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# Hybrid additive manufacturing with titanium powder and aluminum substrates via laser powder bed fusion

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**Abstract**

For the thermal joining of aluminum and titanium, the approach of solely melting the aluminum joining partner, while the titanium partner stays in the solid form, has been commonplace since 1996. This is done to limit the formation of a brittle intermetallic compound layer in the interface. In case of additive manufacturing with titanium powder and aluminum substrates, this approach is not transferrable because the titanium powder has to be melted to create the part. In this study, titanium samples were additively manufactured onto aluminum substrates using a commercial laser powder bed fusion (LPBF) machine. The influences of the energy density during the process on the sample porosity, the characteristics of the interface between sample and substrate, as well as the interfacial tensile strength are analyzed. Despite the melting of both materials, a great potential for high interfacial tensile strength has been found.

**Keywords:** Laser powder bed fusion, additive manufacturing, multi-material

## 1 Introduction

Due to the successive generation of parts layer by layer, the laser powder bed fusion manufacturing process (LPBF or PBF-LB/M for “powder bed fusion - laser beam / metals”) enables complex designs and the integration of additional functionalities [1]. Considering the improvement of structures in terms of high functionality and low weight, multi-material (hybrid) structures are of significant interest for adapting the part properties to specific local requirements [2]. Due to its layer-wise working principle, PBF-LB shows high potential for the generation of multi-material parts and in-situ alloying for graded material properties [3]. While state of research is constantly growing, hybrid and multi-material PBF-LB are currently still at beginning stages [4]. First implementation examples of multi-material PBF-LB production exist for the combination of different alloys based on the same material [5], of stainless steel and copper [6] as well as of aluminum and copper [7]. At the interface between those material pairings, intermetallic phases are formed. In case of aluminum and copper, significant cracking occurred within intermetallic compounds with thicknesses of 200 µm [7]. In addition to increasing interest in multi-material, also the additive manufacturing of hybrid metallic parts using ’preforms’ is developed further [8]. Initial studies show that additional interlayers are needed to improve bonding when titanium powder is used for PBF-LB on stainless-steel substrates [9]. For the combination of aluminum powder and steel substrates, it was found that even though the steel substrate has a higher melting interval compared to the aluminum powder, its melting can only be avoided at comparatively small energy densities [10].

When joining aluminum and titanium, different intermetallic phases can be formed in the interface area. Aluminum-rich phases (i. e. trialuminide Al3Ti) have a high oxidation resistance, but show very brittle material behavior after cooling down due to a low number of slip planes [11]. When joining aluminum and titanium thermally, the cooling process induces significant thermal stresses within the bi-metal component due to the


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significantly different thermal expansion coefficients. These stresses are sufficient to cause failure by cracking without any additional forces [12].

The risk of an interfacial connection failure increases with increasing volume fractions of intermetallic phases in the interface area. If both joining partners (aluminum and titanium) melt during the process, the increased diffusion and mixing of the materials lead to excessive interfacial compound formation [13]. Therefore, the approach of solely melting the aluminum joining partner, while the titanium partner stays in the solid form, has been commonplace for the thermal joining of aluminum and titanium sheets or parts since 1996 [14]. If the thickness of the interfacial intermetallic compound layer is limited to approximately below 2 µm, tensile strengths of about 200 N/mm² have been achieved for different thermal joining processes [15].

## 2 Aim and Scope

Hybrid additive manufacturing using preform substrates offers new design possibilities and room for process chain optimization in terms of manufacturing costs and times. Therefore, the aim of this work is to verify the feasibility of a standard PBF-LB process to produce hybrid titanium-aluminum structures, see [17]. In the study reported here, the additive manufacturing with titanium powder and aluminum substrates is investigated using a commercial PBF-LB system and standard constant process parameters in the build direction of the samples. The hybrid titanium-aluminum samples are examined with regard to the porosity, the interface between sample and substrate, and, for selected parameter sets, the interfacial tensile strength as well as the fracture behavior.

