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FRAUNHOFER RESEARCH INSTITUTION FOR ADDITIVE MANUFACTURING TECHNOLOGIES IAPT

ADDITIVE FATIGUE STUDY

INFLUENCE OF DIFFERENT SURFACE FINISHING METHODS ON MECHANICAL PROPERTIES OF METAL AM COMPONENTS

CONTENT

1_MOTIVATION

INSIGHTS TO BE GAINED

- **Influence of the most relevant post-processing methods for surface smoothing on the mechanical properties, surface quality and geometric accuracy of Additively Manufactured test specimens.**
- **Results of the two investigated materials Ti6Al4V (ELI) and Inconel 718 manufactured by LB-PBF with a focus on fatigue performance.**
- **Knowledge about post-processing costs and process times for 8 different post-processing treatments.**
- **Independent evaluation of the respective processes with at-a-glance depictions that are easy to read.**

Additive Manufacturing (AM) of metal components is already on the way to becoming an established manufacturing method in many industries. Whether in the medical or aerospace sector, more and more industries are using the possibilities of Additive Manufacturing for fast production of cost-effective prototypes. Furthermore, there is a steady increase in the number of AM components involved in small and large series production.

Nevertheless, mass production in particular poses challenges that must be solved in the future if the technology is to be raised to a higher industrial level. In addition to the efforts being made to increase productivity or process stability, surface finishing is another area that offers great optimization potential. Fatigue failure resistance and optimum fluid flowability are just two industrial requirements that demand high surface quality which Additively Manufactured parts often cannot satisfy without proper post-processing.

The aim of this study is to investigate the influence of relevant post-processing methods on surface roughness, dimensional accuracy and mechanical properties, with a strong focus on the fatigue performance of Ti6Al4V (Ti64) and Inconel 718 (IN718) parts manufactured by Laser-Based Powder Bed Fusion (LB-PBF). In this way, it should serve as a quick decision guide to find the most suitable post-process for a specific application.

2_ABOUT FRAUNHOFER IAPT

ABOUT FRAUNHOFER IAPT

Fraunhofer IAPT is one of the leading research institutes in the field of AM. We specialize in the areas of design, processes and systems.

Our objective is to scale up additive processes and technologies and facilitate their transfer to industry, thereby enabling the manufacture of completely new und resource-efficient products.

We can provide you with customized solutions and help launch you as a competitive player in the field of Additive Manufacturing.

More information can be found here: www.iapt.fraunhofer.de

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3_ABOUT THE AUTHORS

ABOUT THE AUTHORS

With this work, the authors of this study, namely Maximilian Kluge (organization, conception), Jan Walter (AM production) and Alexander Bauch (quality assurance and measuring) want to contribute to the industrialization of 3D printing.

Many years of AM experience and daily contact with the typical challenges of post-processing Additively Manufactured parts let them focus on the most critical questions. The aim of the additive surface studies is to generate knowledge that eliminates previous showstoppers while contributing to the further development of Additive Manufacturing – with regard to the entire process chain – as a cost-efficient, reliable production technology.

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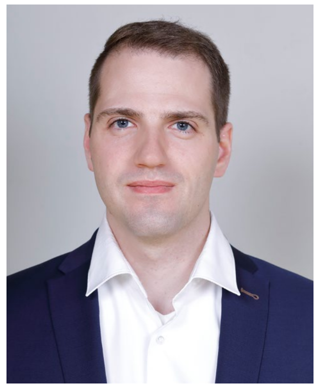

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4_APPROACH OF THE STUDY

4.1_BENCHMARK CRITERIA AND TEST SET-UP

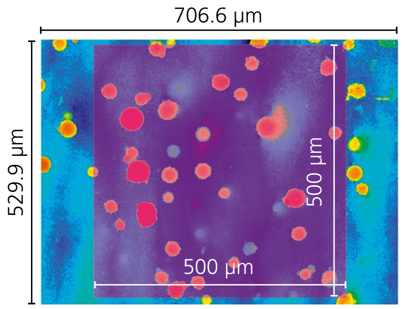
4.1.1_ECONOMIC SURVEY

The costs for performing a surface finishing method depend on the following factors: component size, component complexity, component material, lot size and surface requirements. The limited information available from service providers about the composition of costs, scalability and duration of their surface finishing methods means that an exact quantitative comparison based on the cost criteria of the surface finishing methods would not be valid. The cost criteria are therefore considered in terms of price ranges. In addition, a trend is given regarding the economy of scale for each surface finishing method.

Inquiries were made with various service providers about surface finishing the test specimens. The service providers were responsible for choosing the process parameters at their own discretion to find the best solution with respect to the stated evaluation criteria. The service providers were chosen from among those with experience in finishing Additive Manufactured parts and from those expected to produce the most representative results (e.g. well-established system manufacturers with an Additive Manufacturing background or the inventors of the finishing method).

4.1.2_SURFACE ROUGHNESS

Surface roughness was measured optically with a 3D laser scanning confocal microscope VK-8710 by Keyence. The 3D laser scanning confocal microscope generated a three-dimensional scan of the surface by scanning the surface pointwise in all three spatial directions.
A 20x lens resulted in a scan field measuring 529.9 x 706.6 µm with a lateral measurement resolution of 0.345 µm. Surface roughness was evaluated on a centered area of 500 x 500 µm. The area roughness parameters Sa (arithmetic mean height) and Sz (maximum height) were calculated using an S-L surface in accordance with DIN EN ISO 25178.



Exemplary measurement of an Inconel 718 specimen. The height profile was colorized. The measurement area was marked purple.

S-filter: 2 µm
L-filter: 0.5 mm
F-operator: 2nd order polynomial

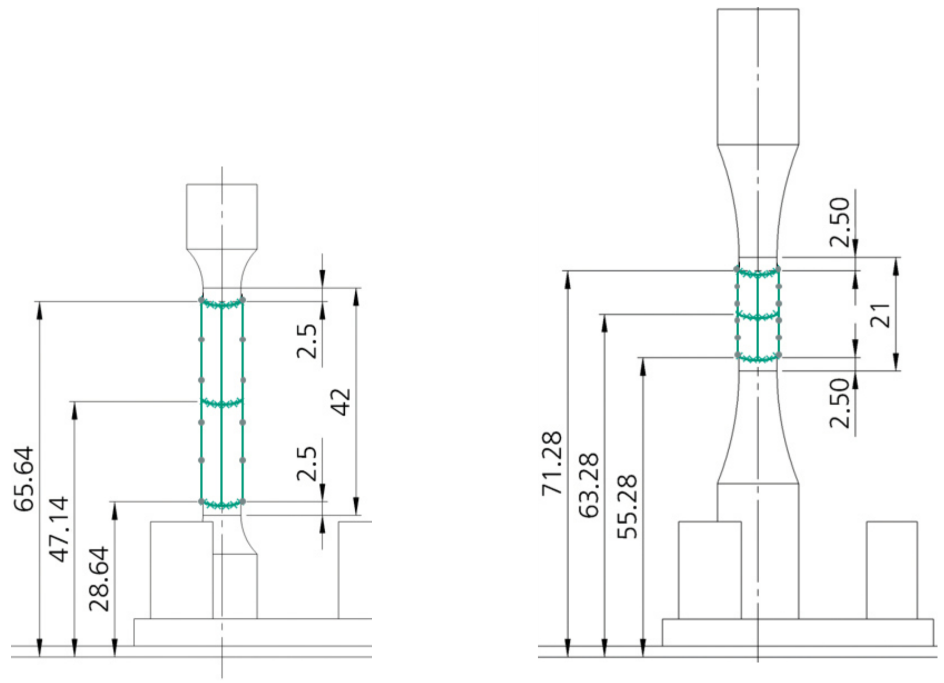
Quality assurance of the manufactured parts was carried out with three measurement points evenly distributed across the test section. Seven evenly distributed measurement points were used for the post-processed specimens.

4.1.3_GEOMETRIC ACCURACY

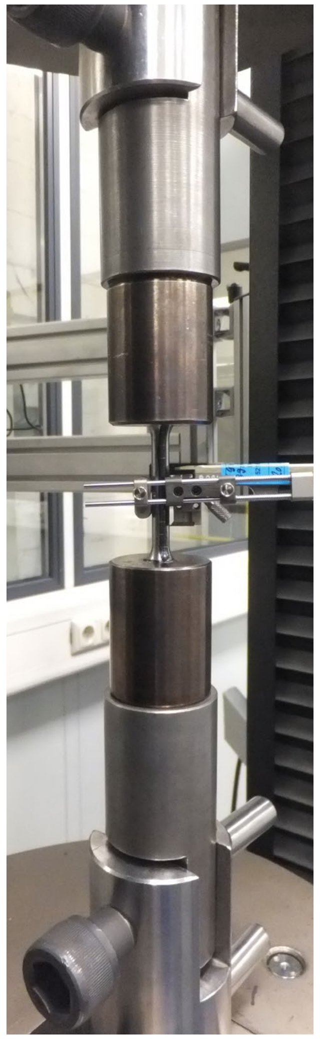
Geometric accuracy was measured by tactile means using a 3D coordinate measuring device LH87 by WENZEL. The coordinate measuring device was equipped with a rotary and swivel head PH10M Plus and a probe consisting of an SP25M probe body, an SM25-1 module and an SH25-1 stylus by Renishaw. The fatigue and tensile specimens were placed vertically in a sample holder and the stylus scanned the specimen pointwise using a stylus ball made of ruby with a diameter of 2 mm.

Four quality criteria were observed to ensure the manufacturing quality and comparability of the test section: diameter, cylindricity, straightness and parallelism.

For measurement-related reasons, diameter and cylindricity were determined by the mean value of two half cylinders on opposite sides of the specimen. Each half cylinder consisted of 18 tactile points on three different height levels. The levels were chosen close to the boundaries (2.5 mm spacing) and in the middle of the test section. The tactile points were spaced at intervals of around 30° on each level. The levels were spaced at intervals of 8 mm for the fatigue specimens and 18.5 mm for the tensile specimens. Parallelism and straightness were calculated by two lines on opposite sides of the specimen. Each line consisted of 6 tactile points (grey point) distributed between the outer levels of the half cylinders. The shape and position tolerances were calculated according to DIN EN ISO 1101.



Tensile (left) and fatigue (right) specimen. Tactile points for straightness and parallelism (grey dots) and for diameter and cylindricity (green crosses).



Test set-up for tensile testing. Specimen clamped in a Quasar 600 by Galdabini. Source: LISEGA

4.1.4_TENSILE STRENGTH

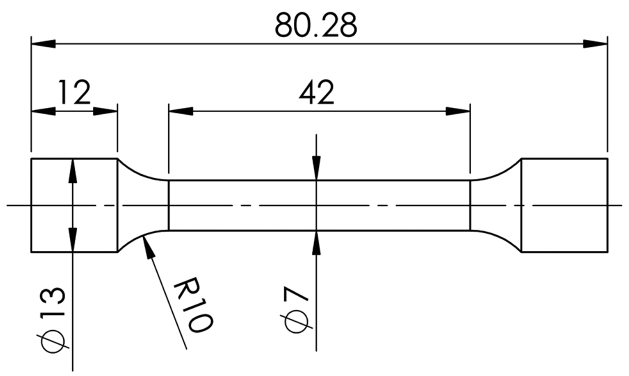
Tensile strength was tested in order to investigate the influence of the different surface finishing methods on tensile strength, yield strength and elongation at break.

The specimens were designed according to DIN 50125 with a test section diameter of 7 mm. The dimensions of the printed specimens were shown in the technical drawing. An M12 thread was machined prior to tensile testing.

Testing was performed according to DIN EN ISO 6892-1 by a service provider using a Quasar 600 by Galdabini with a maximum load of 600kN. The tests were carried out at room temperature with an MFA Mini 2 extensometer by MF Mess- & Feinwerktechnik.

