

The influence of post-process operations on the mechanical properties of titanium alloy Ti-6Al-7Nb, produced by selective laser melting

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Abstract: Even though selective laser melting (SLM) has been available for more than a decade, during few last years the interest in this technology has grown extremely. SLM technology allows to fabricate fully functional and complex metal objects, layer by layer, via selective melting of material using laser beam. However, producing object by melting thin layers of material causes conditions of fast heat removal. This phenomenon leads to equilibrium microstructures, accompanied by the residual stresses which cause the decrease of mechanical properties. The following paper presents the result of research in the field of the influence of the post-process operations, such as machining and heat treatment, on the mechanical properties of alloy Ti-6Al-7Nb build by SLM.

Keywords: selective laser melting, SLM, post-process operations, titanium alloy, Ti-6Al-7Nb

1. Introduction

Selective Laser Melting (SLM) is one of the additive manufacturing technologies. It is also known as layer manufacturing or three-dimensional printing [1]. This freeform fabrication process, which allows to build up object layer by layer via selective melting of material using laser beam, offers enormous opportunities in the field of production of objects (Fig. 1.).

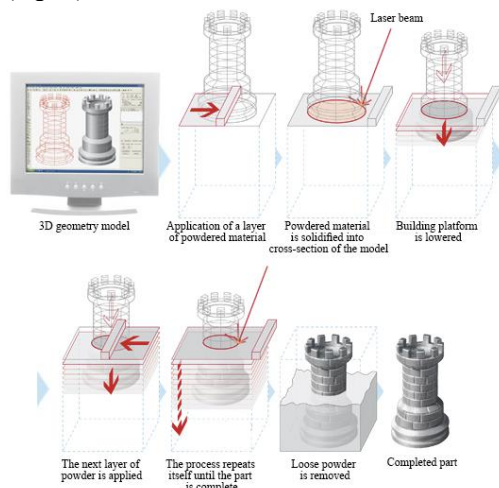


Fig. 1. General functioning of additive technologies which use laser beam to solidify metal powder [2]

Compared to conventional manufacturing technologies, SLM technology has many advantages such as: shorter production time, higher precision of manufacturing the elements, versatility, ability to build completely functional object without removal material and without creating any mold. Instead it uses metal powders (eg. titanium alloys). These

advantages are the key reasons for attempting to apply this technology to industries [3,4,5,6].

However, objects created using SLM technology have strong anisotropy properties, which are a result of directional solidification of individual layers of material. Moreover, laser melting of thin layers of object causes conditions of fast heat removal through solidified bottom layers of the object, as well as through the supporting construction and the platform.

This is especially important for two-phase titanium alloy Ti-6Al-7Nb as the α/β microstructures are very sensitive for thermo-mechanical processing [7]. The large temperature gradient in the material leads to non-equilibrium microstructures, which are accompanied by the residual stresses [3,5,6].

The following work describes the influence of the post-process operations (such as machining and heat treatment) on the mechanical properties of two-phase titanium alloy Ti-6Al-7Nb, produced by SLM.

2. Materials and methods

It is important that objects produced by SLM technology should have high mechanical properties, while preserving resistance to brittle fracture. For this purpose, samples made of titanium alloy Ti-6Al-7Nb have been treated with post-process operations - heat treatment and machining. Then three-point bending test was carried out on the samples according to the standard PN-EN ISO7438.

Samples were differentiated in terms of:

- (1) scanning strategy
 - single layer laser scanning ALT (fig. 2a)
 - double-layer laser scanning XY (fig. 2b)

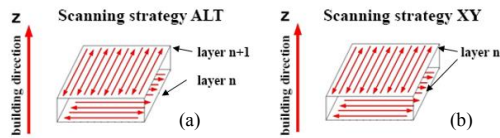


Fig. 2. Scanning strategies: (a) ALT- single layer scanning, (b) XY- double-layer scanning [8]

(2) the orientation of the samples on the working platform during SLM process:

- inclination angle 0° (fig. 3a)
- inclination angle 45° (fig. 3b)

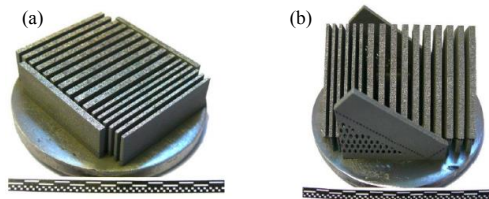


Fig. 3. Samples – methods of building: (a) samples built at inclination angle 0°, (b) samples built at inclination angle 45° [8]

Consequently, in order to carry out the test intended, 84 samples were made. The differentiation of samples is presented in table 1.