The approach of solely melting the aluminum joining partner while the titanium component remains in a solid state should not be applicable for additively manufacturing with titanium powder and aluminum substrate via PBF-LB since the titanium powder must be melted during the process. The melting temperature of the titanium powder is significantly higher than that of the aluminum substrate. Therefore, it is hypothesized that the small melt pools and fast laser beam scanning speeds during PBF-LB, in comparison to typical laser-based thermal joining processes, reduce the interfacial intermetallic compound formation to an extent that adherent and strong interfaces can be generated despite melting of both materials in the interface, compare [17].

## 3 Materials and Methods

In this study, Ti6Al4V powder with a particle size distribution between 15 µm and 45 µm and EN AW 5083 substrates were used to additively manufacture hybrid samples using a commercial PBF-LB system (TruPrint 1000 from TRUMPF). This system operates with a maximum effective laser power of 200 W, a laser wavelength of 1070 nm, and a beam diameter in the working plane of 55 µm with a gaussian-like beam distribution. Argon (purity 4.8) was used to create an inert gas atmosphere with an oxygen level smaller than 0.01%. A bi-directional scanning strategy with a rotation of the scanning vectors between the individual layers of 51° was utilized. The energy density was adopted by varying the laser power and scanning speed. The layer thickness and hatching distance were kept constant at 20 µm and 80 µm respectively. The constant process parameters were selected according to common parameter ranges used for PBF-LB of Ti6Al4V [16]. The laser power and scanning speed were varied over a wide enough range to reach two times and less than half of commonly used energy densities. The variations were carried out to evaluate the influences on the process behavior, especially on the interface characteristics and properties. The first powder layer was manually created by moving the substrates, which were coated with a closed powder layer beforehand, upwards in 10 µm increments until the recoater used in the PBF-LB system had completely removed the powder from the substrate. Thereafter, the substrate was moved down by 20 µm and new powder was applied using the recoater.

The influence of different energy densities (different laser powers and scanning speeds) on the porosity was determined using additively manufactured 5 mm cube samples. These were analyzed using vertical cross sections in the center of the sample and a contrast-based image analysis. For this, a light microscope (ZEISS Axio) and the 'Olympus Stream' analysis software were utilized. The connection areas to the substrates and the direct surface areas of the samples were not taken into consideration within the porosity analysis. The microscope images of the cross sections were also used to determine the 'connection in cross section' (see Fig. 1). Therefore, a pixel-based length analysis was used to measure the percentage of the actual connection length (between the additively manufactured sample and the substrate remaining after the process) from the width of the cube. The measurements were carried out using a scanning electron microscope (SEM) (EVO-MA10 from ZEISS). For the material contrast in the images, a backscattered electron (BSE) detector was utilized. In addition, an energy dispersive X-ray spectroscope (EDS) (Bruker Quantax) was used to determine elemental compositions. Tensile specimens were produced to analyze the interfacial tensile strength (see Fig. 1) between the additively manufactured structures and the substrates. To avoid influences of post-processing steps, the tensile specimens were directly manufactured in a wedge-shape and tested in as-built condition. The tensile testing was performed using a ZwickRoell Z250 RED tensile testing machine and a Xforce HP load cell with a measuring range between 10 N and 5000 N. For each set of examined parameters, five tensile test samples were produced and tested. Therefore, to account for deviations in the samples, the median and the mean positive and negative deviations were calculated. The tensile strengths of all specimens were calculated using the initial connection area (not the actual remaining area after cooling), which was measured using a Keyence VK-9710 laser-scanning confocal microscope and the 'VK Viewer VKH1V1E' software (see Fig. 1). The same confocal microscope and software were used to measure the height profiles of the substrate-sided fracture surfaces of the tensile test samples and to determine the average height differences between the substrates and fracture surfaces.