The following parameters were determined:

- Yield strength Rp0.2 [N/mm²], tolerance ±2.0%
- Tensile strength Rm [N/mm²], tolerance ±1.5%
- Elongation at break A [%], tolerance ±1.6%
- Contraction at break Z [%], tolerance ±2.4%



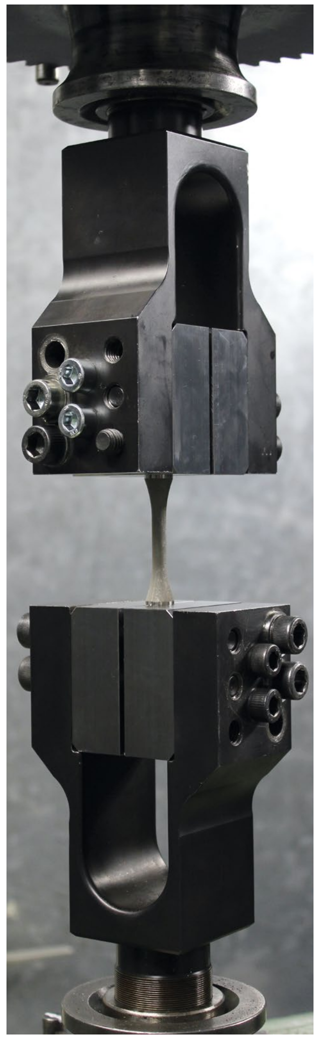
Geometry of the printed tensile specimen. An M12 thread was machined prior to tensile testing.

4.1.5_FATIGUE STRENGTH

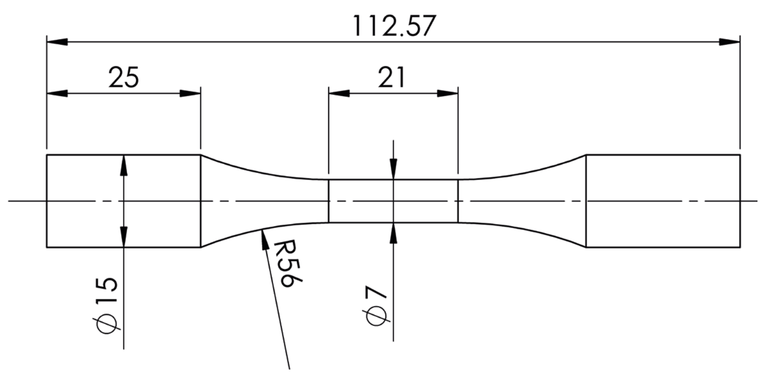
Fatigue strength was tested in order to investigate the influence of the different surface finishing methods on the achievable load levels and number of load cycles.

Specimens were designed according to ASTM E466 with tangentially blended fillets between the test sections and the end. A diameter of 7 mm was chosen for the test section to achieve a good compromise between printed component volume and possible surface finish. The test section was therefore 21 mm long with a blending fillet radius of 56 mm. The clamping section was turned to a diameter of 14 mm prior to testing.

Fatigue testing was performed according to DIN 50100 using the pearl string method by a service provider using a Vibrophore by Amsler for the Ti6Al4V specimens and an HFP 5000 by RUMUL for the Inconel 718 specimens. Both machines had a maximum force of 100 kN and used force as control variable. Axial pulsating tensile stress loading was applied at ambient temperature with a load ratio of R = 0.1 and sinusoidal load signal form. Testing was carried out in a frequency range of 89-91 Hz for Ti6Al4V and a range of 84-86 Hz for Inconel 718, depending on the specific sample. Frequency drop was selected as the failure criterion. The fatigue limit was set to 10^7 cycles referred to as "runout". Both testing machines had class 1 calibration according to DIN EN ISO 7500-1.



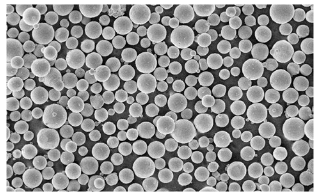
Test set-up for fatigue testing. Ti6Al4V specimen clamped into Vibrophore by Amsler. Source: IABG



Geometry of the printed fatigue specimen. The clamping section was machined to a diameter of 14 mm prior to fatigue testing.

4.2_INVESTIGATED MATERIALS

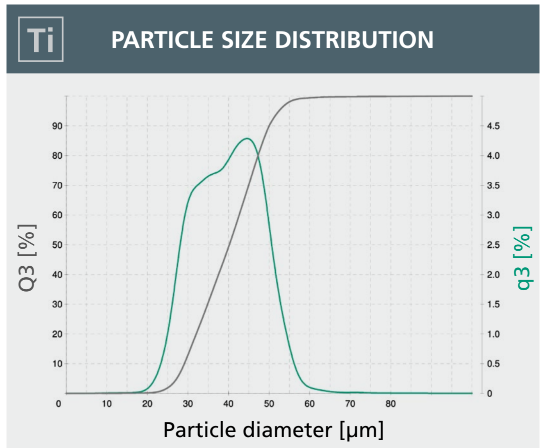
Ti6Al4V and Inconel 718 were chosen for the investigation as these two materials were said to be of most interest by more than 75% of the participants in the online survey conducted during the concept phase and kickoff of this study.
The specimens were manufactured using recycled powder which was sieved after each build job, according to common practice. Virgin powder was added from time to time to replace consumed powder. Particle size distribution and particle shapes were analyzed by Fraunhofer IAPT for this study for quality assurance of the recycled powder.



Scanning electron micrograph (SEM) images of Ti6Al4V powder with 500x magnification.

4.2.1_Titanium alloy Ti6Al4V

Titanium alloys are lightweight; they have high specific strength, show thermal and corrosion resistance and are biocompatible. These characteristics result in broad industrial use of titanium alloy parts for high-performance applications (e.g. for aerospace or medical parts). The machinability of titanium alloys is generally rather challenging and often leads to high machining costs and long lead times in conventional processing. There are therefore many business cases for the Additive Manufacturing of titanium alloy parts, offering substantial cost advantages. Ti6Al4V is widely used today for commercial fabrication with LB-PBF.

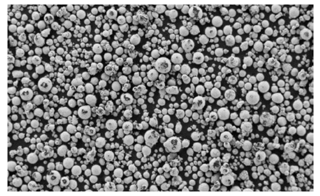


According to the manufacturer's powder certificate, the used powder had a particle size range from 20 µm (D10) to 53 µm (D90) and a chemical composition in accordance with the ASTM B348 Grade 23 and ASTM F3001 standards. The in-house measurements by Fraunhofer IAPT using a Camsizer X2 by Microtrac showed a particle size distribution from 29 µm (D10) to 50 µm (D90).

Chemical composition and particle size distribution of the Ti6Al4V powder.

ELEMENT (WT%)	Al	V	Fe	Y	C	O	N	H	Others each	Others total	Ti
Min.	6.20	3.50									
Max.	6.50	4.50	0.25	0.005	0.08	0.10	0.03	0.012	0.10	0.40	
Result	6.26	4.00	1.14	<0.001	<0.005	0.065	0.016	0.004	<0.02	<0.05	Bal.

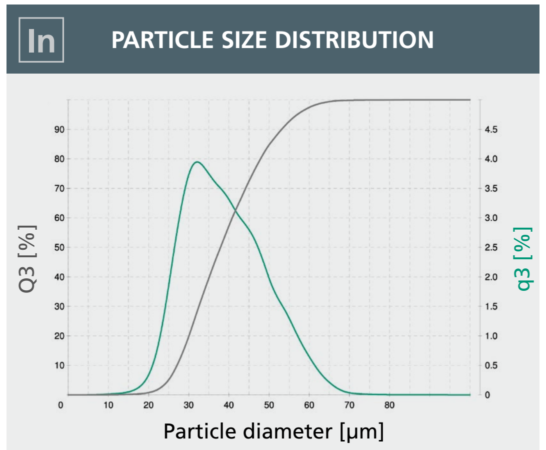
4.2.2_Nickel based superalloy Inconel 718



SEM-images of Inconel 718 powder with 272x magnification.

Nickel-based superalloys generally have a greater strength-to-weight ratio than steel. They usually offer high resistance to corrosion, mechanical and thermal fatigue, shock, creep und erosion at elevated temperatures which makes them ideal for aggressive or extreme environments. However, nickel-based alloys are also known to be very difficult to machine. This is due to low thermal conductivity, the work-hardening effect and the tendency to weld with the tool material at high temperature. All these characteristics indicate great potential for profitable utilization of Additive Manufacturing.
Inconel 718 is widely used for LB-PBF. Its superior mechanical and chemical properties make it predestined for the aerospace, energy, automotive and petrochemical industries. Applications range from high-temperature parts such as turbines and engine components to low-temperature applications such as cryogenic environments. It is also commonly used for ductwork, valves and heat-exchangers.

The chemical composition of the Inconel 718 powder met the typical standards: the manufacturer stated a particle size range from 20 µm (D10) to 63 µm (D90). Powder from two different production charges with the same specification was mixed prior to the first build job. The in-house measurements by Fraunhofer IAPT using a Camsizer X2 by Microtrac GmbH showed particle size distribution from 27 µm (D10) to 53 µm (D90).



Chemical composition and particle size distribution of the Inconel 718 powder.

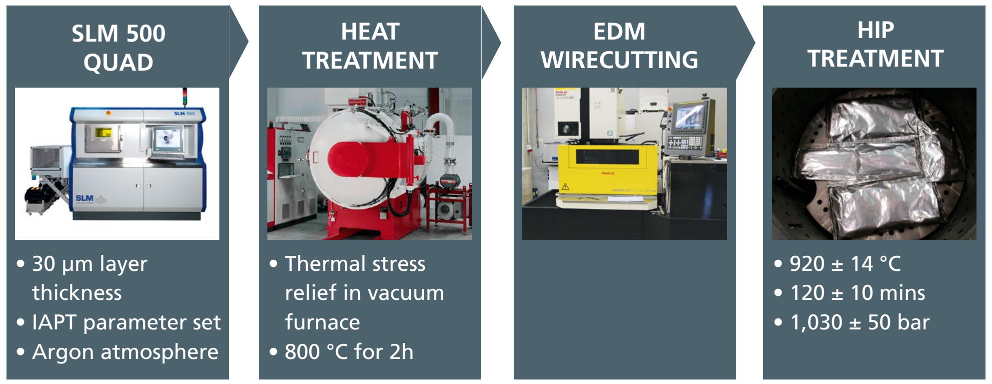
ELEMENT (WT%)	Ni	Cr	Fe	Ta+Nb	Mo	Ti	Al	Cu	C	Si	Mn	B	Co	P	S
Min.	50.00	17.00		4.75	2.80	0.65	0.20								
Max.	55.00	21.00		5.50	3.30	1.15	0.80	0.30	0.08	0.35	0.35	0.006	1.00	0.015	
Result charge A	53.7	18.3	Bal.	5.31	3.0	0.95	0.5	0.04	0.03	0.07	0.04	0.004	0.1	0.008	0.001
Result charge B	53.9	18.2	Bal.	5.27	3.0	0.98	0.5	0.03	0.02	0.08	0.04	0.004	0.2	0.009	0.001

4.3_MANUFACTURING THE SPECIMENS

All specimens were printed on LB-PBF machines at Fraunhofer IAPT. The aim was to print all samples in uniform quality to achieve the best possible comparability and the same starting conditions for all different surface finishing methods. This was ensured by conducting preliminary investigations to optimize the achievable density, especially in regards to contour porosity. In addition, the distances between the specimens and the utilizable areas (which promise consistent quality) on the build platforms were determined appropriately, based on knowledge from past projects. The specimens were systematically distributed equally to compensate for the influence of sample positioning on the build platforms. Furthermore, all parts underwent Hot Isostatic Pressing to eliminate any internal voids formed during printing. Heat treatments were chosen according to specifications commonly used in industry and research.

