toolcraft

TRUMPF

White paper

Evaluation of mechanical properties for Ti6Al4V on the TruPrint 5000 according to aviation requirements

Contents

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Abstract

The following white paper provides insights on how Toolcraft & TRUMPF approached an initial qualification of Ti6Al4V specimen on one of the latest machines released by TRUMPF, the TruPrint 5000. Based on the aviation requirements for additively manufactured parts using the Laser Powder Bed Fusion (LPBF) technology, test build jobs were designed and produced at Toolcraft on their TruPrint 5000 within an industrial aerospace environment. The results in regard of the material properties (computerised tomography, microstructure & grain size, tensile testing, fatigue testing and fracture toughness) which were evaluated and confirmed by certified test laboratories, are the main content of this paper.

Introduction

The aviation industry has always been driven by the development of the latest technologies. New materials and manufacturing technologies enabled significant advances towards the reduction of CO_2 emissions and a more sustainable industry. The use of Laser Powder Bed Fusion (LPBF) is no exception. Meanwhile the industry has taken the step from first prototypes to a serial production of several thousand parts per year. To achieve the corresponding Technology Readiness Level (TRL) that is necessary for a serial production, a substantial number of investigations need to be made.

Within an early stage of a machine qualification, the most important perceptions for the machine users are the mechanical properties and the homogeneity with which they can be generated. This white paper is focusing on a collaborative approach of TRUMPF & Toolcraft to investigate the suitability of the TruPrint 5000 to produce aerospace parts made of Ti6Al4V.

This material is commonly used in the aviation industry due to its excellent properties such as high specific strength and good corrosion resistance. These properties match relevant applications such as structural components, jet engine blades and many other parts within an airplane.
Besides the material, the build job design and industry specific requirements were of significance. In coordination with a European aerospace company, a build job design was agreed that focuses on qualification testing procedures, which contain investigations such as CT scans, tensile & fatigue testing, metallurgical analysis, fracture toughness and many more. The exact target values for the mechanical properties have been refined by the OEM throughout the years and are similar to aviation specific Additive Manufacturing industry standards such as the DIN 65124. Others are company specific and need to be kept confidential. In this case the passages in the white paper indicate if such requirements were fulfilled or not.

Prior to printing the first qualification specimen, additional tensile & fatigue test samples were built on the same TruPrint 5000 machine and tested to enlarge the statistical basis. The following steps included the printing and heat treating of the qualification specimen in an aviation approved industrial environment at Toolcraft as well as analyzing all specimen by qualified test laboratories.
The results shown on the next pages of this white paper are a snapshot of an ongoing continuous improvement process at TRUMPF. The company is driven to provide new machines, features and materials to the aviation market in order to facilitate more applications for the customers.

Machine setup

Several years ago, TRUMPF started its first discussions with aerospace companies to qualify specific materials on the TruPrint 3000 which is a mid-size format, single laser system. Since then, the LPBF technology advanced and for this project, the latest addition in the TRUMPF portfolio, the TruPrint 5000 is the machine of choice. This LPBF system is conclusively targeting the industrial serial production. Three fiber lasers each with a power of up to 500 W, a 100 µm spot size diameter and a 100 % scan field overlap enable an increased output and a very flexible assignment of the lasers to each of the specimen. This matches the industry requirement to decrease the costs of production. With a build envelope of Ø 300 mm (11.8 inch) x 400 mm (15.75 inch) height, the machine is considered a mid-size format system. To leverage the potential for fast turnarounds of build jobs, the part & powder process flow is conducted with suitable peripherals such as a sieving station, unpacking station and powder silo. All these devices are developed around the idea of an exchangeable cylinder principle to allow powder handling in parallel to primary processing.

The machine is equipped with a primary gas flux that removes process emissions such as fume and spatter from the powder bed, and a secondary gas flux to evacuate these process byproducts from the build chamber, suppressing unwanted interaction with the laser beam. As typical for the processing of reactive materials such as Ti6Al4V, Argon was used as shielding gas with a controlled oxygen level below 100 parts per million (ppm) during the complete duration of the build jobs. The virgin powder used for these builds, corresponds with the specifications of aerospace companies for Titanium Grade 5 with a particle size distribution (PSD) of 20-63 µm. The 60 µm thick powder layers were applied with a soft recoater medium (silicon x-lip).

Before the build jobs were started, typical quality tests such as measurement of laser power & laser focus, build job file review and others were performed by Toolcraft to avoid unwanted influences. Additional quality data were recorded through the machine's monitoring systems to provide a holistic set of quality data.

Figure 1: The TruPrint 5000 with its exchangeable cylinder principle and 3 lasers with 100% full field overlap. Complemented by a powder silo, sieving & unpacking station. Depowdering station separately available.

Parameter pre-study

Within this pre-study, 256 density cubes of 10 mm x 10 mm x 10 mm, and 528 tensile samples were built and analysed. Different x-y positions on the substrate plate and the build height z were taken into account in order to examine the homogeneity of the material's properties depending on its position. Furthermore, the influence of the three lasers was also investigated by exposing each sample with one laser.

A design of experiments (DoE) was utilized to identify an appropriate process window for relative densities ≥ 99.9 %. This DoE was extended for each quadrant of the substrate plate, whereby a quadrant represents one of four regions in a cartesian coordinate system.
The density cubes were metallographically prepared and analysed by means of a quantitative metallographic method. The results reveal that the three lasers and the different positions do not have a statistically significant influence on the samples' relative densities in the investigated process window.