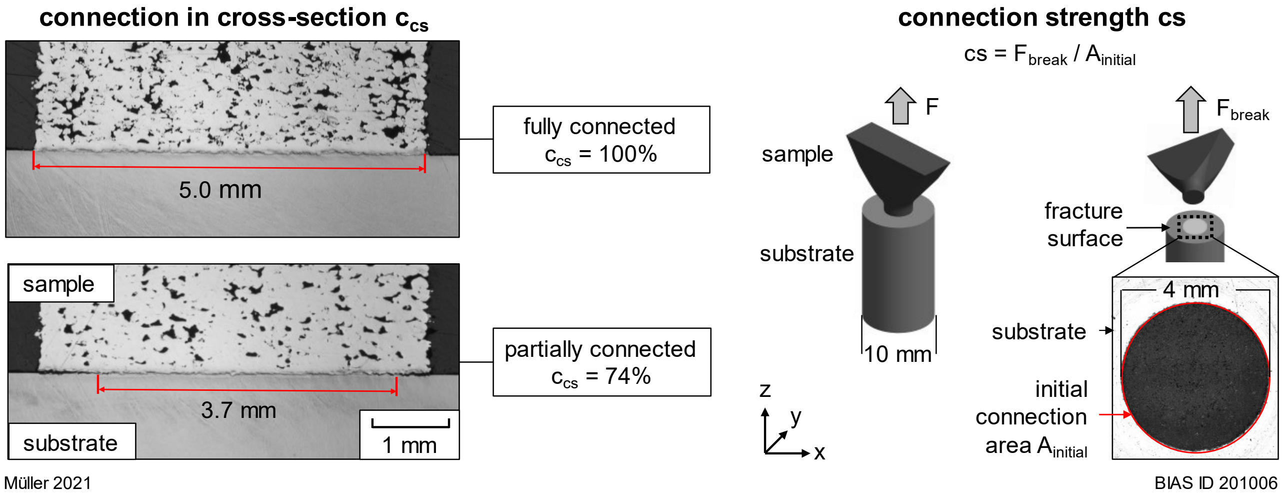



Fig. 1: Determination of the connection in cross-section and the connection strength, according to [17]

The optical properties of the first 20 µm powder layers were examined using a double integrating sphere setup with a laser wavelength of 1080 nm and a diffusely reflecting BaSO4 sphere coating. Thereby, the reflection of the laser radiation at the powder layer and the transmission of the laser radiation through the powder layer were measured. More details regarding the double integrating sphere setup can be found in [17].

## 4 Results

Using the double integrating sphere setup, the transmission of a measuring laser beam with the same wavelength regarding the LPBF processing laser beam through Ti6Al4V powder layers with a thickness of 20 µm was measured as 22%. With a determined reflection of 14%, the absorption of the laser radiation by the titanium powder was calculated as 64%. The influence of the energy density on the porosity and the interfacial connection measured in the cross sections of the Ti6Al4V samples additively manufactured onto EN AW 5083 substrates is shown in Fig. 2 for energy densities between 16 J/mm³ and 152 J/mm³. Three parameter sets resulted simultaneously in a porosity < 0.1% and a complete interfacial connection after cooling.

