MANUFACTURING AND CHARACTERIZATION OF Ti6Al4V ALLOY BY SELECTIVE LASER MELTING

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ABSTRACT

Titanium and its alloys, particularly Ti6Al4V, are widely used, especially in aerospace and medicine due to their relatively low density, high strength, and good corrosion resistance. However, there are formidable challenges in casting, forming, and machining titanium alloys, which result in final products that are considerably more expensive. Additive manufacturing is considered one of the most promising technologies for metallic materials due to its ability to produce complex geometries with high density and accuracy in a short amount of time. It allows the manufacturing of products with complex geometries that cannot be made with traditional metallurgical processes. One of the most widely used technologies for alloys is selective laser melting (SLM).

The most favourable conditions to be used during SLM process for Ti6Al4V alloy powder have been determined in this research. This was done by using process maps and the effect of different process parameters on the mechanical properties and microstructure of SLM samples from Ti6Al4V alloy powder. Three different laser powers and four different scanning speeds were used and the process maps of hardness and porosity were created. With these results, the optimal parameters with the highest hardness and the lowest fraction of porosity in the SLM Ti6Al4V samples were determined.

1. INTRODUCTION

Ti6Al4V is the most useful ($\alpha+\beta$) titanium alloy, owing to its high strength, fracture toughness, low density, and excellent corrosion resistance. Traditional metallurgical processes used in the making of this alloy are expensive and difficult. Additive manufacturing allows the creation of complex shapes, which cannot be made in the traditional way. Selective laser melting (SLM) is one of the most commonly used additive manufacturing techniques (Figure 1). It is used for the production of metallic, ceramic, and composite components. This method often creates defects in the material such as porosity and cracks, but can also create high residual stresses. It is known that the shape and orientation of pores strongly influence the ductility of the material and that they act as nucleation sites for microcracks [1,2,3,4]. Microstructures of SLM-produced parts are different from those in parts made with traditional techniques. This is due to differences in solidification and cooling rates and is evident in different crystal grain sizes.

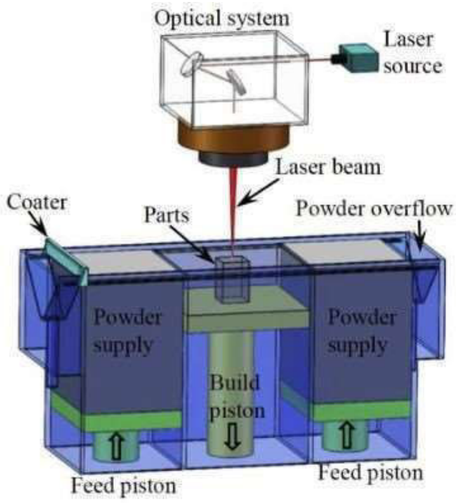


Figure 1. SLM method. Copyright 2019 by Elsevier [5]

There are many parameters at play during the SLM process, which need to be balanced for the best properties of the manufactured part: type of laser, laser intensity/power, laser beam diameter, scanning speed, hatch spacing, layer thickness, scanning strategy (Figure 2a) [6,7,8,9]. Regarding the material, these parameters are important as well: chemical composition, fluidity of the powder, density of the powder, absorption capability, and the distribution, shape and size of powder particles [6,7,8]. Three types of building direction are presented in Figure 2b.