Previous internal investigations have already revealed that relative densities of ≥ 99.9 % can be achieved for Ti6Al4V without deep investigations compared to some other materials. Yet such high relative densities do not assure simultaneously good mechanical properties as well.

Due to its crystal structure at room temperature, Ti6Al4V has a brittle material behavior compared to the majority of metals. Therefore, the elongation at break is a sensitive and thus, an appropriate material property in order to assess the quality of the samples and thereby its process.

Starting from the results of this density DoE, multiple vertically oriented tensile samples were built with the most promising parameters on different x-y-positions of the substrate plate. In a subsequent build job, the complete build volume was filled with tensile samples in order to investigate if the build job height z has an influence on the mechanical properties. In figure 2 the two tensile build jobs are depicted.

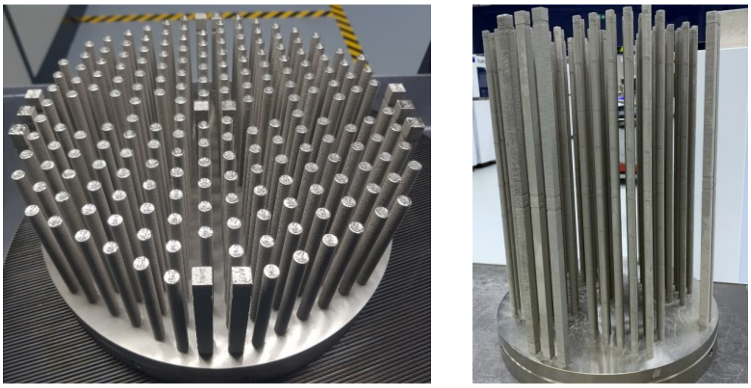

Figure 2:
x-y build job with vertical tensile samples distributed on the x-y-position of the substrate plate. x-y-z build job with vertical tensile samples distributed on the whole build job volume.

In order to gain insight on the material's natural behavior, no heat treatment was applied to the vertical oriented tensile specimens. The horizontal specimens were stress relieved at 650 °C (1202 °F) under vacuum for 2 h in order to decrease the influence of residual stresses. The influence of the surface roughness was eliminated by machining the tensile specimens to a diameter of 5 mm with an initial length of 25 mm.
The results of the machined tensile samples, depicted in figure 3 and figure 4, reveal a yield strength of 1125 MPa ± 11 MPa and a tensile strength of 1265 MPa ± 9 MPa for the x-y build job. It is pointed out that these achieved strengths are significantly above the requirements of ASTM F2924. The low standard deviations demonstrate furthermore the high homogeneity over the substrate plate. Not only the high homogeneity but also the reproducibility are proven by the results of the x-y-z build job achieving a yield strength of 1129 MPa ± 11 MPa and a tensile strength of 1256 MPa ± 13 MPa.

The horizontal build job confirms the achieved quality with yield strength of 1137 MPa ± 10 MPa and a tensile strength of 1254 MPa ± 4 MPa. Regarding the measured strengths, no influence is visible depending on the build orientation of the samples.

In most cases high strengths are associated with lower elongation at break. However, despite these high strengths an elongation at break of 10,3 % ± 0,7 % has been obtained in the x-y build. For the complete build volume, the elongation at break is even 11,5 % ± 1,5 %, whereas for the horizontal build job a lower elongation of 7,3 ± 0,4 % is achieved. This lower elongation can be attributed to the inherent anisotropy given by the build orientation.

Obviously, the different build orientation affects the elongation more than strength. Besides, the standard deviation for the x-y-z build job is slightly higher than for the lower x-y build job. It can be presumed that this deviation does not only result from the influence of the build job height but also from the higher number of samples.

In conclusion, the achieved tensile properties demonstrate a high homogeneity for non-heat treated Ti6Al4V-samples given by the process conditions of the TruPrint 5000 with its extensively qualified parameter. It provides an exceptional precondition for heat treatments and high isostatic pressing aiming at decreasing process-inherent anisotropy.

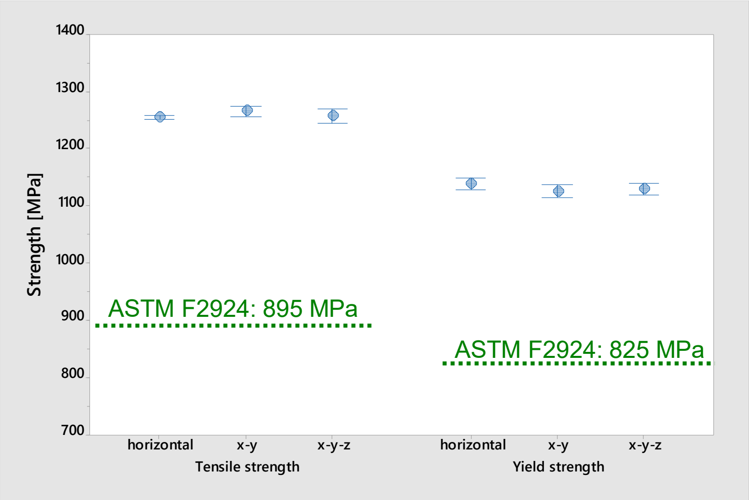

Figure 3:
Measured yield and tensile strengths for machined tensile samples without heat treatment.