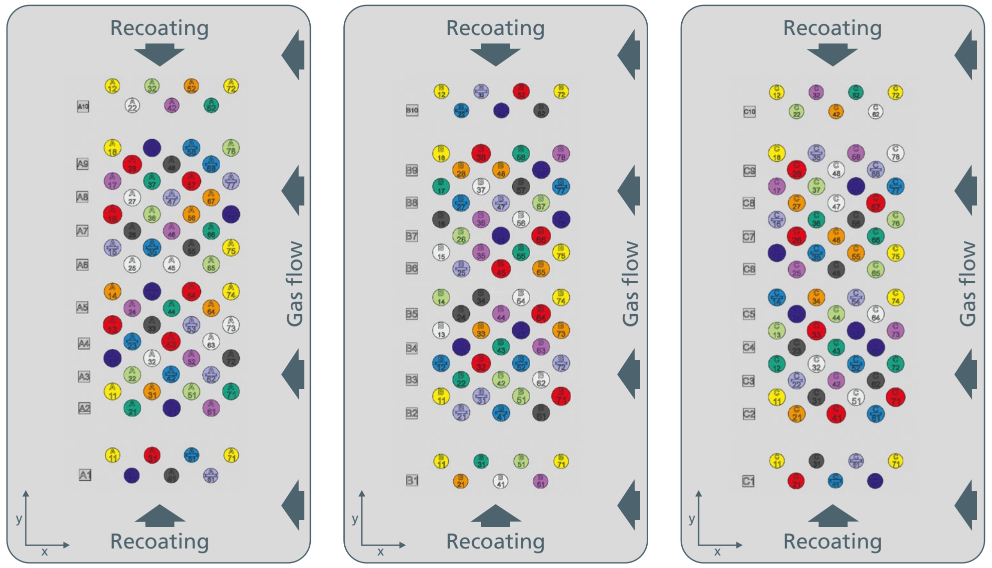
4.3.1_ Manufacturing the Ti6Al4V Specimens

All titanium parts were printed at Fraunhofer IAPT on a SLM 500 Quad HL by SLM Solutions. A parameter set developed by Fraunhofer IAPT with a layer thickness of 30 µm was used to achieve a good As-Built surface quality. The parts were built with a single contour path after hatching, with energy density of about 39 J/mm³. Powder Recoating was carried out with a flexible blade. The process took place in an argon atmosphere.
Before being separated from the build plates by means of a wire EDM machine, all build jobs underwent Stress-Relief heat treatment in a vacuum furnace at a temperature of 800 °C for 2 hours. In the final step, all specimens were subject to Hot Isostatic Pressing at 920 °C for 2 hours at 1,030 bar in an inert gas environment.



Manufacturing steps for Ti6Al4V specimens.

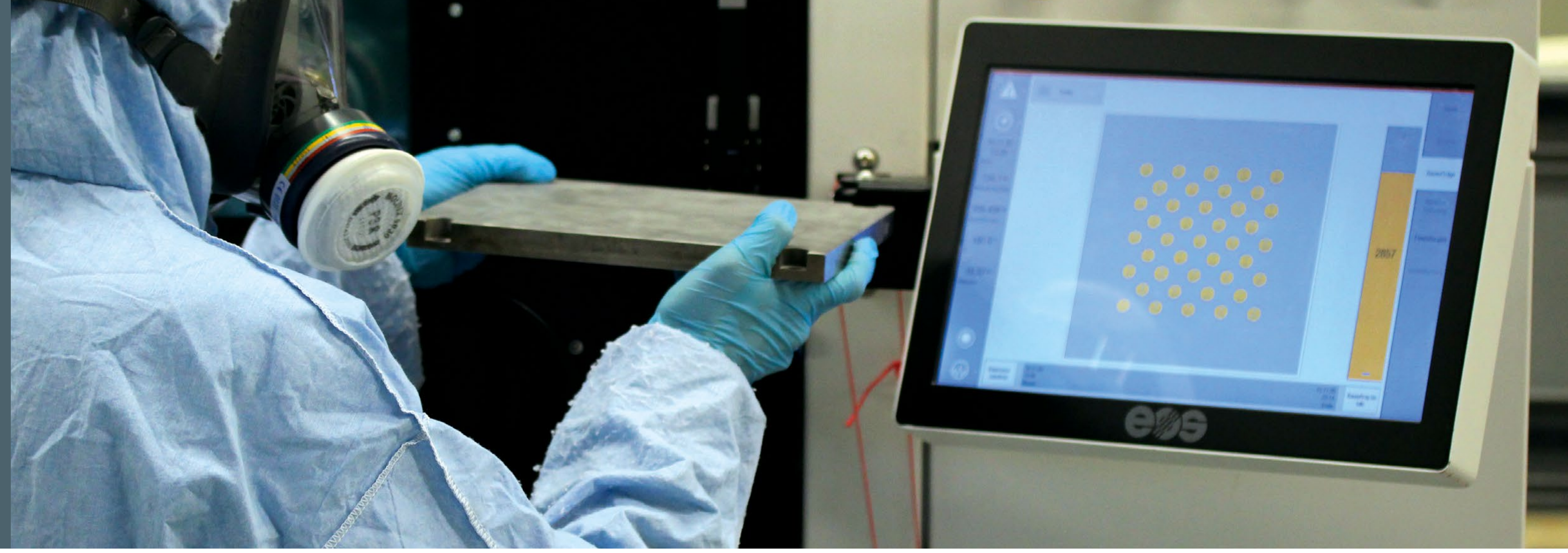
The specimens were positioned on the build platform in a checkered pattern with the vertical middle axes spaced at a distance of 35 mm to each other in the X-direction and 30 mm in the Y-direction. The distance to the edge of the build plate was 80 mm on each side in the X-direction and 70 mm on each side in the Y-direction. Only laser 2 and laser 3 were used for the fatigue specimens (always without laser overlap) whereas the tensile specimens were printed with laser 1 and laser 4.



Data preparation of the 3 titanium build jobs, showing the distribution of the specimen sets and the limited use of the build platform space to achieve uniform quality for all sets.

- Set for As-Built
- Set for Abrasive Blasting
- Set for Chemical Polishing
- Set for DryLyte
- Set for Electrochemical Polishing
- Set for Grinding
- Set for Isotropic Superfinishing
- Set for Vibratory Finishing
- Set for Vibratory + DryLyte
- Reserve set
- Accompanying samples

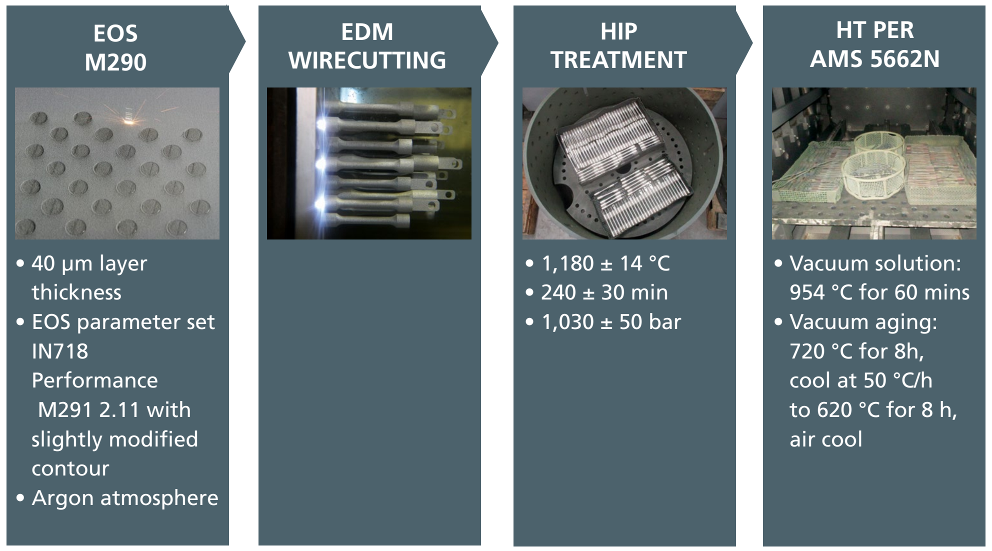
The great extent of the study meant that three build jobs were necessary to print all specimens. In total it took 143 hours to print all 168 fatigue specimens, 42 tensile specimens and 30 density cubes (including a set for backup and accompanying manufacturing samples for quality assurance).



4.3.2_ Manufacturing the Inconel 718 Specimens

The Inconel 718 specimens were printed on an EOS M290 using the standard EOS parameter set "IN718 Performance M291 2.11" with a slightly modified contour path, as this showed a decreased contour porosity during pre-tests. The energy density of the hatching was about 90 J/mm³, followed by two contour paths. The parts were built with a layer thickness of 40 µm, the Powder Recoating was done with a flexible blade and the process took place in an argon atmosphere.

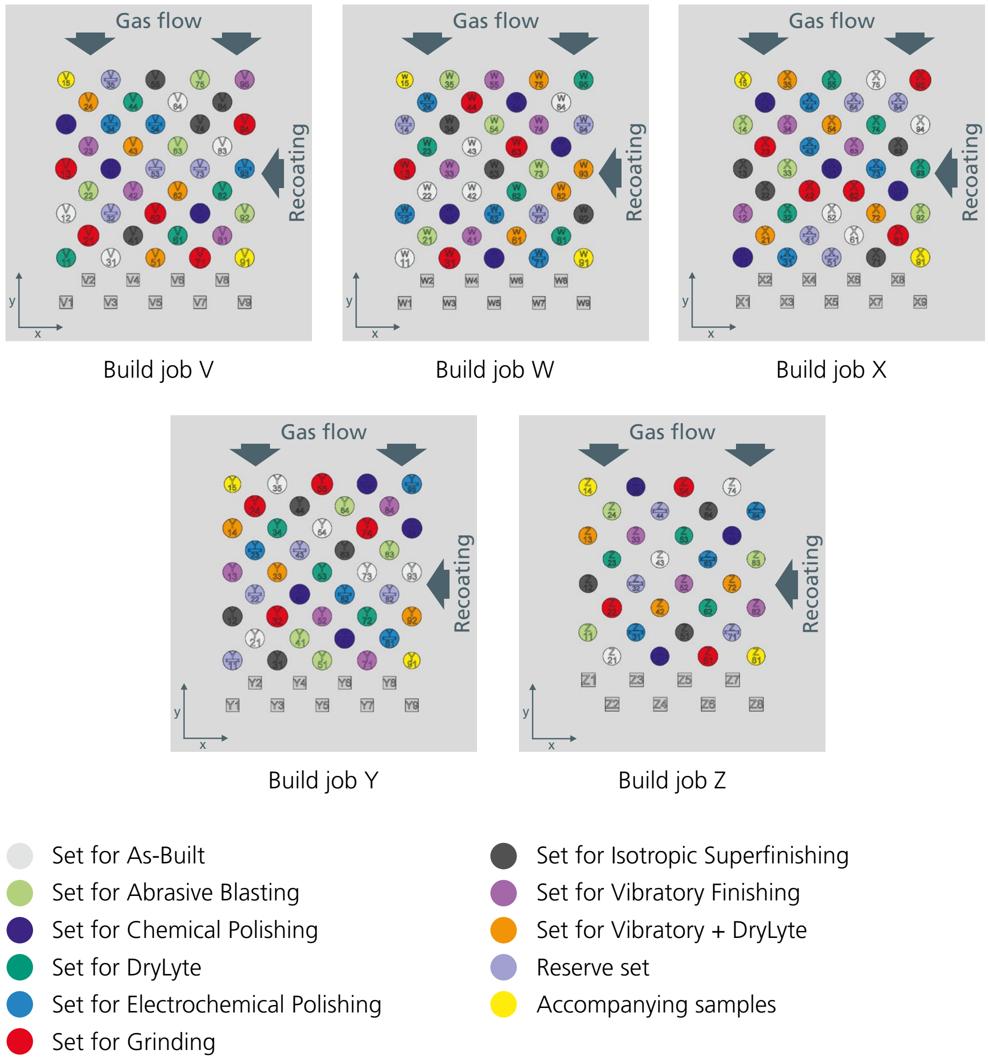
After the specimens were separated from the build plates by means of a wire EDM machine, all parts underwent Hot Isostatic Pressing at 1,180 °C for 4 hours at 1,030 bar in an inert gas environment. This was followed by heat treatment according to AMS 5662N in a vacuum furnace. The solution annealing temperature was 954 °C for 1 hour. The temperature during aging was 720 °C for 8 hours, then dropped at a rate of 50 °C per hour to 620 °C, where it was held for another 8 hours until air cooling.



Manufacturing steps for Inconel 718 specimens.

All fatigue specimens were systematically distributed between four build jobs, while all tensile specimens were printed in a fifth build job. All parts were positioned on the build platform in a checkered pattern with the vertical middle axes spaced at a distance of 35 mm to each other in X- and Y-direction. The distance to the edges of the build plate was 45 mm on each side (respectively 55 mm for the tensile samples).

All five build jobs took about 250 hours in total to build. 159 fatigue specimens, 37 tensile specimens and 44 density cubes (including a set for backup and accompanying manufacturing samples for quality assurance) were printed in Inconel 718 for this study.



Data preparation of the 5 Inconel 718 build jobs, showing the distribution of the specimen sets and the limited use of the build platform space to achieve uniform quality for all sets.

5_QUALITY ASSURANCE

The comparability of all specimens must be ensured in order to compare fatigue and tensile strength after different surface finishing processes. Key aspects include visible and microscopic defects, together with the geometry and the surface of each specimen. This section gives a brief overview of all testing methods used and their observed effects.