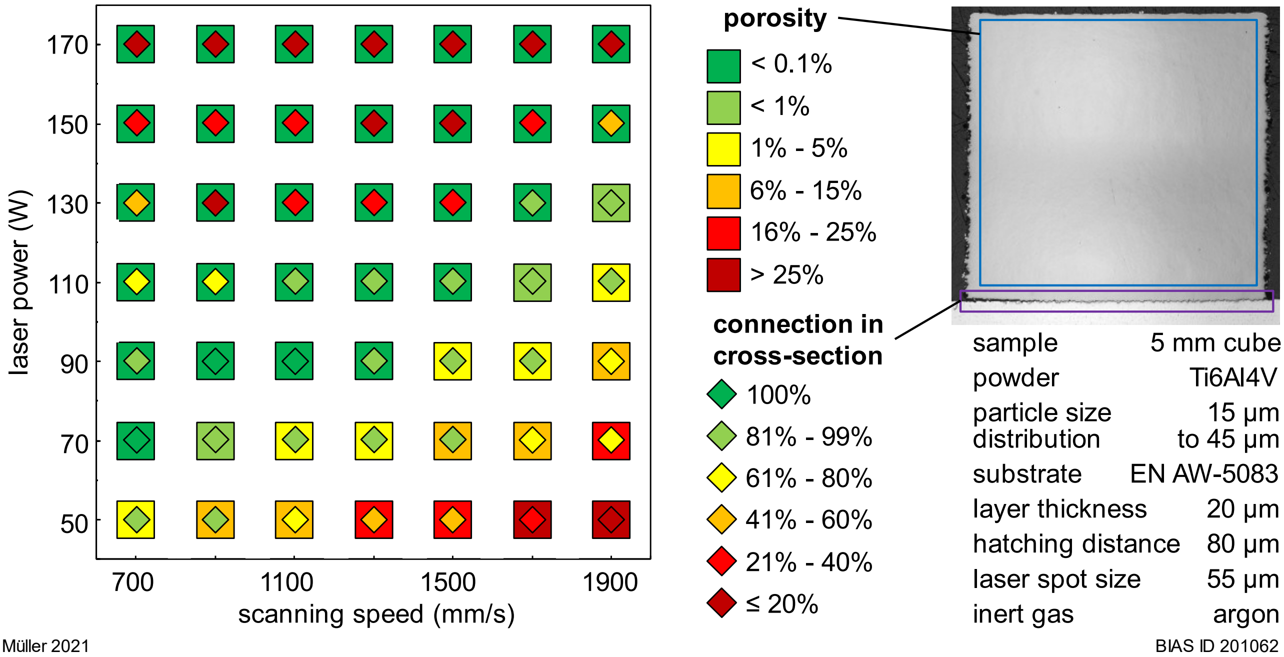
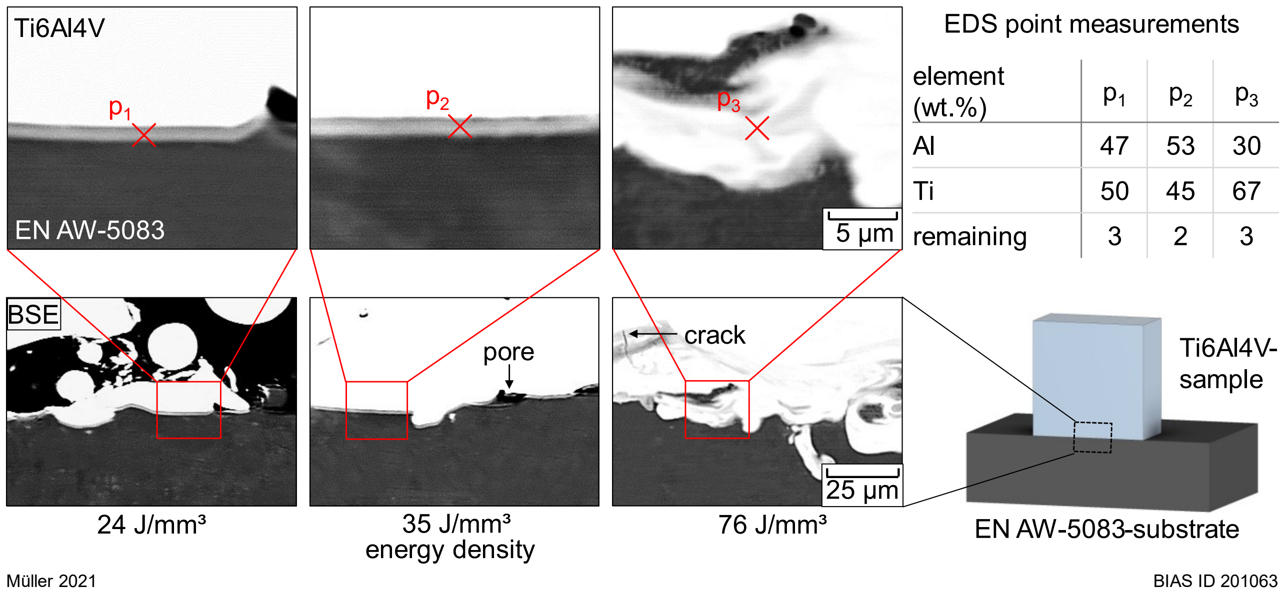