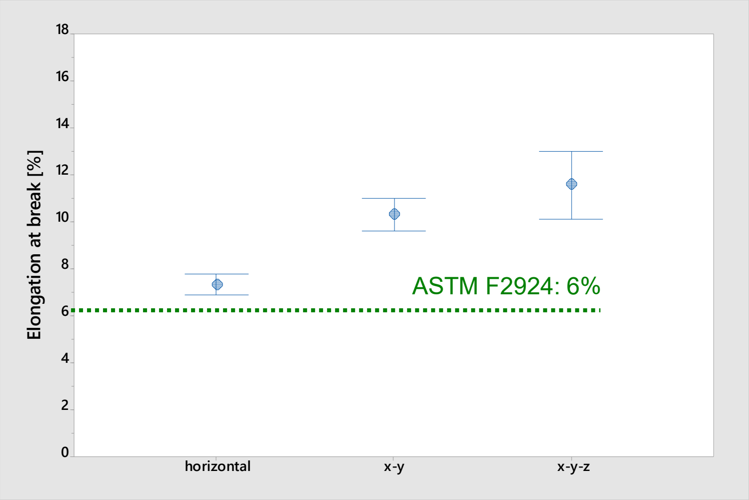

Figure 4:
Measured elongations at break for machined tensile samples without heat treatment.

Build job layout for qualification build jobs

The qualification build jobs included in total 75 test samples based on nine specific test geometries which are depicted in figure 5. For each test geometry specified, material analysis were conducted in certified laboratories. The following analyses were performed

- Computerised tomography (CT)
- Microstructure analysis
- Roughness measurements
- Chemical analysis
- Tensile testing – as-built
- Penetration testing
- Tensile testing – machined
- Fatigue – Type FCE (cylindrical samples)
- Fatigue – Mini T Type (flat samples)
- Fracture toughness
- Fatigue crack propagation
- Bearing stress

Figure 6 illustrates the positions of each specimen. Due to the extensive quantity of results only the most relevant material analysis will be presented within this white paper. Further results can be provided on request.

The build job layout was designed in consideration of different x-y positions on the substrate plate and particularly, in terms of the gas outlet. Both horizontal and vertical orientations are represented by each test specimen. In the middle column of figure 5 the nesting for each build job is visible. In order to take all three lasers into account, each test geometry was placed in at least three locations in one build job. The laser assignment was conducted with TruTops Print Multilaser Assistant which is depicted in the right column of figure 5. Each color represents one specific laser.