A **visual inspection** was carried out after the build process, looking for visible defects such as misalignment, warpage or discoloration. As a quick inspection method, it was suitable for an initial assessment of the success of the build job. However, in-depth investigations were necessary for final evaluation.

Density analysis was carried out before (As-Built) and after Stress-Relief heat treatment as well as after Hot Isostatic Pressing (HIP) to detect defects such as porosity and cracks in the material. Defects have a negative influence on the mechanical properties of the material and should therefore be minimal, homogeneously distributed, not in the contour area to avoid crack induction and equal among all specimens. Accompanying samples were subject to density analysis using optical microscopy and software-based region-of-interest evaluation.

Heat treatment has an impact on the **microstructure** due to grain growth and a shift in the lattice. The microstructure verifiably influences mechanical properties such as yield strength, tensile strength and elongation, thus making it necessary to verify the success and uniformity of the applied heat treatments. Optical microscopy was used to examine the microstructure.

Surface roughness was measured to ensure the same initial conditions for all specimens. A laser scanning confocal microscope was selected to create a three-dimensional scan of the surface. Software-based analysis was used to calculate the arithmetic mean height (Sa) and maximum height (Sz) of each specimen. Significant changes in surface roughness refer to changes in thermal management during printing, caused by more or less partially molten powder. Steady surface roughness is therefore an indicator for a stable build process.

Controlling geometric accuracy is essential to ensure the comparability of all specimens so that due account is taken of instabilities during data preparation, machine set-up or the process. To this end, tactile measurements of diameter, testing area cylindricity, parallelism and straightness were carried out using a coordinate measurement machine. An actual/target comparison was carried out as well as a comparison of each specimen.

Various quality criteria were used to ensure that all specimens were in a consistent initial condition. No critical differences were observed between the specimens. The specimens were therefore used for surface finishing and mechanical testing.

Ti

5.1_TITANIUM

5.1.1_Density
Accompanying samples measuring 10 x 10 x 12 mm (width x length x height) were used to investigate the resulting density before and after every heat treatment. The inverted pyramid shape was suitable for easy removal without wire EDM and for inspecting the down-facing surface. Specimens of every build job were analyzed.

Preparation was carried out according to the standard sequence: embedding in a polymeric matrix, wet grinding with SiC grinding paper and polishing with a diamond suspension up to a grain size of 1 µm.

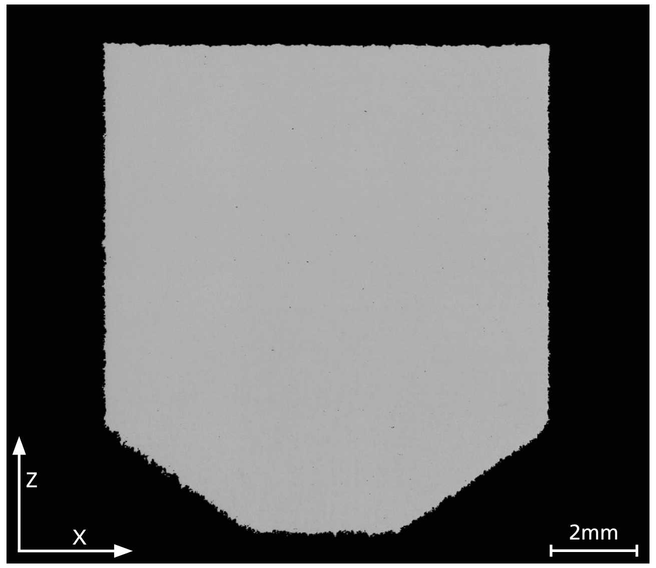
Images were taken with a digital microscope VHX-5000 by Keyence using 50x magnification and dark-field illumination. Multiple images were merged for one specimen. Density was calculated with software based on the region of interest (ROI) using a threshold of 125 [-].

Some long thin scratches were visible due to manual preparation, but no clustered pores or signs of contour porosity were observed. As expected, heat treatment at 800 °C for 2 hours does not influence the minimum measured density of 99.97% achieved in As-Built condition. Subsequent HIP treatment at 920 °C and 1,030 bar for 2 hours increased the minimum measured density to over 99.99%.

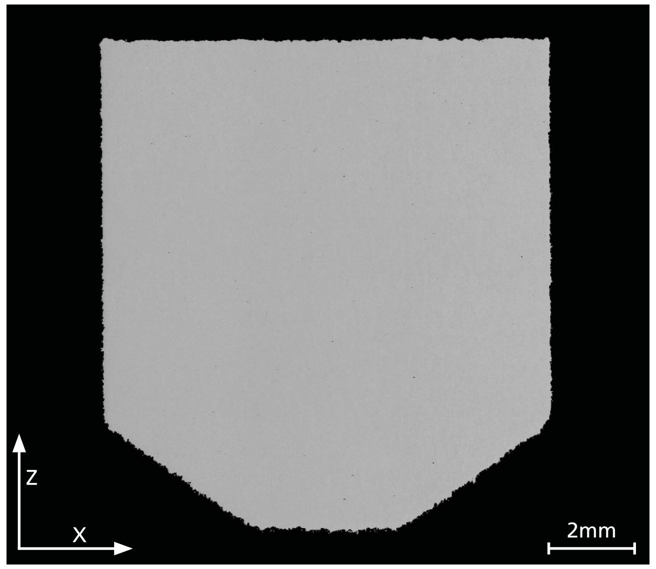
CONDITION	MIN.	MAX.	MEAN	STD	DENSITY [%]
As-Built	99.974	99.984	99.979	0.004	> 99.97
HT	99.979	99.992	99.985	0.005	> 99.97
HIP	99.999	99.999	99.999	0.001	> 99.99

Overview of measured density for Ti6Al4V accompanying samples.

AS-BUILT

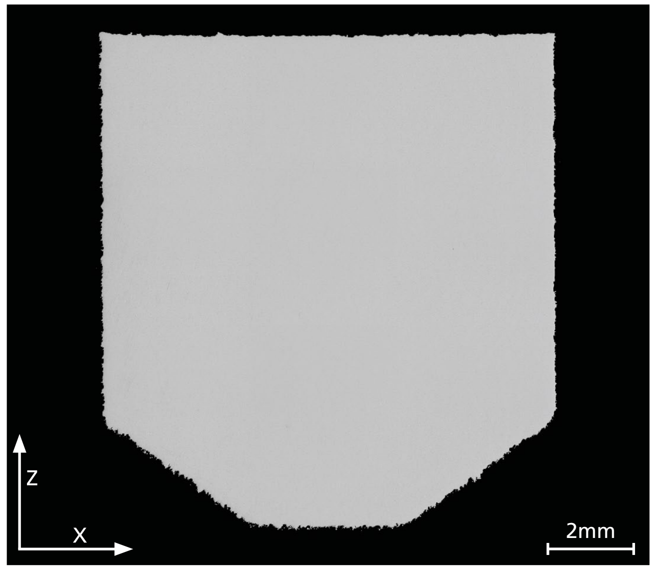


HEAT TREATMENT



Stress-Relief heat treatment at 800 °C for 2h in argon atmosphere.

HT + HIP



HIP treatment at 920 °C and 1,030 bar for 2h.

Ti

5.1.2_Microstructure

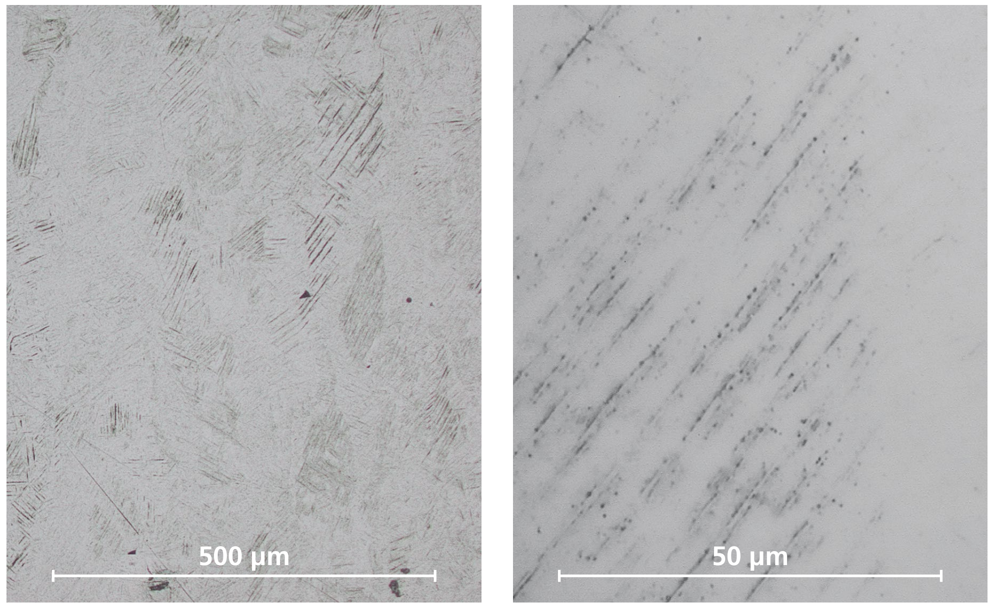
Accompanying samples measuring 10 x 10 x 12 mm (w x l x h) were used to investigate the influence of heat treatment and pressure on the microstructure. Specimens of every build job were analyzed.

Specimens were prepared as described in the previous section (see density). For light microscopy, the specimens were additionally etched for 10 seconds using Titan-Etch by TitanTech.

Low magnification images were captured using a light microscope GX51 by Olympus with 100x magnification. High magnification images were acquired with magnification of 1000x.

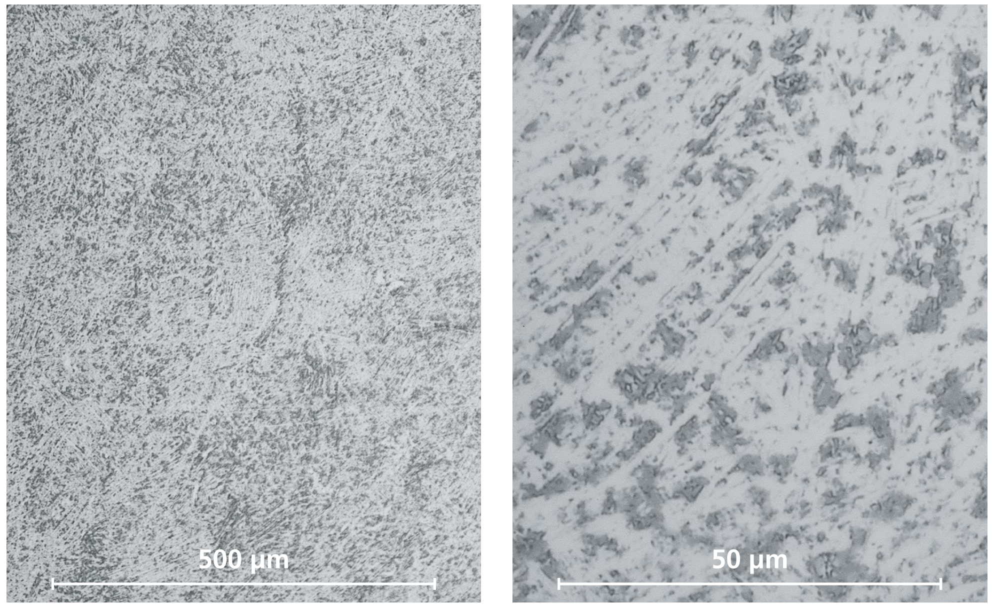
Starting from an As-Built, fine, needle-shaped α' martensite, the microstructure changed after Stress-Relief heat treatment to a mixture of α and β phase. The subsequent HIP process resulted in a coarser α phase lamellar microstructure with a lath width of around 5 µm and an increase in β phase.
After each investigated thermal postprocessing step, the microstructure was revealed as expected and described in literature and showed no abnormalities.

