nominal shear stress τ_{nom} is given by:

$$\tau_{nom} = \frac{F}{A} = \frac{F}{n \cdot \frac{1}{4}\pi d^2} \quad (1)$$

where, F is the applied shear force, n is the number of pins and d is the pin diameter. The maximum allowable shear stress τ_{max} can be determined from the material's Ultimate Tensile Strength (UTS):

$$\tau_{max} = 0.6 \cdot \sigma_{UTS} \quad (2)$$

From prior experimental trials, in which additively manufactured tensile test samples were tensile tested, the UTS of LPBF titanium was determined to be 1014 MPa. Following the ASTM D5868 norm, the shear force is projected on the total SLS joint surface, in this case 25.4 mm by 25.4 mm. Hence, from Equations (1-2), the equivalent SLS shear strength can be computed based on the pin geometry and arrangement. This is illustrated in Figure 4, in which the pin diameter is varied up to 1.4 mm. The four lines indicate four different pin matrix arrangements ranging from 4x4 to 7x7.

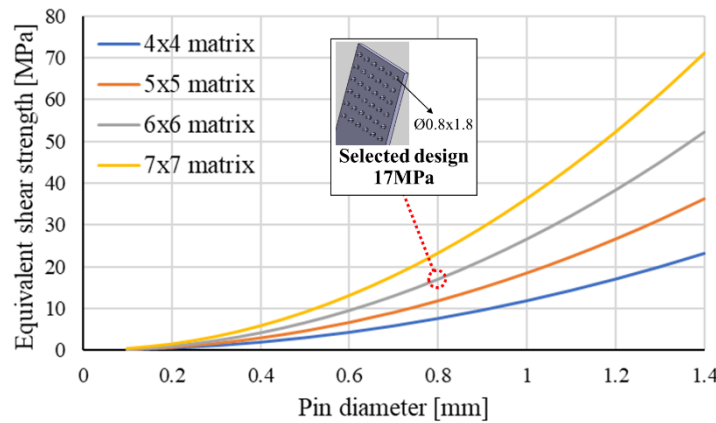


Figure 4: Equivalent shear strength as a function of the pin diameter and pin arrangement.

4. RESULTS AND DISCUSSION

4.1 Fabrication of SLS specimens

LPBF of the titanium samples was successfully done, as shown in Figure 2. From five samples, the average surface roughness was determined at two locations both in length and width

directions, which is aligned with the build direction and across, respectively. The surface roughness results are listed in Table 1. As can be expected from LPBF, surface roughness values are relatively high compared to other manufacturing techniques; e.g. for sheet metal titanium an Ra of about 1 μm is common, while LPBF produces surfaces that are about tenfold rougher. The measured roughness values are in line with other studies that have characterised LPBF of titanium alloy Ti-6Al-4V [13]. Also, as expected, in the build (i.e. length) direction, in which layers are continuously stacked on top of each other, the surface roughness is higher compared to the in-plane (i.e. width) direction.

Table 1: Surface roughness of LPBF-fabricated titanium samples.

Sample ID	Length (Ra) [μm]	Width (Ra) [μm]
11905-18	11.10	9.44
	14.10	8.63
11905-19	13.99	12.31
	13.34	14.31
11905-20	9.80	9.28
	10.26	8.45
11905-21	16.11	9.63
	12.21	9.31
11905-22	9.23	8.18
	10.44	7.64
average	12.06	9.72
std. dev.	2.26 (19%)	2.05 (21%)

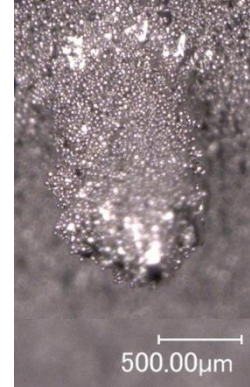


Figure 5: Microscopic image of a pin of $\varnothing 0.8 \times 1.8$ mm.

For joining methods that rely on mechanical interlocking, a high surface roughness is desired. Hence, intrinsically LPBF is a good manufacturing technology for this purpose, alongside the ability to efficiently fabricate protruding features on a flat plate as one monolithic part. The high surface roughness can also be observed in Figure 5, which shows a microscopic image of a single pin. The image shows many powder particles that are partly welded to the part being the cause of the intrinsic high surface roughness. The measured pin diameter is 825 μm , a little wider than the nominal value of 800 μm . This discrepancy can partly be attributed to the accuracy of the LPBF process. Also the partly-attached powder particles impede an accurate measurement.