Samples of Ti-6Al-7Nb, directly after SLM process, have microstructure of martensite α' due to fast heat removal. (fig. 4) [10]. To improve mechanical properties of hardened alloy which has undergone the SLM process, annealing process should be performed in order to reduce residual stresses. This would result in an increase of material's strength.

Table 1. Summary of built samples

Methods of building samples				
Scanning strategy/Inclination angle to the working platform				
	ALT/45°	XY/45°	ALT/0°	XY/0°
Thickness [mm]	1	1	1	1
No. of samples	9	9	9	9
Thickness [mm]	2	2	2	2
No. of samples	12	12	12	12

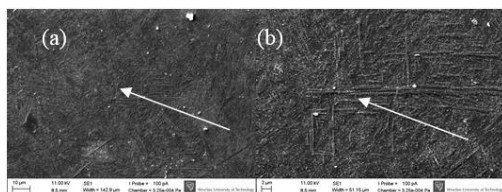


Fig. 4. Microstructure of Ti-6Al-7Nb alloy after SLM process, (a,b) arrows indicate martensite α' , etched microsection; SEM [10]

In figure 5 it is shown that noticeable results in the reduction of residual stress during the heat treatment (annealing) occur at temperatures above 480°C after a few hours. However, after increasing the temperature to 620°C it can be observed that a significant reduction of residual stress occurs just after 15 minutes from the start of the heat treatment process.

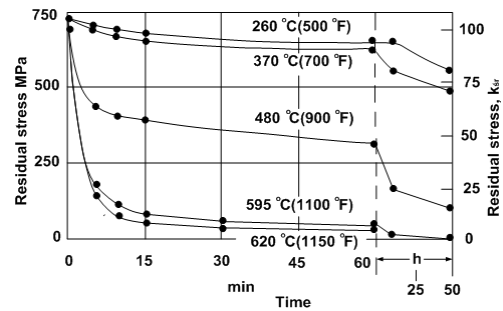


Fig. 5. The influence of time and temperature to the residual stress in objects made of Ti6Al4V [11]

Determining the heat treatment parameters is also important in order to avoid reaching conditions conducive to growing of grains. The aim of annealing process is to reduce residual stress but next to determining the temperature and duration of the process it is also important to define the way of heating and cooling samples. Cooling too fast affects the occurrence of the undesirable residual stress. To avoid this problem, basing on heat treatment parameters presented in reference [9], the following annealing parameters were assumed:

- temperature: 620°;
- annealing duration: 2h;
- heating and cooling: with furnace
- protective atmosphere: Argon

Table 2. Summary after post-process operations

Methods of building samples				
Scanning strategy/Inclination angle to the working platform				
	ALT/45°	XY/45°	ALT/0°	XY/0°
Series no.	1	2	3	4
Series no.	5	6	7	8
Series no.	9	10	11	12
Series no.	13	14	15	16
	State just after SLM process			
	Heat treatment – post-process operation			
	Machining – post-process operation			

In the next phase 2mm thick samples were machined - milling the surface layer. In this group there were both annealed samples and samples of material directly after SLM process. After milling, the nominal thickness of the samples was 1 mm. Samples used in the test are presented in table 2.

3. Theory or Calculations

Samples presented in table 2 were used for three point bending test. Measurements were taken using the Instron 3384 testing machine equipped with a head compatible with standard PN-EN ISO7438 and dedicated to three point bending tests. Due to the size of the samples, pillars Ø10mm were used in accordance with the PN-79/C-89027. It was then possible to reduce the distance between the pillars and to use shorter samples for the bending test. On this basis the distance between pillars was determined to span 19mm (fig. 6).

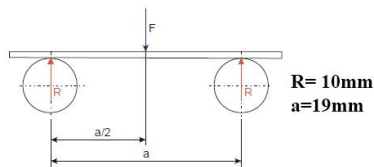


Fig. 6. Three-point bending test.

Bending test was run with a speed of 1 mm/min.

During the bending test there were recorded changes of bending force and position of the stamp in the time. Recorded data was used to calculate the value of the flexural stress according to equation (1).

$$\sigma = \frac{3 \cdot F \cdot a}{2 \cdot b \cdot h^2} \quad (1)$$

Where:
 F – bending force
 a – distance between pillars
 b – weight of sample
 h – height of sample

The test was stopped each time that the maximum value of bending stress was reached, at the moment of destruction of samples.