AS-BUILT



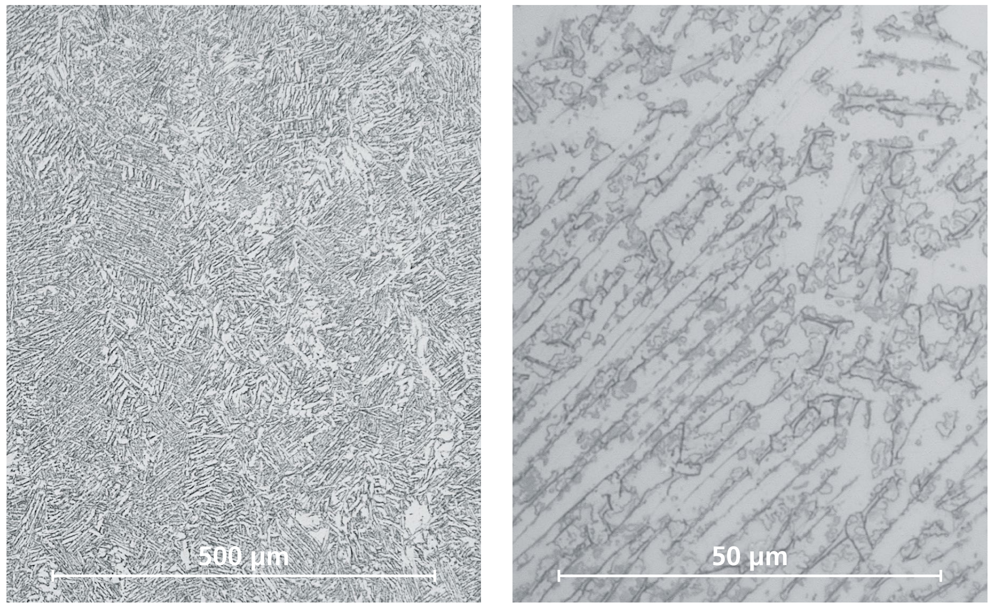
As-Built condition shows a fine, needle-shaped martensitic α' microstructure.
***Left:** Low magnification (100x) light microscope image.*
***Right:** High magnification (1000x) light microscope image.*

HEAT TREATMENT



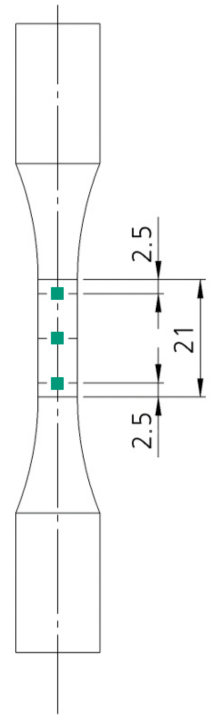
Stress-Relief heat treatment at 800 °C for 2h in argon atmosphere, leading to a mixture of α and β phase. The α phase had a fine lamellar shape.
***Left**: Low magnification (100x) light microscope image.*
***Right:** High magnification (1000x) light microscope image*

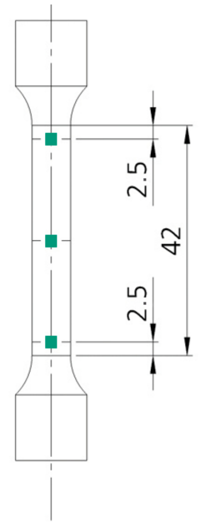
HT + HIP



HIP treatment at 920 °C and 2,000 bar for 2h resulted in a coarser α phase lamellar microstructure. The α laths were widened to around 5 µm. In addition, the β phase increased.
***Left:** Low magnification (100x) light microscope image.*
***Right:** High magnification (1000x) light microscope image.*

Ti





Roughness measurement points on fatigue (top) and tensile (bottom) specimens.

5.1.3_Roughness Measurement

Surface roughness measurement and analysis were performed according to DIN EN ISO 25178 using an S-L surface as described in chapter 4.1.

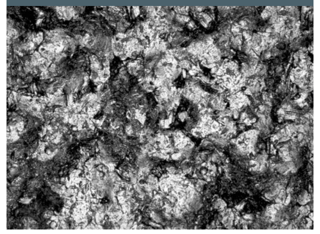
Three measurements were done on each specimen. The positions were chosen close to the boundaries and in the middle of the test section. All measurements were done on the same side of every specimen to ensure the same orientation towards gas flow and recoater during printing.

Comparability of the specimens was ensured using two area roughness parameters: arithmetic mean height Sa and maximum height Sz. The arithmetic mean height was defined as the sum of the difference in height of each point to the arithmetic mean of the measured area. The maximum height was defined as the sum of the maximum peak height and the maximum pit depth of the measured area.

BEST

TYPICAL

WORST



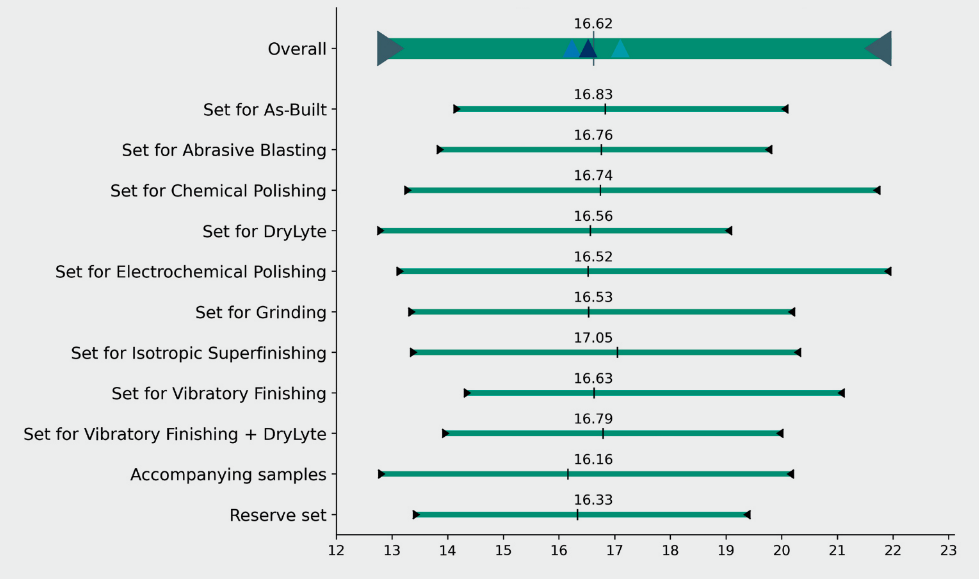
Build job A showed the highest arithmetic mean height Sa compared to build job B and C. However, the arithmetic mean height of every build job was close to the overall arithmetic mean height of 16.62 µm. The same number of specimens from each build job was assigned to each finishing method set. There were only minor differences of up to 0.46 µm (around 3%) between the arithmetic mean height of every set and the overall arithmetic mean height.

The mean maximum height values (Sz) of all build jobs were very close to the overall mean of 145.27 µm, leading to the assumption that all build jobs were comparable in maximum height. The maximum deviation between the mean value of each finishing method set and the overall mean was just 9.30 µm (around 6%). The mean value for the Vibratory Finishing set was closer to the measured minimum value, which indicates the existence of a single outlier.

The recorded images showed that partially molten powder was the main driver for roughness. Partially molten particles with a particle size ranging from 29 µm (D10) to 50 µm (D90) can therefore increase the arithmetic mean height and maximum height.

Overall, no deviations were identified which would have made it necessary to rebuild the specimens.

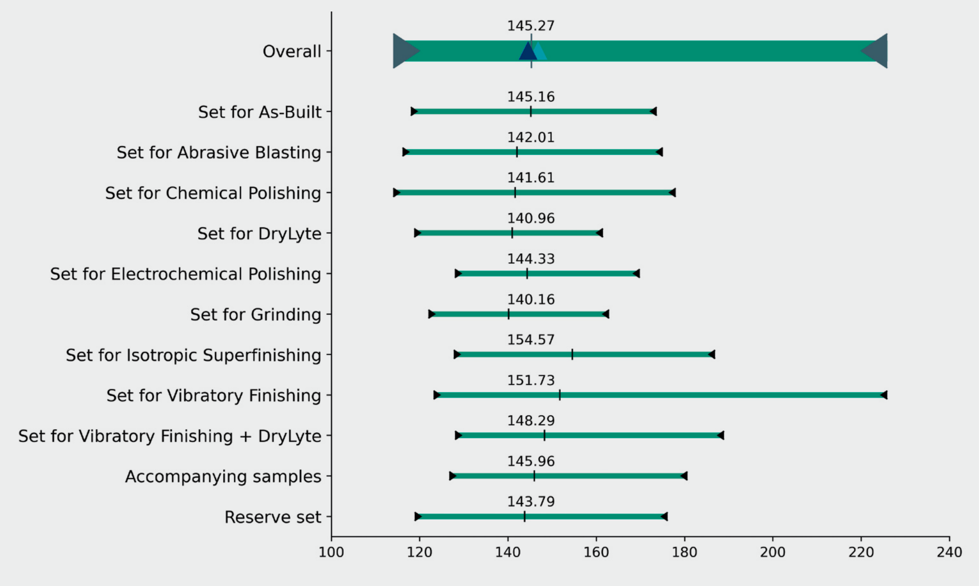
ARITHMETIC MEAN HEIGHT Sa



Measurement results for arithmetic mean height Sa after printing for Ti6Al4V specimens.

minimum
maximum
mean
mean of build job A
mean of build job B
mean of build job C

MAXIMUM HEIGHT Sz



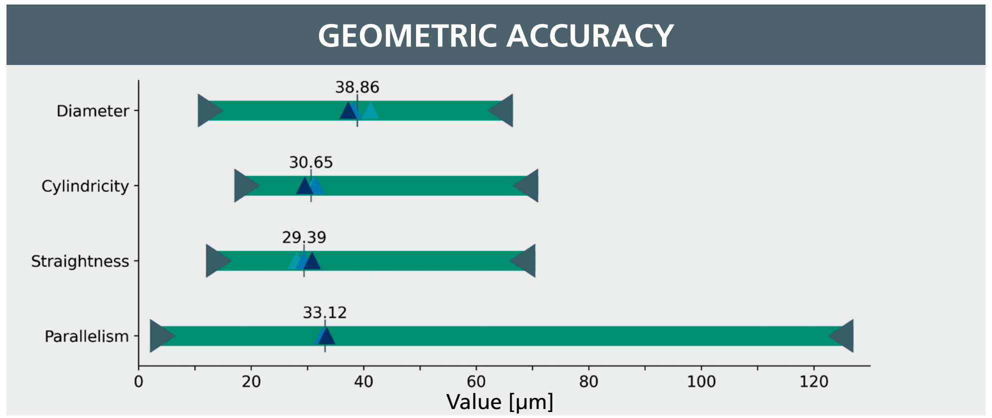
Measurement results for maximum height Sz after printing for Ti6Al4V specimens.

minimum
maximum
mean
mean of build job A
mean of build job B
mean of build job C

Ti

5.1.4_Geometric Accuracy

Geometry is important for mechanical testing. Diameters are particularly important due to the stress calculation of force divided by the cross-sectional area. This is why the geometric accuracy of the test section was investigated. The measurements were carried out with a coordinate measurement machine according to the description in chapter 4.1.
The measurement results of all specimens showed that the mean diameter was 38.86 µm larger than the target value. Mean cylindricity and straightness were close to each other with a value of 30.65 µm and 29.39 µm. The values ranged from 10.5 µm to 71 µm and coincided well with the powder diameters between 29 µm (D10) and 50 µm (D90). This applies particularly in view of the fact that the roughness measurement already showed partially molten powder particles to be the main influencing factor. Parallelism between 2 µm and 127 µm with a mean value of 33.12 µm was in the range of the double powder diameter, which was reasonable. The mean values for cylindricity, straightness and parallelism were closer to the minimum which pointed to a few high outliers. Only slight differences were observed between the build jobs. The build jobs were therefore considered to be sufficiently equal.



Measurement results for geometric accuracy after printing for Ti6Al4V specimens.

minimum
maximum
mean
mean of build job A
mean of build job B
mean of build job C

The following statements were derived from the mean value of a set of specimens assigned to a surface finishing method in relation to the overall mean value:

- Diameter deviation was in the range of ±7.91 µm.
- Cylindricity deviation was in the range of ±3.99 µm.
- Straightness deviation was in the range of ±1.98 µm.
- Parallelism deviation was in the range of ±8.79 µm.

Tactile measurement of geometric accuracy did not show any significant differences between build jobs and surface finishing sets. All samples made of Ti6Al4V were considered comparable.

In

5.2_INCONEL

5.2.1_Density
Accompanying samples measuring 10 x 10 x 12 mm (width x length x height) were used to investigate the resulting density before and after every heat treatment. The inverted pyramid shape was suitable for easy removal without wire EDM and for inspecting the down-facing surface. Specimens of every build job were analyzed. The notch was caused by the labelling.