Vacuum autoclave consolidation resulted in composite panels with a panel thickness of 2.24 mm. Ultrasonic C-scan inspection revealed no voids or incorrect consolidation anomalies. During hot press forming the pins fully penetrated the composite material acting as anchor points. Due to the high pressure the thickness of the composite material was reduced by about 0.5 mm at the joint overlap region. Figure 6 shows a section of the hot-pressed laminate with two hybrid titanium-composite joints. The top surface of the composite relies an imprint of the 6-by-6 matrix of pins, however no through penetration was observed. By machining the contour of Figure 3(b) from the composite, the SLS test samples are produced.



Figure 6: Laminate section with two hot-pressed hybrid titanium-composite joints.

4.2 Testing results

The shear stress results of the SLS tests are shown in Figure 7. Figure 7(a) shows the measured shear stress as a function of the strain for the LPBF samples with pins. Conversely, Figure 7(b) shows the results of the reference case without pins. For the reference case, all production and test steps are similar only LPBF samples without pins are used. Hence, in this case the joint strength relied solely on the surface roughness. For the pinned samples, the first sample (i.e. 11906-1) slipped in the gripper of the tensile tester due to insufficient clamping force and is therefore taken out of the presented results. The maximum shear stress of this sample was however similar to the presented results only more strain was incorrectly recorded. In the case of samples without pins not all samples survived the hot pressing, cutting and handling prior to shear testing. Hence, only five results out of ten anticipated samples are presented.

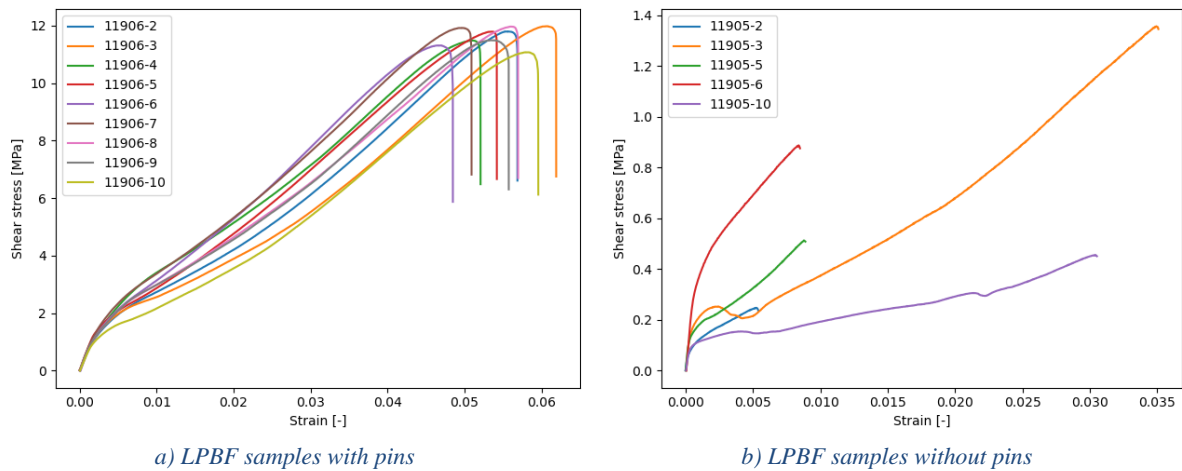


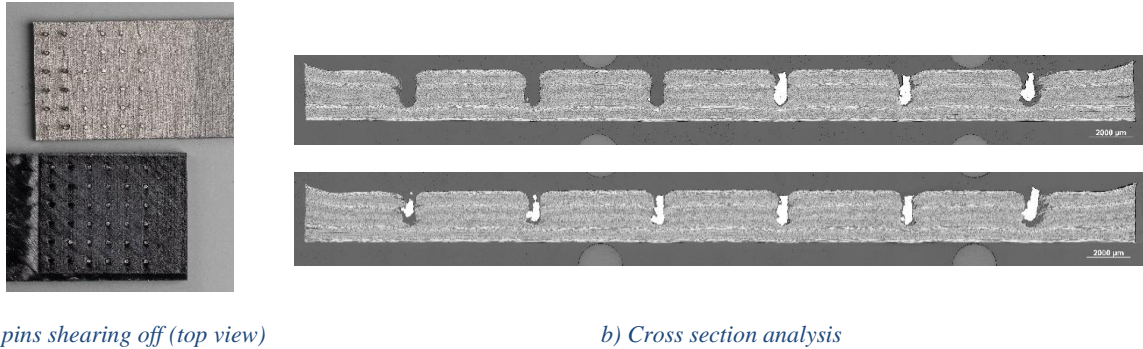
Figure 7: Single lap shear test results.