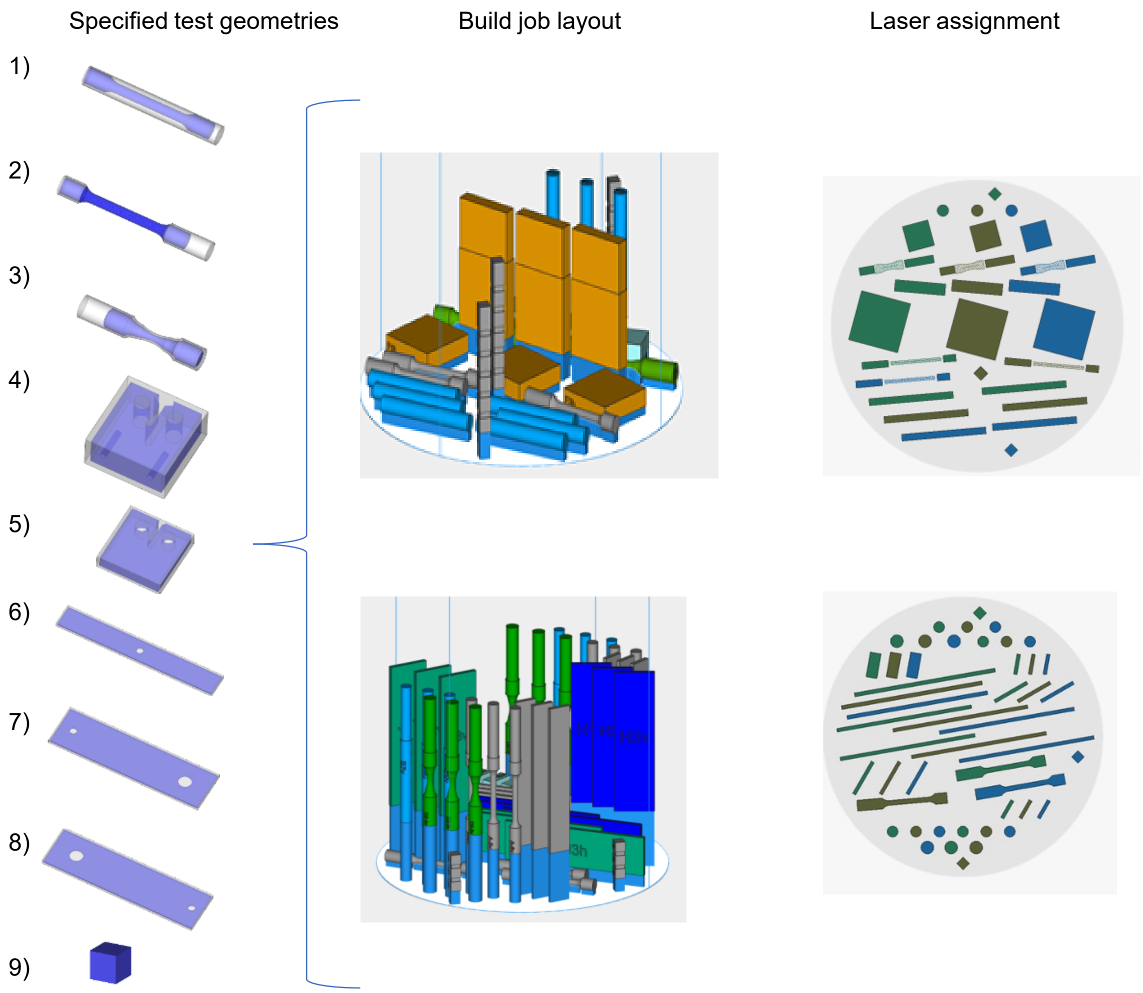

Figure 5:
Left column: Eight specified test geometries which are distributed on two build jobs by considering different x-y positions on substrate plate as well as horizontal and vertical orientations of the samples (see middle and right column). 1) Tensile samples, 2) Tensile samples as-built, 3) Fatigue cylindrical sample, 4) Fatigue crack growth, 5) Fracture toughness, 6) Fatigue flat samples, 7) and 8) Bearing stress and 9) Metallurgical analysis. In the right column, the laser assignment of each test geometry is visualized by using TruTops Print Multilaser Assistant.

Location of specimens for material analysis

CT

Tensile testing - machined

Fatigue – Type FCE (cylindrical samples)

Fatigue – Mini T Type (flat samples)

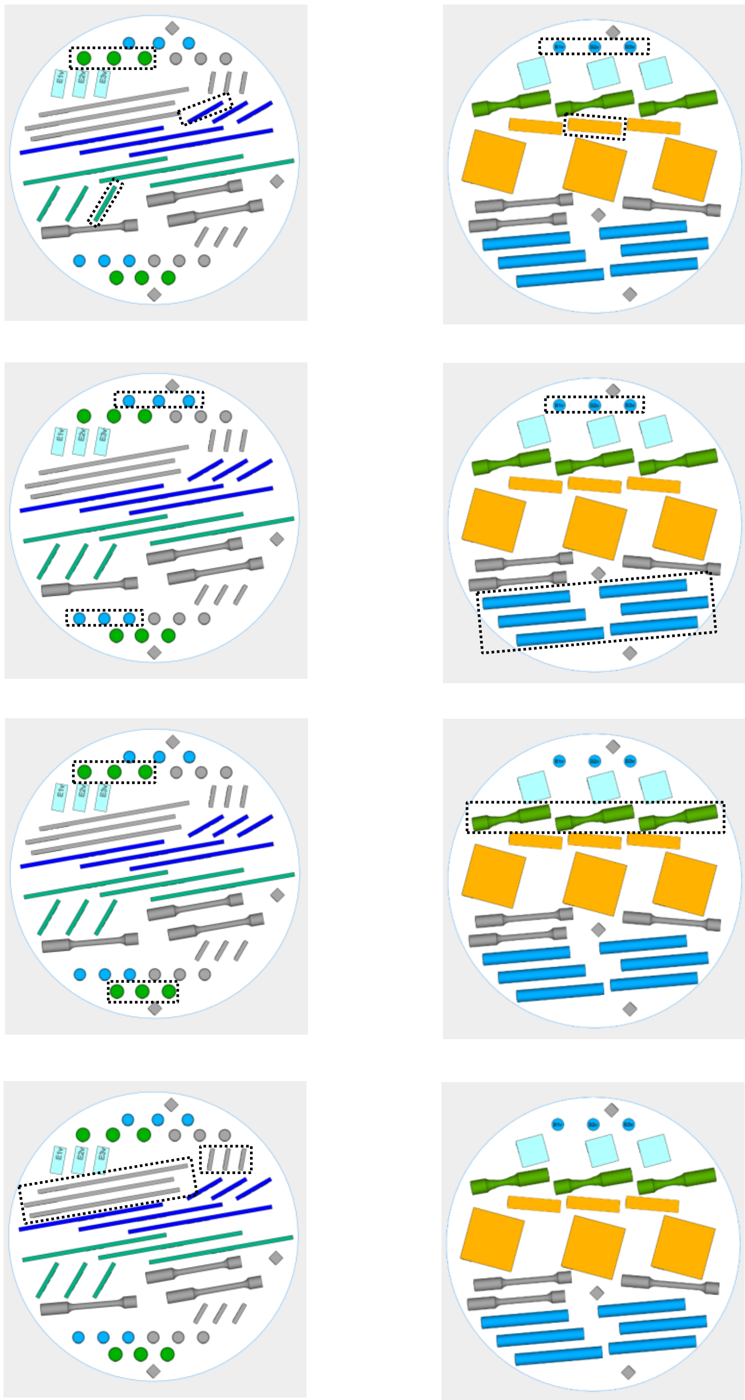

Figure 6:
Left column: Material analysis presented in this white paper. Middle and right column: Top view of build job 1 and 2 with selected specimens for analysis marked with a dashed frame.