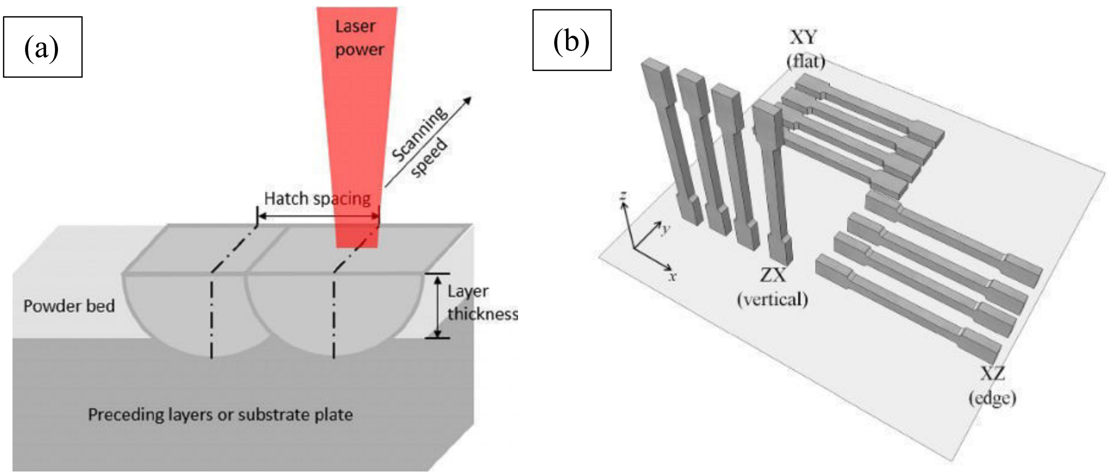


Figure 2. (a) Visualization of parameters during SLM process. Copyright 2015 by American Institute of Physics Publishing [10]; (b) Types of building direction. Copyright 2014 by Elsevier [11]

Microstructures of SLM manufactured samples from Ti6Al4V alloy are known to predominantly consist of acicular martensite α', which grows from columnar β grains (Figure 3). Its presence provides the part with high tensile strength, but at the same time makes it more brittle and less ductile. Especially the ductility is, compared to the samples created by traditional metallurgical techniques, drastically lower.

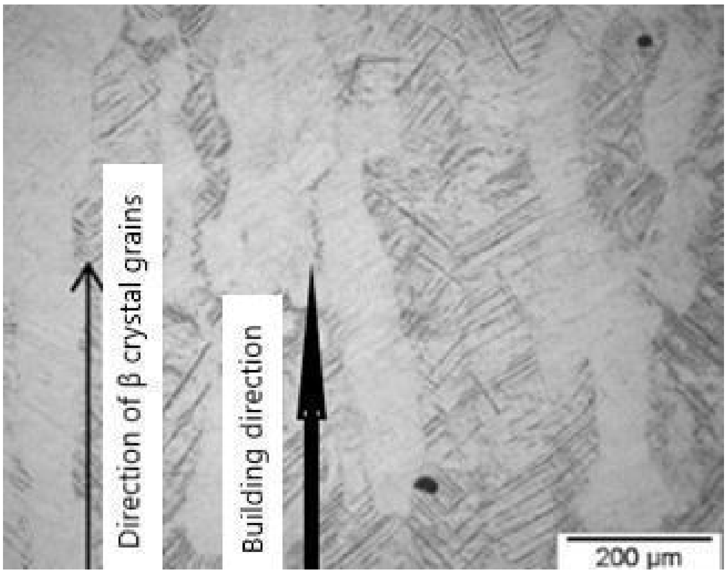


Figure 3. Typical microstructure in SLM manufactured Ti6Al4V sample [12]

2. EXPERIMENTAL WORK

The powder is commercially available and was bought on the market. Experimental work consisted of chemical analysis with ICP-OES, fluidity of the powder, which was measured according to the ASTM B213 standard, apparent density according to the ASTM B212 standard, angle of repose according to the ASTM C1444 standard, and tap density according to the ASTM B527 standard. The powder was spherical and had an average diameter of 24 µm (Figure 4).

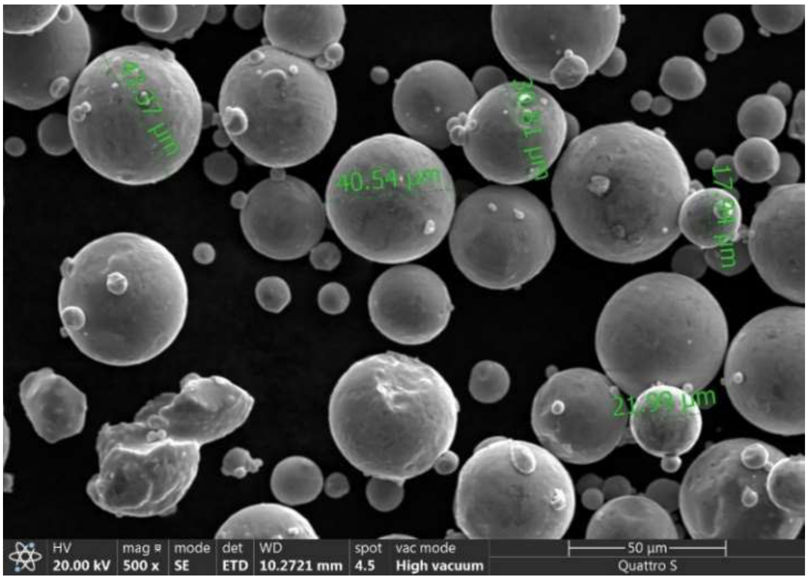


Figure 4: SEM photo of the used Ti6Al4V powder

Following the analyses, the samples were produced using the SLM method. Three different laser powers and four different scanning speeds were used. Other parameters remained constant. The parameters are shown in Table 1.