Preparation was carried out according to the standard sequence: embedding in a polymeric matrix, wet grinding with SiC grinding paper and polishing with a diamond suspension up to a grain size of 1 µm.

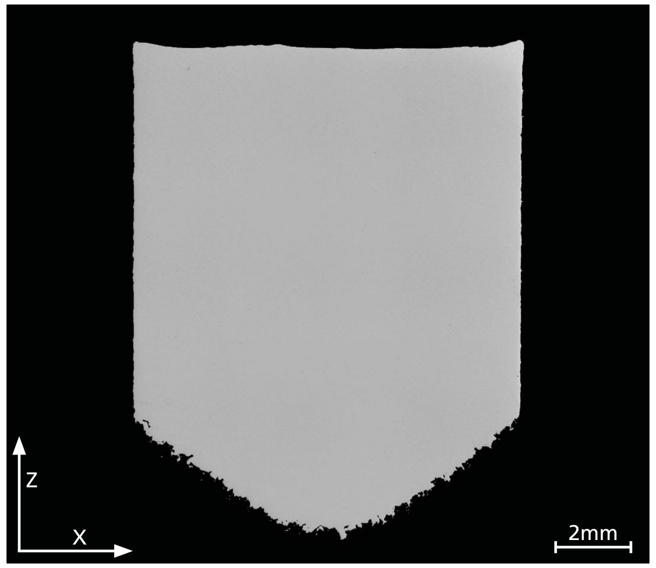
Images were taken with a digital microscope VHX-5000 by Keyence using 50x magnification and dark-field illumination. Multiple images were merged for one specimen. Density was calculated with software based on the region of interest (ROI) using a threshold of 125 [-].

Some long thin scratches were visible due to manual preparation, but no clustered pores or signs of contour porosity were observed. The As-Built specimens showed a density of >99.98%. HIP treatment at 1,180 °C and 1,030 bar for 4 hours increased the measured density slightly to >99.99%. Subsequent heat treatment according to AMS 5662N (see chapter 4.3) did not show any influence on the measured density.

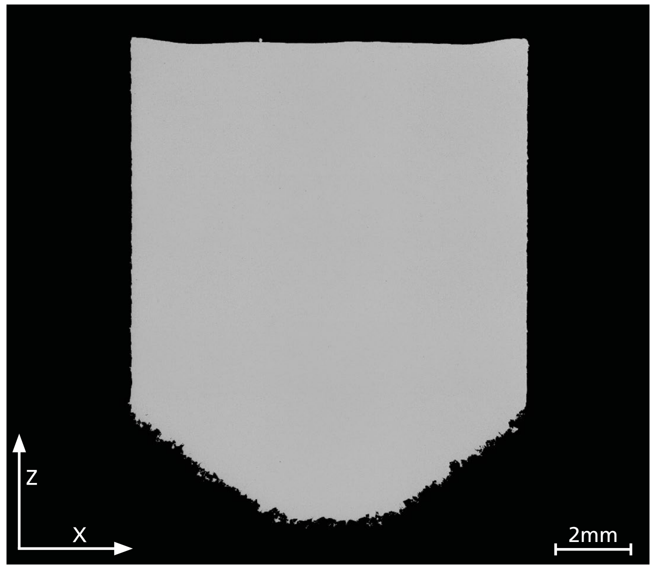
Overview of measured density for Inconel 718 accompanying samples.

CONDITION	MIN.	MAX.	MEAN	STD	DENSITY [%]
As-Built	99.989	99.991	99.990	0.001	> 99.98
HIP	99.991	99.997	99.993	0.0022	> 99.99
HIP + HT	99.990	99.998	99.994	0.003	> 99.99

AS-BUILT

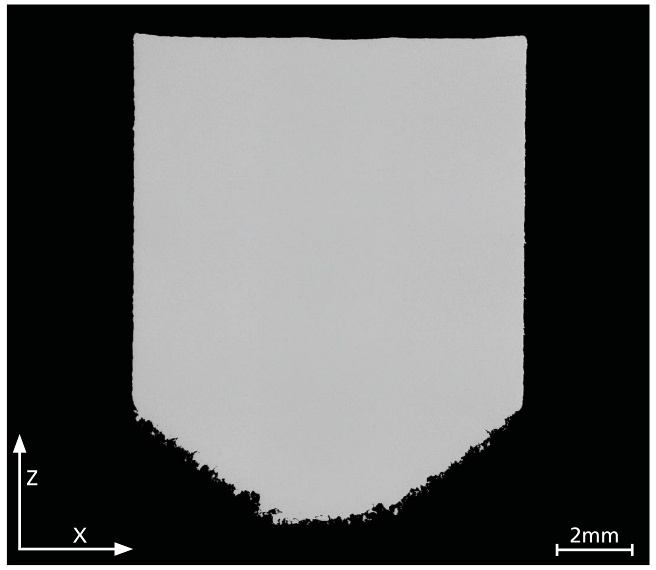


HIP



HIP treatment at 1,180 °C and 1,030 bar for 4h.

HIP + HT



Heat treatment according to AMS 5662.

In

5.2.2_Microstructure

Accompanying samples measuring 10 x 10 x 12 mm (w x l x h) were used to investigate the influence of heat treatment and pressure on the microstructure. Specimens of every build job were analyzed.

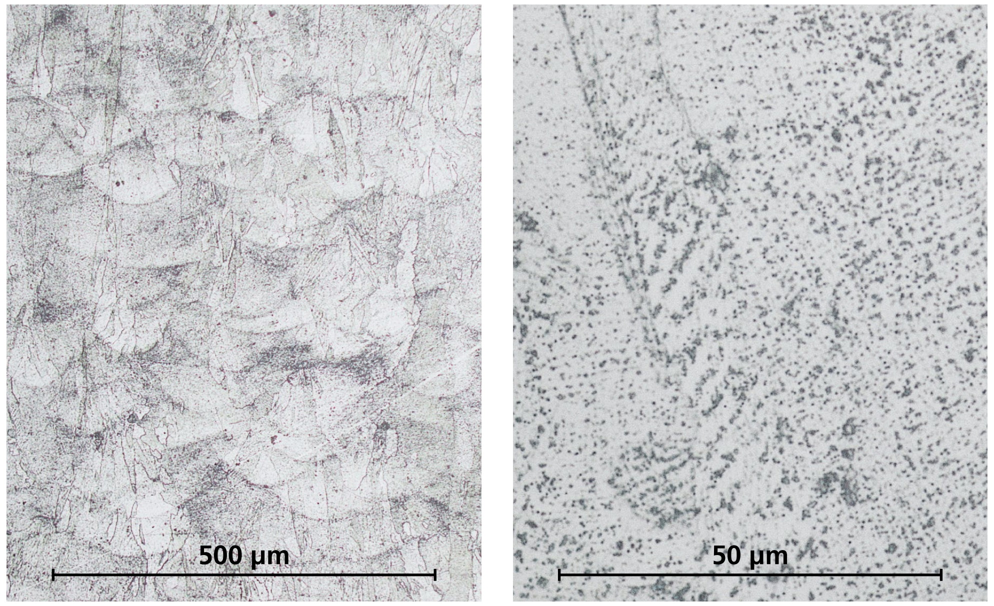
Specimens were prepared as described in the previous section (see density). For light microscopy, the specimens were additionally etched for 10 seconds using an etchant according to Adler by CRIDA Chemie.

Low magnification images were captured using a light microscope GX51 by Olympus. with 100x magnification. High magnification images were acquired using magnification of 1.000x.

Starting from the As-Built columnar dendritic grain structure with different types of precipitates in the interdendritic regions, the microstructure changed after Hot Isostatic Pressing into a coarser and more equiaxed grain structure. The precipitates were well distributed in the material. Further heat treatment led to homogenization of the microstructure.

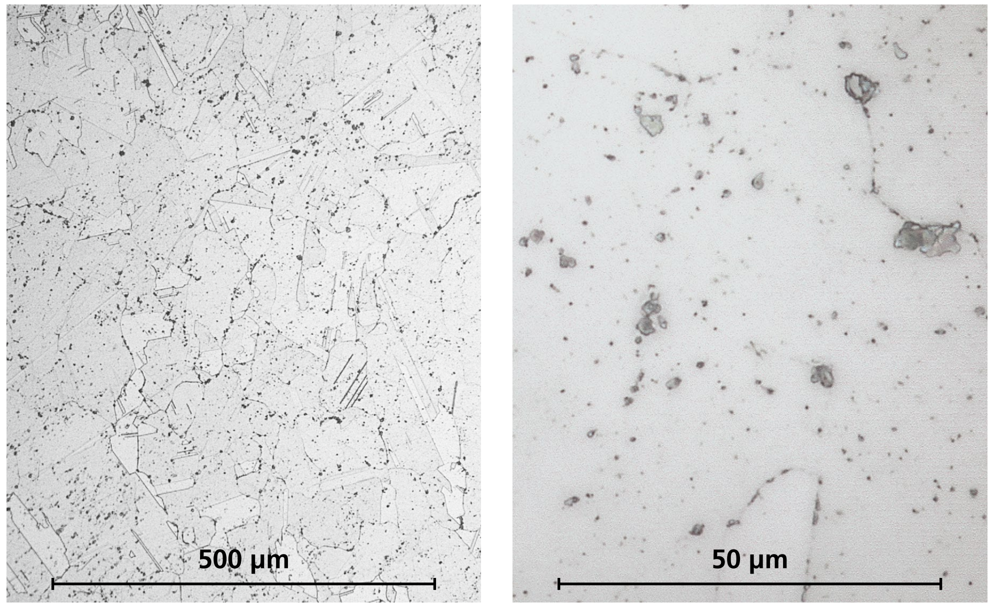
After each investigated thermal postprocessing step, the microstructure was revealed as expected and described in literature, and showed no abnormalities.

AS-BUILT



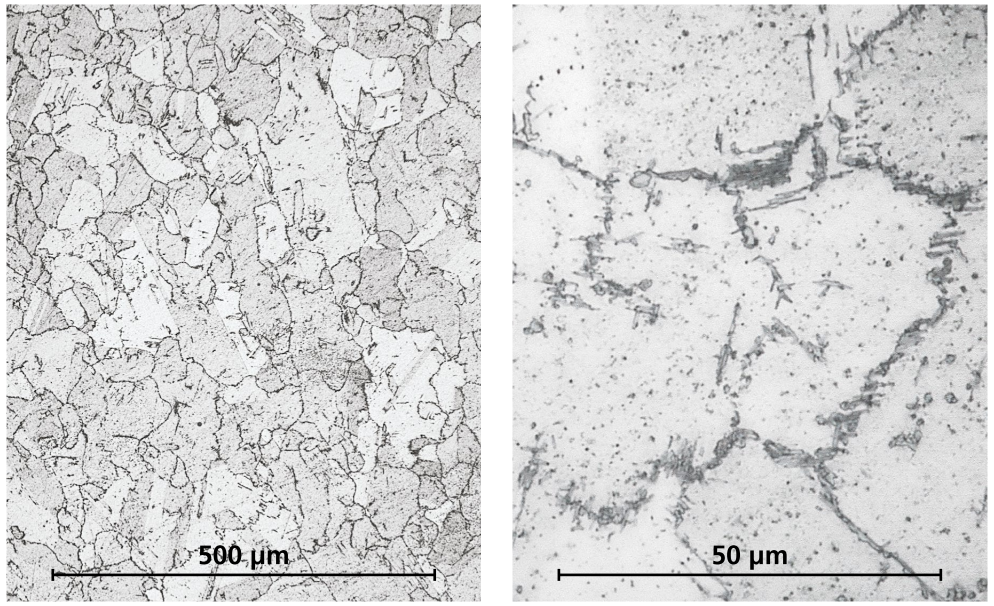
As-Built condition showed a columnar dendritic grain structure preferably in the build direction.
Left: *Low magnification (100x) light microscope image.*
Right: *High magnification (1000x) light microscope image.*

HIP



HIP treatment at 1,180 °C and 1,030 bar for 4h led to a coarser and more equiaxed grain structure with well distributed precipitates.
Left: *Low magnification (100x) light microscope image.*
Right: *High magnification (1000x) light microscope image.*