Process chain

A general overview of the process chain during the qualification build jobs is visualized in figure 7. Specified Ti6Al4V Grade 5 powder was utilized for producing the build jobs. As pre-processing step, the build job layout was defined at TRUMPF. Afterwards, the build jobs were conducted on a TruPrint 5000 with a preheating temperature of 200 °C (392 °F).
In figure 8 the two finished build jobs are depicted. The completed build jobs were stress relieved at 650 °C (1202 °F) for 2.5 h in vacuum before separation. A defined number of specimens were determined for CT investigations in order to examine the occurrence of possible existing defects such as gas pores, lack-of fusion or inclusions in the as-built condition.
All test samples were treated with a high isostatic pressure (HIP) for 2 h at 920 °C (1688 °F) and under a pressure of -1000 bar. The following material analysis were carried out for samples after HIP.

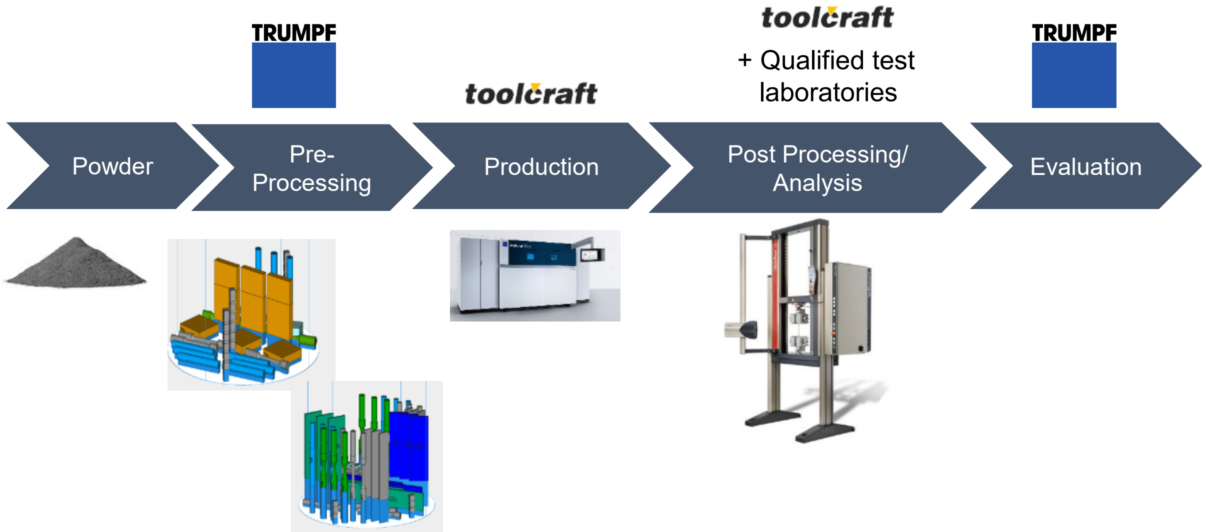

Figure 7:
Process chain for the qualification build jobs.

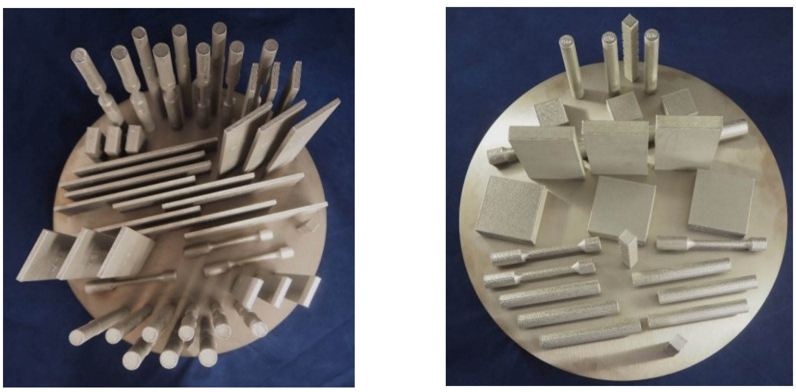

Figure 8:
Nine specified test geometries which are distributed on two build jobs including different x-y positions on substrate plate as well as horizontal and vertical orientations.

Results

As stated in the previous chapters, the subsequent analysis will be addressed on the next pages.

- CT scans before and after HIP
- Microstructure analysis
- Tensile testing – As-built
- Tensile testing – Machined
- Fatigue - Mini T Type
- Fatigue – Type FCE
- Fracture toughness

Computerised tomography

Due to the complexity of the LPBF process, several investigations need to be made in order to detect and evaluate potential defects. Internal defects like lack of fusion, pores, inclusions and cracks can influence the static and dynamic properties of the material. Therefore, such defects should be kept to a minimum. With its capability of a nondestructive analysis and the possibility to detect three dimensional defects, the CT is the method of choice.

The DIN 65124 describes different safety classes which lead to a limitation of different defect sizes. The standard distinguishes between safety class A, B and C, whereas the highest requirements are described in safety class A and B with no existing cracks and all pores or inclusions must be below a value of 200 µm for static and below 100 µm for dynamic requirements. An addendum allows one pore or inclusion which is up to 200 µm per 25 cm³ volume, if volume parts are produced.

The samples were analyzed by a certified laboratory with a computerised tomography (Phoenix V-tome-x M). Before the HIP process, small and uncritical defects were detected (see figure 9). The largest measured pore in all samples was 0.13 mm (0.0051 inch) and the largest inclusion was 0.16 mm (0.0063 inch).

After HIP, all pores are closed (see figure 10) and all analyzed samples fulfill the requirements of the safety class A and B of DIN 65124.