Table 1. Parameters used during experimental work

Sample	Laser power P [W]	Scanning speed v [mm/s]	Layer thickness t [μm]	Hatch spacing H [μm]	Laser beam diameter d [μm]
MP300/400	300	400	30	30	60
MP300/600	300	600	30	30	60
MP300/800	300	800	30	30	60
MP300/1000	300	1000	30	30	60
MP200/400	200	400	30	30	60
MP200/600	200	600	30	30	60
MP200/800	200	800	30	30	60
MP200/1000	200	1000	30	30	60
MP100/400	100	400	30	30	60
MP100/600	100	600	30	30	60
MP100/800	100	800	30	30	60
MP100/1000	100	1000	30	30	60

The samples were modeled in Solidworks and printed using Aconity 3D MINI printer located at the Institute for Materials and Technology in Ljubljana (Figure 5a). Samples were later metallographically prepared for microstructural analyses. These were done with ZEISS Imager Z2mlight microscope and Thermo Fisher Scientific FEGSEM Quattro scanning electron microscope, equipped with an EDS detector by Oxford Instruments located at the Department of Materials and Metallurgy at the Faculty of Natural Sciences and Engineering (University of Ljubljana) (Figure 5b). Hardness tests were performed using HV1 Vickers method. Tensile tests were performed according to the SIST EN ISO 6892-1 A224 standard. Samples were tested based on their building direction (XZ and XY (Figure 2b)).

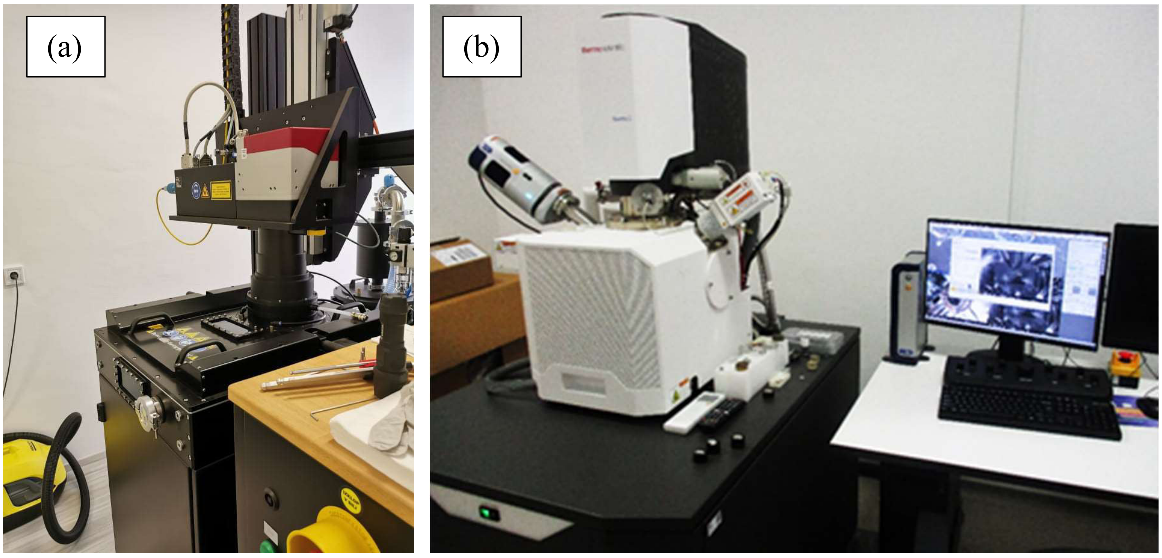


Figure 5. (a) Light microscope ZEISS Imager Z2m; (b) Electron microscope Thermo Fisher Scientific Quattro with an Oxford Instruments EDS detector

3. RESULTS

The chemical analysis has shown that the powder consists of 6,1wt% Al, 3,8 wt% V, and 0,22 wt% Fe with the remaining amount consisting of Ti. Other characteristics of the powder were also measured: fluidity was on average 2,05 g/s, tap density 2,56 g/cm^3, angle of repose 53,75°, and apparent density 2,43 g/cm^3.