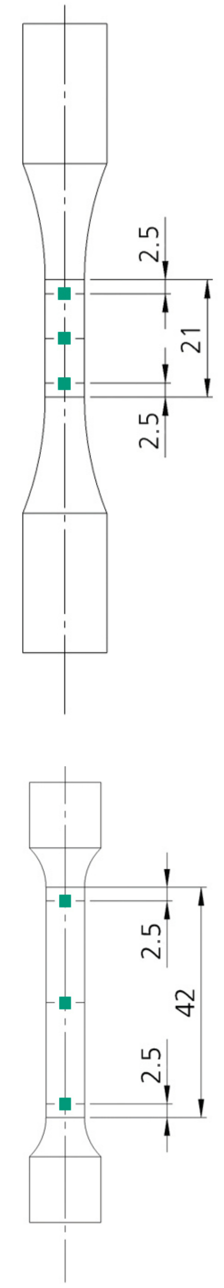
HT + HIP



Heat treatment according to AMS 5562
- *Solution annealing heat treatment at 954 °C for 1h.*
- *Aging at 720 °C for 8h then furnace cooling at a rate of 50 °C per hour.*
- *Aging at 620 °C for 8h until air cooling caused further homogenization of the microstructure.*

Left: *Low magnification (100x) light microscope image.*
Right: *High magnification (1000x) light microscope image.*

In

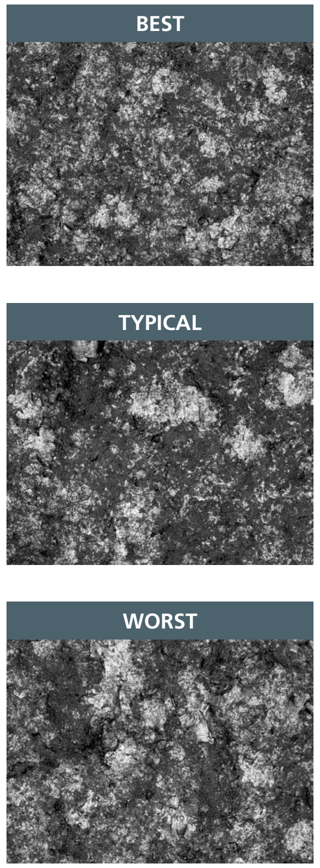


Roughness measurement points on fatigue (top) and tensile (bottom) specimen.

5.2.3_Roughness measurement

Surface roughness measurement and analysis were performed according to DIN EN ISO 25178 using an S-L surface as described in chapter 4.1.

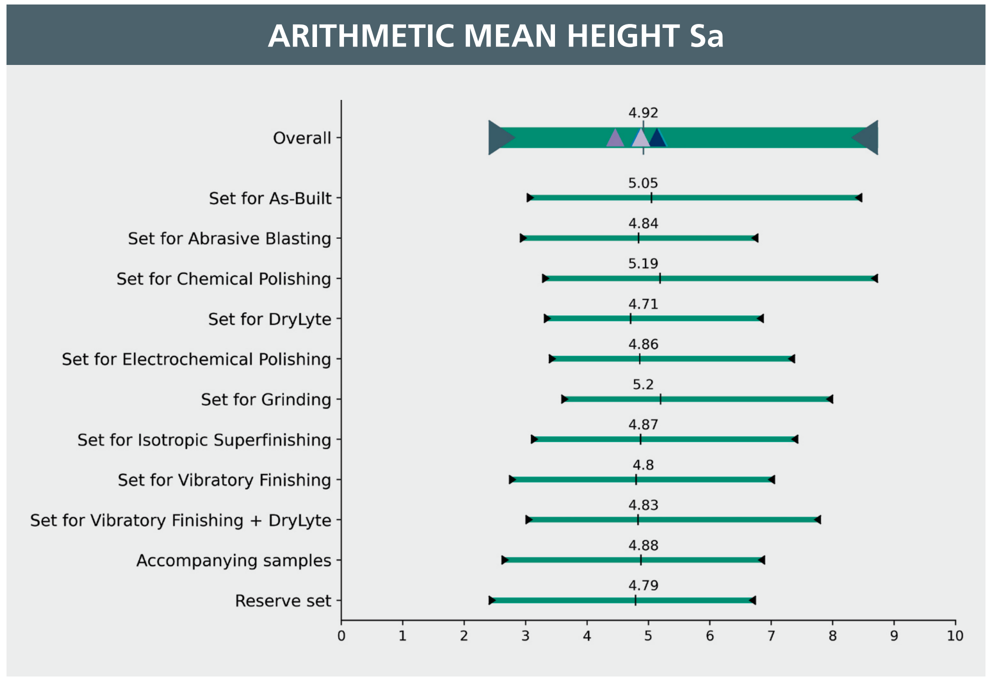
Three measurements were done on each specimen. The positions were chosen close to the boundaries and in the middle of the test section. All measurements were done on the same side of every specimen to ensure the same orientation towards gas flow and recoater during printing. Comparability of the specimens was ensured using two area roughness parameters: arithmetic mean height Sa and maximum height Sz. The arithmetic mean height was defined as the sum of the difference in height of each point to the arithmetic mean of the measured area. The maximum height was defined as the sum of the maximum peak height and the maximum pit depth of the measured area.



Build job X shows the highest and build job Z the lowest arithmetic mean height Sa compared to build jobs V, W and Y. This may be because build job Z only consisted of tensile specimens. However, the arithmetic mean height of every build job is close to the overall arithmetic mean height of 4.92 µm. The same number of specimens from each build job was assigned to each finishing method set. There were only minor differences of up to 0.28 µm (around 6%) between the arithmetic mean height of every set and the overall mean value of the arithmetic mean height.

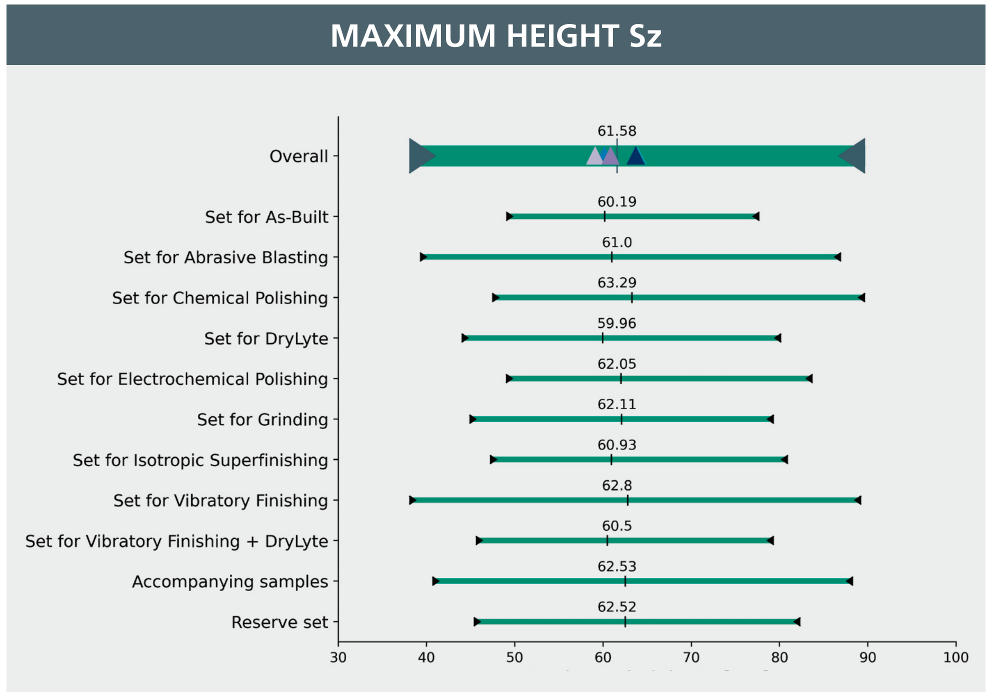
The mean maximum height values (Sz) of all build jobs were very close to the overall mean of 61.58 µm, leading to the assumption that all build jobs were comparable in maximum height. The maximum deviation between the mean value of each finishing method set and the overall mean was 1.71 µm (around 3%). Obvious outliers in single measurements of maximum height were eliminated due to measurement noise. The specimens made from Inconel 718 showed only occasional partially molten particles with a particle size ranging from 27 µm (D10) to 53 µm (D90). Each partially molten particle therefore had a considerable influence on the arithmetic mean height but not on the maximum height.

Overall, no deviations were identified which would have made it necessary to rebuild the specimens.



Measurement results for arithmetic mean height Sa after printing for Inconel 718 specimens.

- minimum
- maximum
- mean
- mean of build job V
- mean of build job W
- mean of build job X
- mean of build job Y
- mean of build job Z



Measurement results for maximum height Sz after printing for Inconel 718 specimens.

- minimum
- maximum
- mean
- mean of build job V
- mean of build job W
- mean of build job X
- mean of build job Y
- mean of build job Z

In

5.2.4_Geometric Accuracy

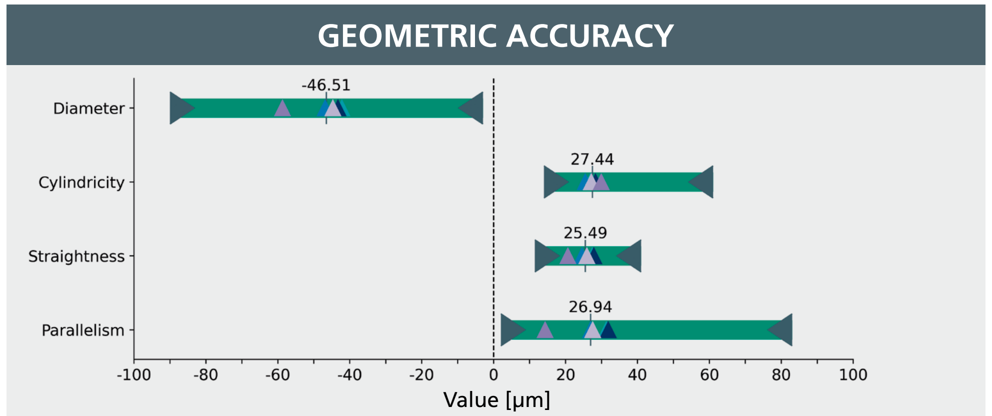
Geometry is important for mechanical testing. Diameters are particularly important due to the stress calculation of force divided by the cross-sectional area. This is why the geometric accuracy of the test section was investigated. The measurements were carried out with a coordinate measurement machine according to the description in chapter 4.1.

The measurement results of all specimen showed that the mean diameter was 49.51 µm smaller than the target value. Mean cylindricity and straightness were close to each other with a value of 27.44 µm and 24.49 µm. The values ranged from 11.5 µm to 61 µm and coincided well with the powder diameters between 27 µm (D10) and 53 µm (D90). This applies particularly in view of the fact that the roughness measurement already showed partially molten powder particles to be the main influencing factor. Parallelism ranged from 2 µm to 83 µm with a mean value of 26.94 µm. The mean values for cylindricity and parallelism were closer to the minimum which pointed to a few high outliers.

The tensile specimens built in build job Z showed a noticeably better result for straightness and parallelism. This is not critical due to separate fatigue and tensile testing. Only slight differences were observed between build jobs V, W, X and Y containing the fatigue specimens. The build jobs were therefore considered to be sufficiently equal.

Measurement results for geometric accuracy after printing for Inconel 718 specimens.

minimum
maximum
mean
mean of build job V
mean of build job W
mean of build job X
mean of build job Y
mean of build job Z



The following statements were derived about the mean value of a set of specimens assigned to a surface finishing method in relation to the overall mean value:

- Diameter deviation was in the range of ±5.91 µm.
- Cylindricity deviation was in the range of ±2.17 µm.
- Straightness deviation was in the range of ±2.10 µm.
- Parallelism deviation was in the range of ±6.50 µm

Tactile measurement of the geometric accuracy did not show any significant differences between build jobs and surface finishing sets. All samples made of Inconel 718 were considered comparable.

6_SURFACE FINISHING METHODS AT A GLANCE

The following section explains the operating principles of the investigated surface finishing methods and names the specific parameter settings used for the methods within this study.