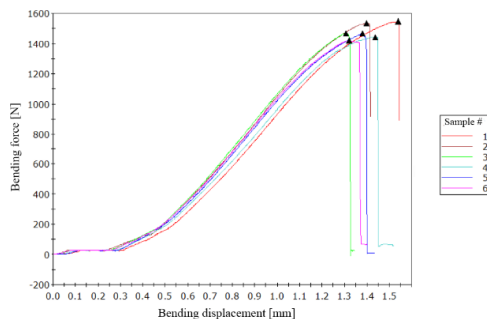


Fig. 7. The example of recorded bending test result – bending curve for the series no. 13.

The ending moment of the bending test was shown at the bending curve (fig. 7). It is defined as the pitch (by 40% minimum) of the load between the two successive measured points.

4. Results/Discussion

The results of the three point bending test are shown in figure 8. The graph shows the average values of the maximum bending stress and calculated standard deviation, depending on the type of the post-process operations and parameters of the SLM process.

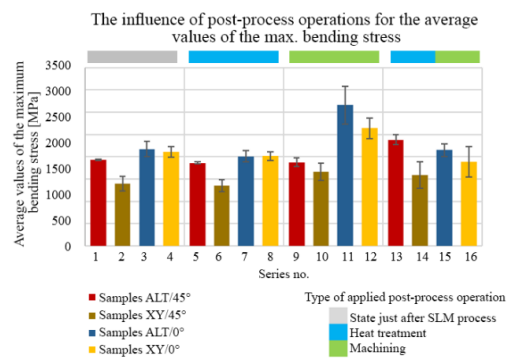


Fig. 8. The influence of post-process operations for the average values of the maximum bending stress

It can be observed that for samples which were built using the ALT scanning strategy, oriented on 45° inclination angle to working platform, none of the post-process operations, applied separately, improved the mechanical properties. Only the combination of high-temperature annealing and milling, improves the flexural strength of 500MPa, which is the increase of 25%. The effect of the post-process operations for the samples built using XY scanning strategy at an angle of 45° is negligible. The increase of the flexural strength for these samples was about 250MPa only after the milling surface. The combination of annealing and milling effects in increasing the strength only 150 MPa, compared to the material properties just after SLM process.

The flexural strength of the samples built using ALT and XY scanning strategy at the angle of 0° reaches the highest value only when using milling as a post-process operation. The increase of maximum value of flexural strength is due to removing, during milling process, the notches which were at the contact point between samples' surfaces and metal powder which has not completely melted. Applying only the annealing as a post-process operation results in no significant reduction of the flexural strength of the material compared to the samples just after SLM process. Performing both the heat treatment and the machining does not change the flexural strength.

In the presented graph it is shown that the maximum bend strength is reached by the sample built using ALT scanning strategy, at an inclination angle of 0° to the working platform with applied machining. Slightly less flexural strength characterizes the samples also constructed at an inclination angle of 0° to the working platform with applied XY scanning strategy.

However, the smallest value of the bend strength is reached by the samples built using the XY scanning strategy at the angle of 45°, regardless to the post-process operations. It can be seen that the applied annealing at 620° C for 2 hours does not increase the bending strength, regardless of the assumed SLM process parameters.

5. Conclusions

In this paper it was proved that after a three-point bending test a significant improvement of the mechanical properties of Ti-6Al-7Nb samples (created using SLM technology) occurred after applying only one post-process operation – milling. This is due to removal of the notches (during the milling process) which before were placed at the contact point between samples' surfaces and metal powder that has not completely melted. These notches lead to creation of the microcracks, which reduce the bending strength of the material. Applying both post-process operations – annealing and milling – enhances mechanical properties of the samples but only the ones that were built using ALT scanning strategy and were oriented at the inclination angle of 45° to working platform.

Annealing and machining do not significantly increase yield and resistance to brittle fracture of the samples which were built at angle 45° using the XY scanning strategy. Annealing of the samples in the temperature of 620°C for 2 hours did not result in the improvement of the mechanical properties of the material. Moreover, annealing, using the mentioned parameters, caused some decrease in flexural strength of the material. It is probable that the applied heat treatment following the excessive growth of grains and/or extensive diffusion of oxygen causes brittleness. In order to know the exact reason, it is necessary to conduct further investigations including microscopic examination to determine the microstructure of the material.

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