Fig. 2: Influence of laser power and scanning speed on the porosity and the connection in cross-sections of titanium-aluminum hybrid samples, data from [17]

In Fig. 3, exemplary BSE images of the interfacial areas are shown for increasing energy densities from left to right. At a low energy density (24 J/mm³: 50 W and 1300 mm/s), the formation of intermetallic compounds is limited to a layer of 1 µm thickness. However, significant lack of fusion porosity on the titanium side (white in the image) is observable. When slightly increasing the energy density (35 J/mm³: 50 W and 900 mm/s), the porosity in the titanium is reduced and the intermetallic compound layer is approx. 1.5 µm thick. For higher energy densities, the substrate strongly melted and a dominant mixing of titanium and aluminum occurred. Irregularly distributed intermetallic compounds and cracks are present in a 40 µm wide area around the interface.




| element (wt.%) | $p_1$ | $p_2$ | $p_3$ |
|---|---|---|---|
| Al | 47 | 53 | 30 |
| Ti | 50 | 45 | 67 |
| remaining | 3 | 2 | 3 |

Fig. 3: BSE images of the connection areas of titanium-aluminum hybrid samples as well as EDS point measurements. [17]

Fig. 4 shows the tensile strength of titanium-aluminum tensile specimen produced with different energy densities in the range of 24 J/mm³ (50 W and 1300 mm/s) to 76 J/mm³ (110 W and 900 mm/s) as well as exemplary correlating height profiles of substrate-sided fracture surfaces. In the case of an energy density of 35 J/mm³ (50 W and 900 mm/s), the highest strengths occurred with a median value of 94 N/mm² and a mean positive deviation up to 151 N/mm² (maximum individual sample value 170 N/mm²). Thereby, the average height difference between the substrate surface (=initial interface) and the fracture surface lies at a small negative value, i.e. mainly some microns in the direction of the aluminum (Fig. 4 height measurement in the middle). At a smaller energy density of 24 J/mm³ (Fig. 4 left height measurement), the significantly lower strength correlates with a change of the fracture surface average height level in the direction of the titanium side (positive red peaks in Fig. 4 left). Otherwise, an increase in the energy density to 76 J/mm³ results in a connection strength of below 5 N/mm². The corresponding fracture surface (Fig. 4 right height measurement) lies at an average height of 42 µm, i.e. significantly within the height level of the initial aluminum substrate.