The results show that the hardness achieves the largest value at 200 W and 1000 mm/s (Figure 6). Meanwhile, the proportion of porosity is by far the highest when 300 W of laser power and 800 mm/s scanning speed are used (Figure 7). This could be a consequence of reusing the powder. It is also worth noting that the porosity was not so severe across the whole sample. The region with the worst porosity was chosen to be presented as it could affect the properties of the manufactured part if ignored. Based on these results two combinations of parameters were chosen for further testing (200 W/400 mm/s and 200 W/1000 mm/s).

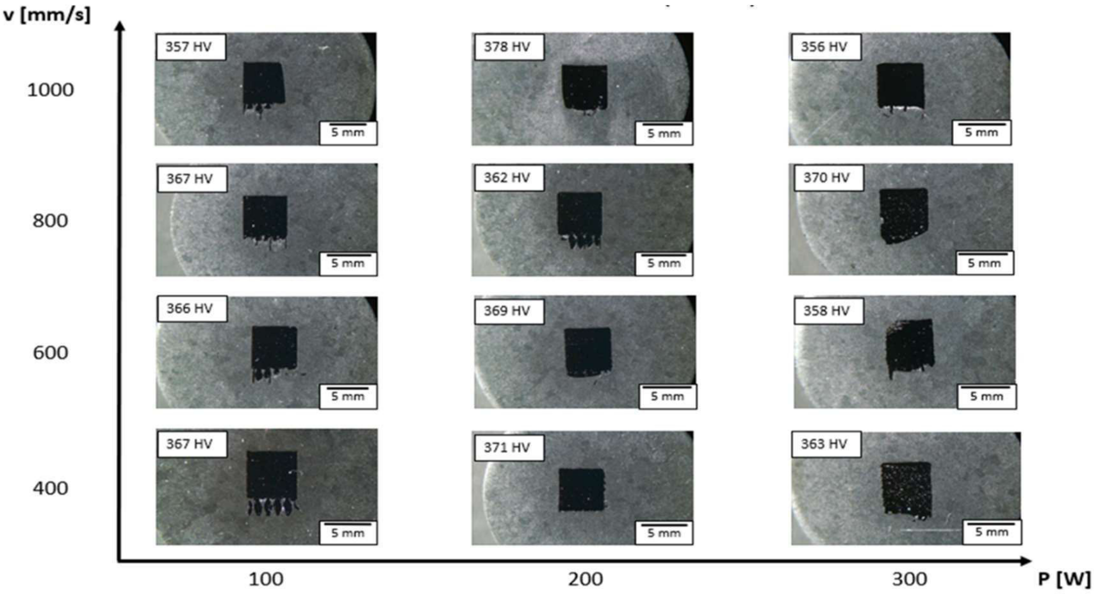


Figure 6. Hardness values at different parameters [HV1]