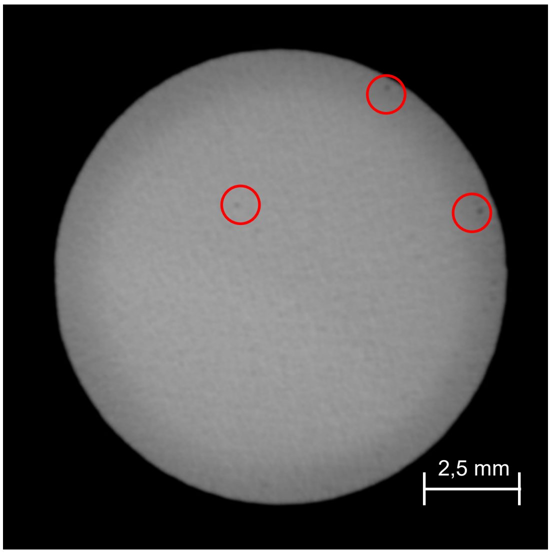

Figure 9:
Sample showing three small pores which are found during CT analysis after LMF process.

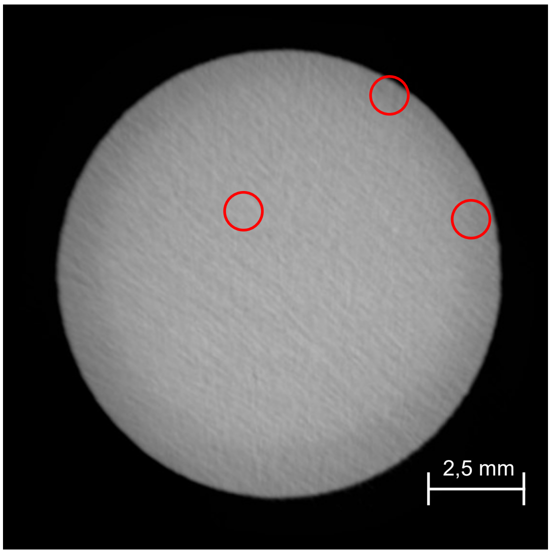

Figure 10:
Sample showing the same section referring figure 9 after HIP. All pores are closed. Requirements of DIN 65124 are fulfilled for safety class A and B.

Microstructure analysis

Density cubes were printed within the two build jobs. Cubes were analyzed before and after HIP process in order to compare the influence. For microstructure analysis the cubes were sectioned in two different directions referring figure 11. Afterwards the samples were embedded, ground and polished. Kroll etching solution was applied to visualize the microstructure of the Ti6Al4V samples. Finally, the grain size was analyzed according to ASTM E112.

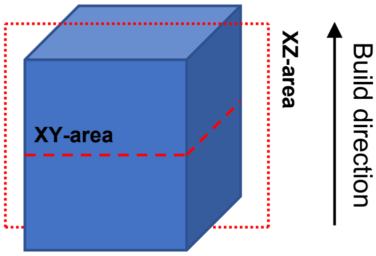

Figure 11:
Microstructure analysis are carried out in two different directions.

Figure 12 shows the typical as-built, coarse columnar grains along the building direction (XZ-area) due to remelting of the layers. The grain size diameter in this direction is M-11.0 which leads to roughly 0.794 mm diameter grain size referring to ASTM E112. In XY-area (figure 13) the grains are sliced vertically to the solidification direction, which results in a smaller apparent grain size. More grains are counted which results in grain size number of G2.0 with a mean diameter of about 0.1796 mm. After HIP treatment, the microstructure is reoriented which is demonstrated in figure 14 and 15. No difference can be seen in both directions XZ or XY with a grain size of G2.0.

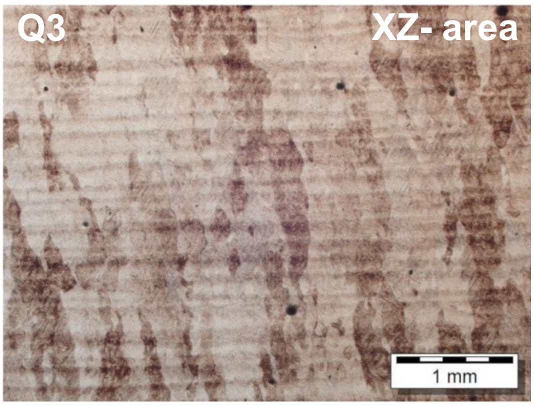

Figure 12:
As-built sample: Q3 XZ-area
Grain size ASTM E112 = M-11.0
Grain diameter ~ 0.794 mm

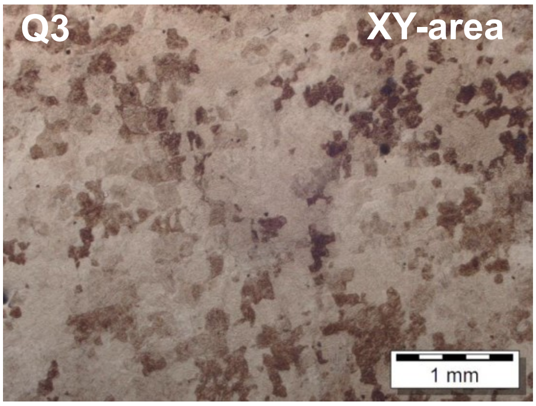

Figure 13:
As-built sample: Q3 XY-area
Grain size ASTM E112 = G2.0
Grain diameter ~ 0.1796 mm