The shear stress results of the LPBF samples with pins are very consistent. The average maximum shear stress is 11.6 MPa with a relatively low standard deviation of 0.30 MPa (i.e. 2.6%). In all cases, a brittle, abrupt failure was observed at a strain of about 5-6%. Compared to the modelled prediction of 17 MPa shear strength, the experimental results are lower. This can be explained by a number of model assumptions; e.g., local stress concentrations at the edges of the SLS contact area knocking down the nominal shear strength and pin bending have been ignored, as well as zero-defect fabrication of the pins is assumed the model.

In contrast, the reference samples without pins failed on average at a maximum shear stress of 0.70 MPa with a relatively high standard deviation of 0.39 MPa (i.e. 56.6%). The low maximum shear stress in combination with large variation in stress and strain, and the fact that only 50% of the samples survived the fabrications steps, indicate that a hybrid joint between titanium and PAEK without additional out-of-plane protrusions solely relying on surface roughness as interlocking mechanism is a very weak, unreliable joint. Also, the relatively high surface roughness of about 10 μm (R_a) does not provide any significant mechanical interlocking in the case of a hot-pressed, titanium-PAEK joint. This is a testimony to the aforementioned fact that titanium-PAEK joints are particularly challenging due to chemical incompatibility and mismatches of thermo-mechanical properties.

Figure 8 shows images of the post-mortem optical investigation. Figure 8(a) shows a top view of the faying surfaces of, in this case, Sample 11906-7. The image shows that 25 pins were sheared off and 11 pins were pulled out by the SLS test. Notably, most of the pulled-out pins

are at the edge of the titanium sample. The higher pull-out rate at the edge can be explained by the fact that for a SLS test some bending and peeling may occur at the edge compared to e.g. a double lap shear test. Optical investigation of all pinned samples showed that, on average, 26 pins are sheared off by the SLS test; hence, Figure 8(a) is representative for the entire test set of pinned samples.



a) pins shearing off (top view)

b) Cross section analysis

Figure 8: Post-mortem optical investigation of shear-tested joints with pins.

Figure 8(b) shows the microscopic images of two cross-sections of the composite along the centre line of the diagonal of the 6x6 matrix. The images highlight the different failure mechanisms. In three cases (i.e. the top-left three empty holes), the pins were pulled out. In the other nine cases, the pins were sheared off. The bottom-right case best illustrates that the pin was first bent and partly pulled out of the laminate before shearing off. Also, the pins show deformation near the base of the pins as well as along the length. Pin elongation and necking seems to occur prior to shearing off. Likely the aforementioned partly-attached powder particles that are present on the pins act as local anchor points that provide grip during pin pull out, leading to elongation and necking of the pins before brittle shear-off failure. The observed 5-6% strain before failure can be attributed to the pin deformations; however, as the curves are all continuous, no intermittent crack-stopping behaviour is exhibited.

As the hybrid titanium-composite joints without pins showed poor results, it can also be concluded that the surface-to-surface contact area between the pins did not aid in improving the pinned joint strength. Hence, the 17x improvement can be solely attested to the out-of-plane protruding pins interacting with the carbon fibre-reinforced thermoplastic composite. Accordingly, if the surface-to-surface adhesion between titanium and PAEK can be improved, e.g. by chemical surface preparation, laser texturing or additional interface materials, the pinned hybrid joint can also be further enhanced.

5. CONCLUSIONS

In this study, hybrid titanium-composite joints were developed using additive manufacturing (AM) and thermoplastic welding via hot press forming. The results show that the use of out-of-plane protrusions (pins) on the metal adherend significantly enhances the joint strength compared to hybrid joints without out-of-plane enhancements other than an AM-intrinsic high surface roughness. The average maximum shear strength of the pinned samples was 11.6 MPa, which is substantially higher than the 0.70 MPa achieved by the reference samples without pins. Although the experimental results were lower than the modelled prediction of 17 MPa, this study truly demonstrates the potential of AM and thermoplastic welding for the creation of strong and reliable hybrid joints. The post-mortem analysis revealed that pin shearing off

and pull-out were the primary failure mechanisms, with most pins being sheared off during the single lap shear tests.

The findings of this study contribute to the development of advanced hybrid joints for aerospace and high-performance engineering applications, in which structural efficiency, weight reduction, durability and predictability are critical aspects. Future research focuses on optimizing the pin design, material selection and manufacturing processes to further improve the joint strength and reliability.

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