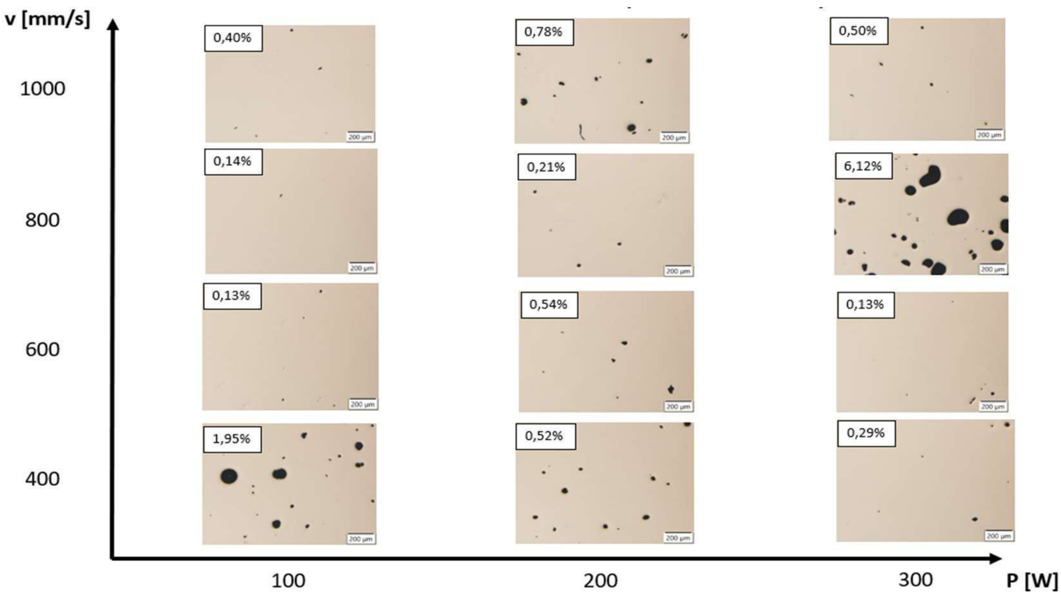


Figure 7. Porosity proportion at different parameters

The microstructures of both samples consist of martensite α', which has grown from the grain boundaries of elongated columnar β grains. These are oriented in the building direction. With higher scanning speeds, the columnar β grains become thinner (Figure 8).

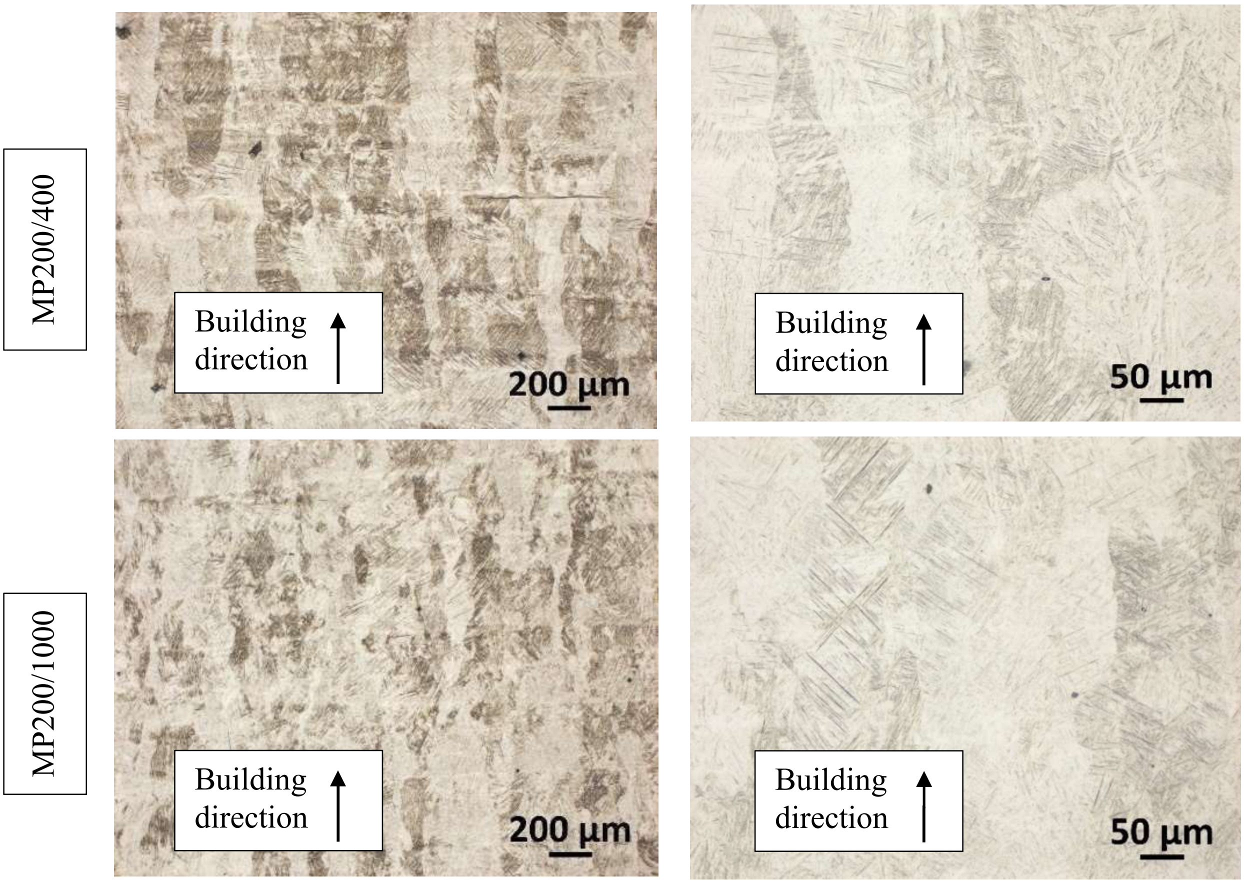
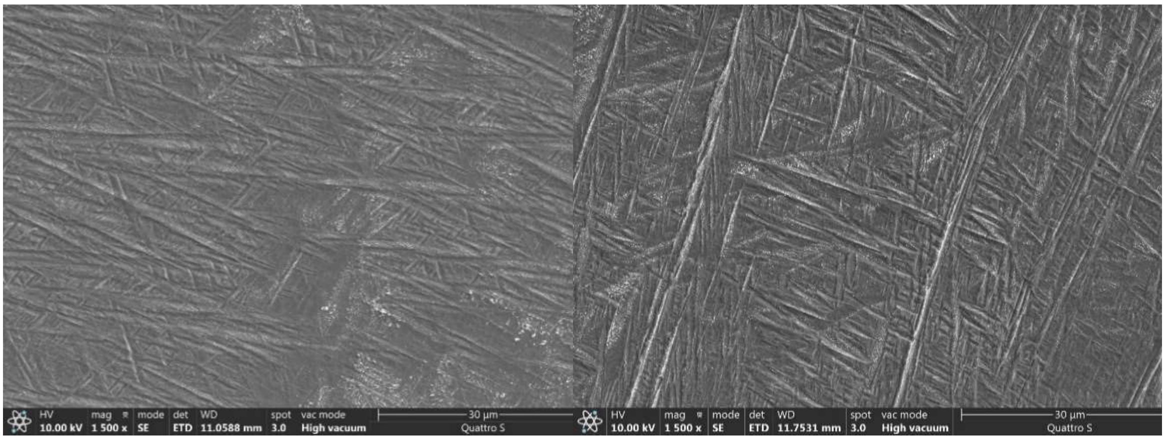