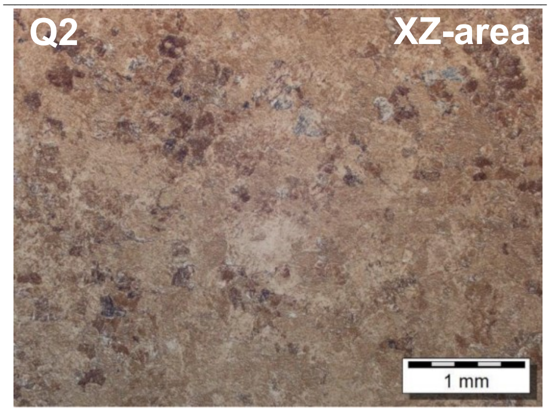

Figure 14:
HIP sample: Q2 XZ-area
Grain size ASTM E112 = G2.0
Grain diameter ~ 0.1796 mm

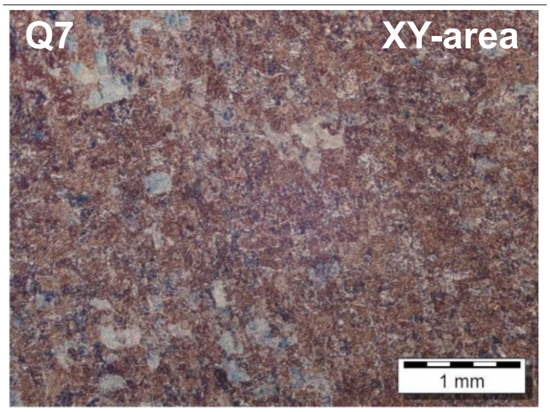

Figure 15:
HIP sample: Q7 XY-area
Grain size ASTM E112 = G2.0
Grain diameter ~ 0.1796 mm

Tensile analysis

For tensile testing, 15 samples (DIN 50125, Shape C) were produced and tested according to DIN EN 2002-1 under different orientations (0° = xy-orientation, 90° = z-orientation).
All characteristics of the specimens were evaluated in view of 3 σ, which means the error bars are spread over 3 times standard deviation. Therefore, it is likely to expect the results of a sample within the error bars with a probability of 99.73 % (figure 16).

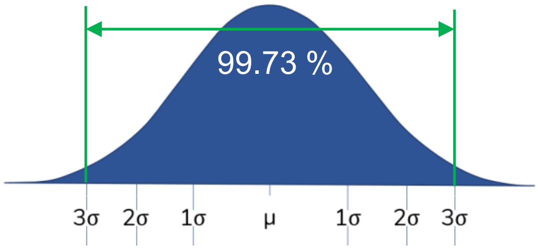

Figure 16:
Expectancy range of the results by using mean within 3 σ.

The results for the tensile testing are shown in the figure 17 and figure 18. In addition, the requirements of ASTM F2924 are plotted in the respective graphs. The results show that all specimens are above the requirements for yield strength and tensile strength, though slight differences can be seen between the horizontal and vertical specimens. These anisotropies are typical of the LMF process. With the subsequent HIP process, the variabilities and especially the anisotropy were reduced and almost equalized. The results of the elongation at break and the reduction of area are shown in figure 18. Due to the high strength, the material can be brittle, which can lead to a low elongation at break. All results are above the requirements of the standard. Neglecting the orientation, an averaged elongation at break of 15.2 % [14.4; 16.0] and 38.7 % [33.5; 43.8] for the reduction of area with a corresponding 99.73 % confidence interval have been obtained. Detailed results depending on the orientation are shown in figure 18.

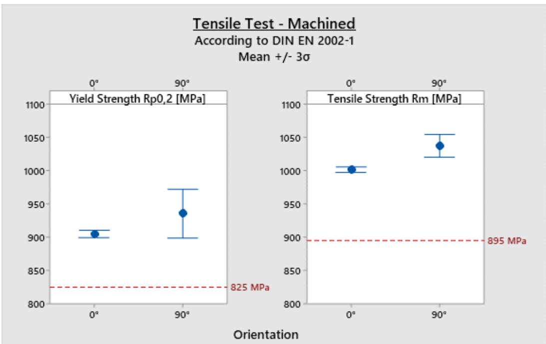

Figure 17:
Results of tensile testing – Yield strength $Rp_{0,2}$ and tensile strength R_m for machined samples.

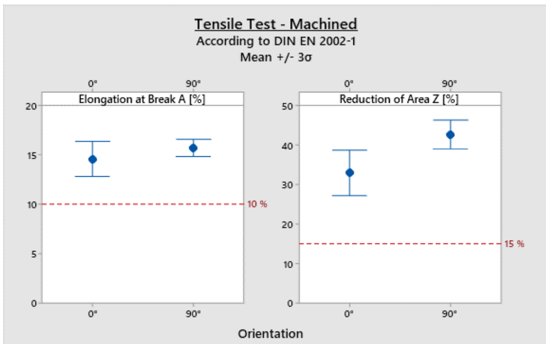

Figure 18:
Results of tensile testing – Elongation at break A and reduction of area Z for machined samples.