Categorization of investigated surface finishing processes

- Machining with undefined cutting edge: Abrasive Blasting, Vibratory Finishing, Grinding
- Finishing with chemical additives: Chemical Polishing, Isotropic Superfinishing
- Finishing with electric power: Electrochemical Polishing, DryLyte
- Finishing method combination: Vibratory Finishing and DryLyte

6.7_VIBRATORY FINISHING

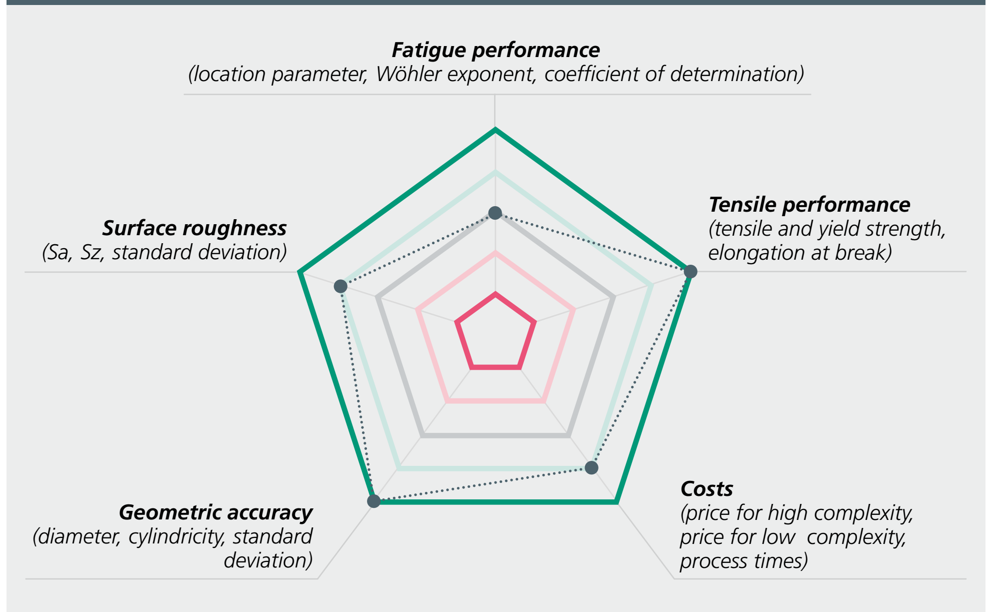
Vibratory Finishing is a machining process with an undefined cutting edge that aims to improve the surface quality of relatively small parts by deburring, edge rounding, smoothing, polishing, matting or grinding. The parts to be surface-finished are placed in a container together with the grinding medium. An oscillating or rotating movement of the container results in a relative movement between the parts and the grinding medium. This causes material to be removed from the parts. Edge rounding is a common phenomenon. The removal rate can be influenced by the choice of grinding medium, rotation speed and grinding duration.

Surface finishing of the specimens was carried out by AM Solutions in a rotary vibrator type R125 EC. The specimens were finished in one batch for each material with free movement of the parts in the abrasive medium. Surface finishing for the titanium specimens consisted of the RÖSLER Keramo-Finish® process which was performed for 7 hours with 70 kg of the abrasive medium type RAM4 15/18 S+10/15 S, 50 l/h of water and 200 g/h of the rubbing compound type RAM-C 23.

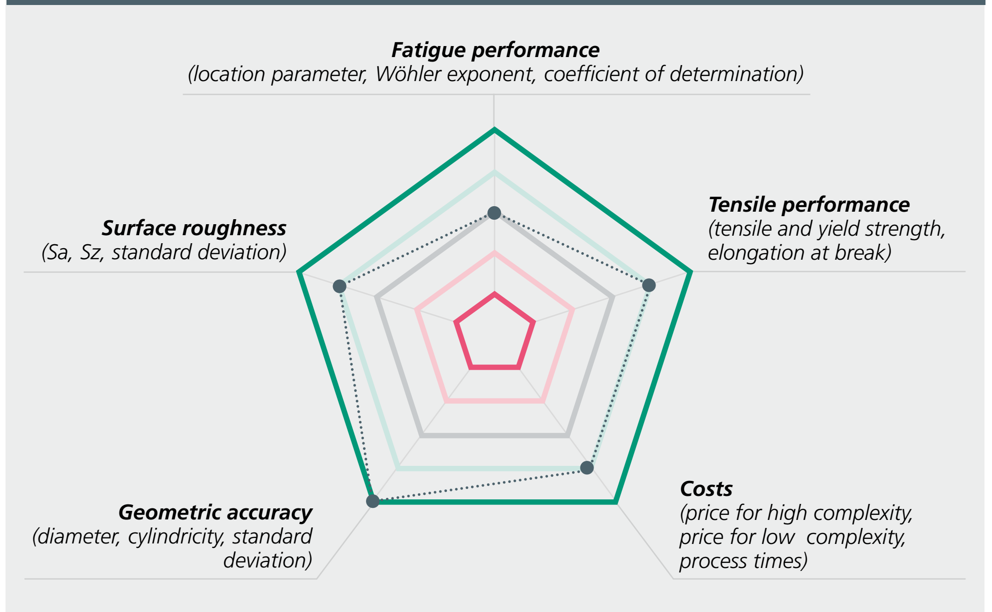
120 kg of abrasive medium type RAM11 09/09 SV01 T05 and 1.5 kg of rubbing compound type REM-GP 31 were used for grinding the Inconel specimens (12 hours). The same abrasive medium was used for washing (1 hour 20 minutes) in combination with the compound type RAM-C1 (250 g/h) and 50 l/h of water.

In the last step, all parts were dried using a rotary dryer RT 250 Euro with drying medium type SV16N. After surface finishing, the average diameter in the test area was 6.928 mm for the titanium specimens and 6.878 mm for the Inconel specimens.

Ti VIBRATORY FINISHING OF TITANIUM



In VIBRATORY FINISHING OF INCONEL

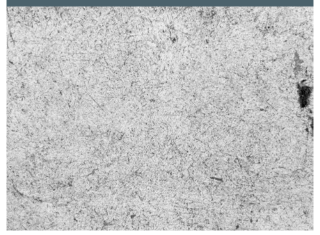


excellent (outside)
good
moderate
weak
poor (center)

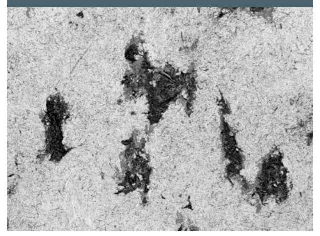
In

8.7_VIBRATORY FINISHING

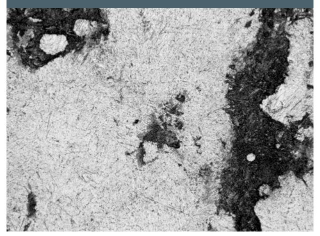
BEST



TYPICAL



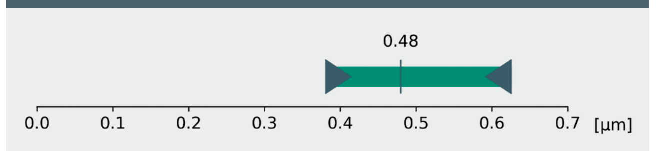
WORST



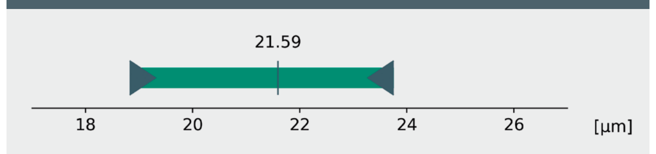
Vibratory Finishing decreases the mean value of the arithmetic mean height Sa by 91% and the maximum height Sz by 66%. This indicates the existence of a few notches on the surface. The figures show that most of the surface is ground. The resulting roughness is mainly due to the baseline waviness of the printed layers.

There is a great increase in geometric accuracy, while the diameter has shrunk by only around 80 µm. Most of the reduction in diameter comes from removing partially molten particles, with only a relatively small amount of material being removed from the actual surface of the specimens.

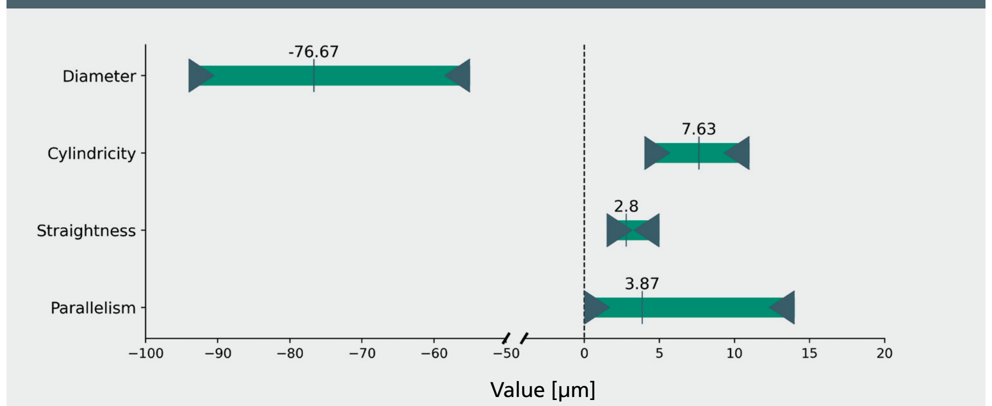
ARITHMETIC MEAN HEIGHT Sa



MAXIMUM HEIGHT Sz

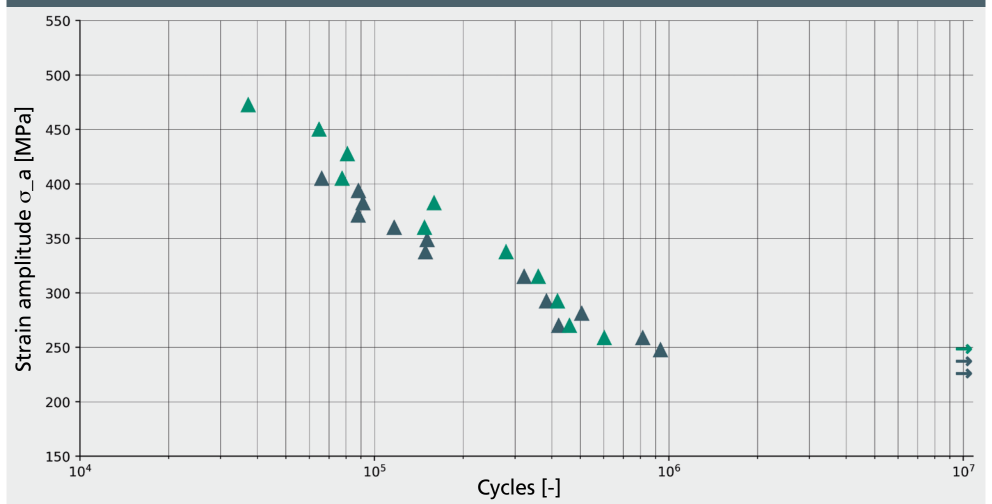


GEOMETRIC ACCURACY



minimum
maximum
mean

FATIGUE BEHAVIOR

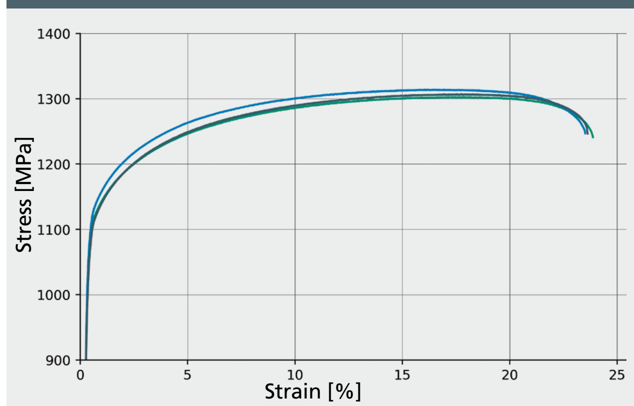


Vibratory Finishing
As-Built
runout

The location parameter at 10^5 cycles increases from around 375 MPa to 401 MPa but the Wöhler exponent decreases from around 5.35 to 4.41 compared to the As-Built specimens. A runout with a strain amplitude of around 248 MPa can be observed. There are marginal improvements in the tensile properties.

The decrease in the Wöhler exponent together with the increase in the location parameter results in a better fatigue performance below around $4*10^5$ cycles and a worse fatigue performance above, compared to the As-Built specimens. By contrast, a runout with a higher strain amplitude is achieved. Although the Sa value is improved by more than 90%, there is only a slight increase in fatigue performance, due to the remaining grooves on the surface.

TENSILE BEHAVIOR



Tensile strength [MPa]	1,308±6
Yield strength Rp0.2 [MPa]	1,059±10
Elongation at break [%]	22±1
Young's modulus [GPa]	198±7

specimen A
specimen B
specimen C