Figure 8. Microstructures in samples produced with chosen parameters - optical microscope

Microstructural analysis with SEM makes needles of acicular martensite α' more clearly visible. They have a "fishbone" shape, which is caused by the changes in the scanning direction. The martensite is much more pronounced at higher scanning speeds (Figure 9).



MP200/400 MP200/1000

Figure 9. Microstructures in samples produced with chosen parameters – SEM

The MP200/400 sample also had its tensile strength measured (Table 2). Three measurements were performed per building direction (XZ and XY). Samples built in XZ direction have an average tensile strength of 1185,67MPa, while those built in XY direction have an average of 1251,67 MPa. The average elongation was 5,7 % for XZ samples and 3,03 % for XY samples. The tensile strengths of similar samples found in the literature are between 1000 MPa and 1200 MPa [13,14,15].

Table 2. Tensile test results for MP200/400 sample

MP200/400	Length L_o[mm]	Final length L_u [mm]	Tensile strength R_m [MPa]	Elongation A [%]
XZ1	30	31,92	1170	6,4
XZ2	30	32,00	1176	6,7
XZ3	30	31,21	1211	4
Average			1185,67	5,7
XY1	30	30,69	1250	2,3
XY2	30	30,89	1270	3,0
XY3	30	31,14	1235	3,8
Average			**1251,67**	**3,03**

4. CONCLUSIONS

Samples from Ti6Al4V alloy in a powder form were produced using the SLM method. Different parameters were used and their effect on the properties analysed. Based on the experimental work the following conclusion can be made:

- Based on the hardness and level of porosity, the best parameters are 200 W of laser power and a scanning speed of 400 mm/s.
- Both of these parameters affect hardness more than they do porosity, except at 300 W of laser power and 800 mm/s scanning speed, which is an anomaly, that could be caused by reusing the powder.
- The Microstructure of Ti6Al4V samples consists of α' in the form of needles, which grow from the grain boundaries of prior columnar β grains. The width of β grains depends on the scanning speed.
- The tensile strength of Ti6Al4V samples is between 1000 MPa and 1300 MPa. Their ductility is low. This is caused by the acicular martensite and residual stresses.
- The building direction affects the mechanical properties. The tensile strength of the samples built in XY direction was 66 MPa higher than that of samples built in XZ direction.

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