Fatigue analysis

For fatigue testing, two types of machined FCE 12,5 Type A samples (with a Kt = 1.035, R = 0.1, frequency of 75 Hz) and Mini T-Type samples (with a Kt = 2.3, R = 0.1 and a frequency of 15 Hz) were produced according to DIN EN 6072.
The results of the S-N-curves are shown in figure 19 and figure 20 demonstrating the dependency of the upper stress σ_o and the cycles of failure Nf. The two build directions are visualized with blue / gray dots and arrows indicating runout samples which were still intact after testing. The red line describes the requirements of the common aviation standards. No differences are visible between the tested orientation and all samples fulfill the requirements. The results of the different test types are combined, and a support curve is interpolated. Afterwards, maximal net stress values were calculated for the cycles of 10,000, 100,000 and 1,000,000 (figure 21).

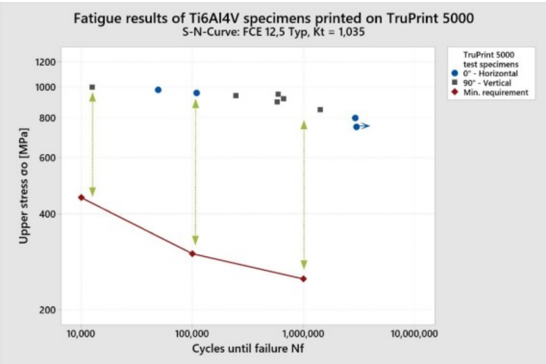

Figure 19:
Results of fatigue testing – Type FCE 12,5 Typ A (Kt = 1.035, R = 0.1, frequency 75 Hz)

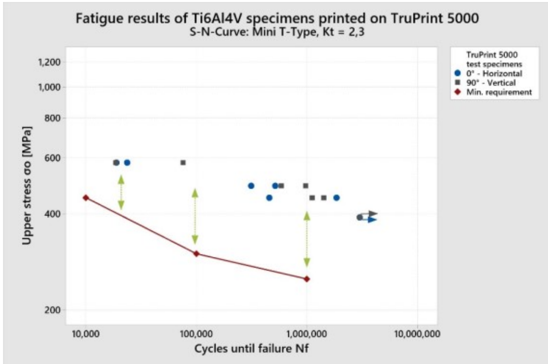

Figure 20:
Results of fatigue testing – Mini T-Type (Kt = 2.3, R = 0.1, frequency 15 Hz)

Testing type	Cycle of failure	Max. net stress [MPa]
Type FCE 12,5 Type A	10,000	1038
	100,000	953
	1,000,000	875
Mini T-Type	10,000	617
	100,000	533
	1,000,000	460

Figure 21:
Calculated results of testing type Type FCE 12,5 Typ A and Mini T-Type specimens.

Fracture toughness analysis

To test the fracture toughness, 6 specimens with different orientations (0° = xy-orientation, 90° = z-orientation) were produced.
According to ASTM E399-20 the specimens were machined to CTW20B10 shape.
The test results in figure 22 reveal that the orientation of the specimens has an influence on the achieved fracture toughness. In detail, it is obvious that the vertical samples perform better with a mean value of 83.2 MPa√m than the horizontal samples with a mean value of 70.7 MPa√m. In conclusion, the measured fracture toughness exceeds the minimal requirement of 50 MPa√m.

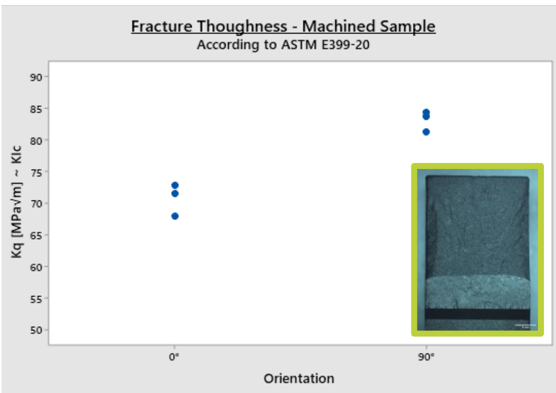

Figure 22:
Results of machined fracture toughness specimens according to ASTM E399-20.

Conclusion & outlook

As elaborated in the previous chapters, the TruPrint 5000 is capable to provide qualitative and homogeneous material properties fulfilling the high requirements in aerospace. Through a continuous improvement process, it is possible to provide machines that offer a high process stability and repeatability, which is needed to enable a serial production for the aviation industry. In fact, this is such an important topic because it allows the OEM's to step away from part-based qualification and implement a process-based qualification, that focuses on the machine and the material rather than on specific parts or geometries. The advantages are significant: Faster transfer of parts into serial production, less qualification effort and associated time as well as cost savings.

Besides the achievements illustrated in this white paper, there are still further topics that need to be investigated. TRUMPF's process capability projects (Cpk) are focusing on additional topics like machine independent part quality or machine parameter transferability. These criteria are essential for a customer's serial production, as they determine how flexible parts can be transferred from one machine to another without the need of major adaptions. The target of TRUMPF is clearly to provide machines that behave identical in this matter. Detailed results of these projects will be published later in 2021.

In order to decrease distortion by process induced residual stresses, the TruPrint 5000 is also available with a preheating temperature of 500 °C. Internal and external pre-studies have already demonstrated the advantages of such higher preheating temperatures. This allows aerospace customers to address a wider range of potential parts, not only limited to specific titanium alloys, but also hard-to-process nickel-based superalloys often used for jet engine applications. First results have already been published by TRUMPF with more content to be released soon.

Find out more about the capabilities of the TruPrint 5000

TRUMPF

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