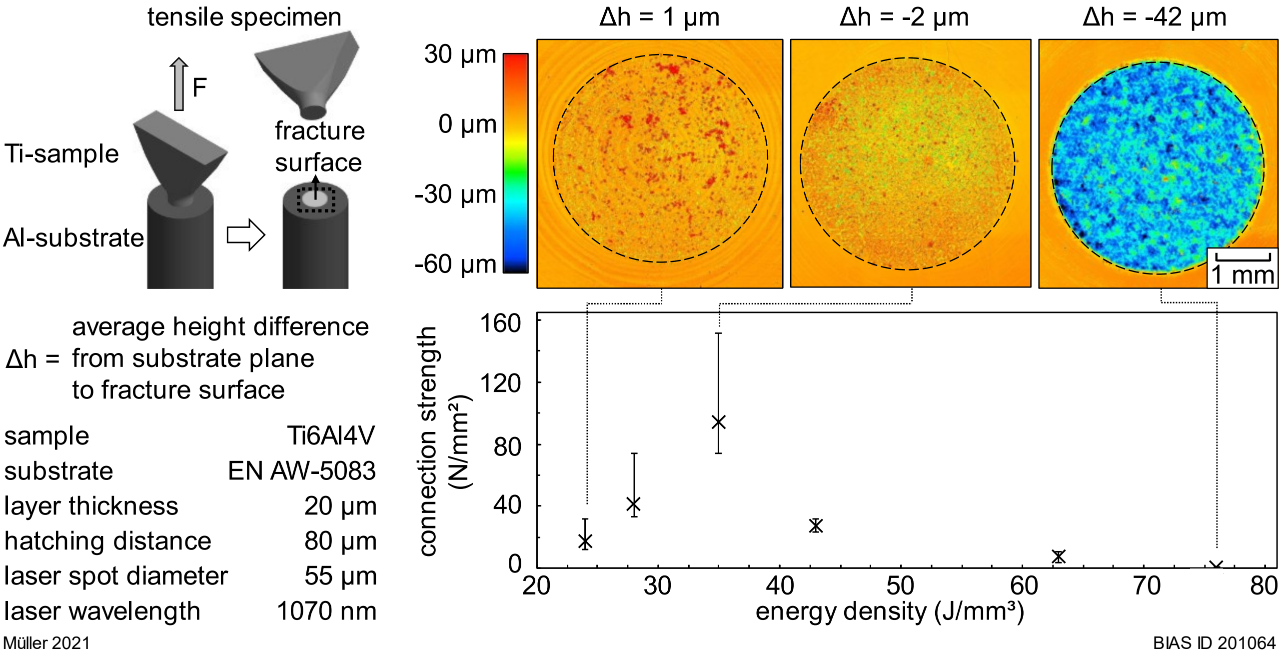



Fig. 4: Connection strengths and height profiles of the substrate-sided fracture surfaces of titanium-aluminum tensile specimen. [17]

## 5 Discussion

The hypothesis, namely that the small melt pools and fast laser beam scanning speeds during PBF-LB, in comparison to the typical laser-based thermal joining processes, reduce the interfacial intermetallic compound formation in the case of titanium powder onto aluminum substrate to an extent that adherent and strong interfaces can be generated despite melting of both materials in the interface, is supported by this study (see also [17]). The experiments have demonstrated that parameters exist that result in low porosity within the additively manufactured titanium volume as well as simultaneously in a completely connected interface to the aluminum substrate. Firstly, the transmission of laser radiation through a 20 µm thick titanium powder layer is low (22%). Additionally, the Fresnel absorption of laser radiation of the wavelength used is much less in the case of aluminum than for titanium. Secondly, the high thermal conductivity of aluminum increases the thermal conduction into the substrate volume and the corresponding heat loss. This results in high temperature gradients near the interface and rapid cooling. This can explain the comparatively marginal melting of the aluminum, despite the contact with molten titanium having a much higher melting temperature, and the formation of thin intermetallic compound layers with thicknesses < 2 µm (see Fig. 3). Comparable to the findings for conventional joining of aluminum and titanium as well as for multi material PBF-LB of aluminum and copper [7], it could be shown that thin intermetallic layers are not prone to cracking and show high bonding strengths, while bigger intermetallic layers are susceptible to cracking and only have minor bonding strengths. A distinct assignment of the present intermetallic phases to known aluminum titanium phases (TiAl, Al3Ti, Ti3Al) was not possible. The aforementioned reasons can explain the fact that strength values of up to 170 N/mm² were achieved for individual tensile test samples. The rough surfaces (as-built condition) and the notch stress effect due to the specimen shape might be two reasons for the remaining gap to the values of > 200 N/mm² [15] being reported for conventional aluminum-titanium joints.

## 6 Conclusion

For the hybrid additive manufacturing of titanium samples onto aluminum substrates using a commercial PBF-LB machine with a constant layer thickness (20 µm) and constant energy densities in build direction, it can be concluded that, rather contradictory to the state of the art in laser-based joining of aluminum and titanium:

The manufacturing of titanium powder onto aluminum substrates shows high strength potential as dense titanium volume can already be built up, while only small amounts of intermetallic compounds are formed at the interface.

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