CHANGES IN MECHANICAL PROPERTIES DUE TO HEAT TREATMENT ON ADDITIVE MANUFACTURED Ti-6Al-4V

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Resume

Laser-based additive manufacturing (AM) of Ti-6Al-4V has become increasingly important for use in components of transportation devices. The most significant advantage over conventional steel structures is the reduction in specific weight. Complex geometries can be produced with the layer-by-layer manufacturing process and the personalised, unique part production can be faster and produced with the lower costs and less material waste than the conventional manufacturing techniques. Between the manufacturing process of an additively manufactured part and its use, the post-processing is an essential factor related to the strength properties or porosity of the finished product. The heat treatment is a possibility to change the final part properties.

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1 Introduction

Additive manufacturing (AM), also known as 3D printing, is a technology with a lot of potential in the modern manufacturing industry, where metallic materials, including the important engineering materials, steel, aluminium and titanium can be manufactured with metal-based AM [1-3].

Titanium alloys are widely used in the aerospace industry, medical applications and motorsports despite the high costs compared to other materials [4]. In equilibrium, at ambient conditions, Ti-6Al-4V (Ti6Al4V, Ti64) is a dual-phase material; primary phase α-Ti (HCP) co-exists with β-Ti (BCC). Increasing utilization of additive manufacturing (AM), enables fabrication of stronger and lighter parts with more intricate geometries [5].

This alloy is therefore used for many airframes and engine parts. Furthermore, there are many actual applications of this alloy in aircraft where the high reliability is required and further, the availability of abundant data promotes its application. In airframes, it is used for general structural material, bolts, seat rails and the like. In engines, due to the relatively low allowable temperature of about 300 °C, the alloy is used for fan blades, fan cases and the similarly in the intake section, where temperatures are relatively low [6].

Ti-6Al-4V is a frequently chosen material due to the lower mass compared to structural steels, resistance to temperatures occurring in flight, resistance to corrosion, as well as the possibility of joining titanium with composite materials [7].

The DMLS (Direct Metal Laser Sintering) method is similar to the SLM (Selective Laser Melting) method, which uses a laser to melt metallic powder layers. The metallic powder is spread on a movable platform and a laser beam heats particles of metal powder in specific places, causing their melting. After a finished layer, the mobile platform is lowered and another layer of powder is applied to the melted layer. All over again, the powder melting process is carried out. These operations are repeated until the manufactured part is created. After that, the manufactured part is heat treated and the supports are removed.

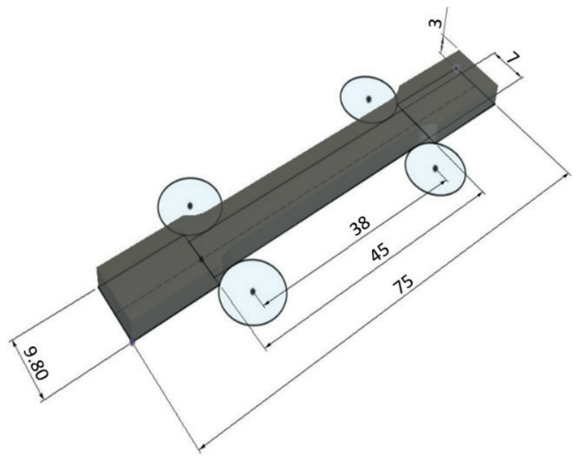

Figure 1 Tensile test sample geometry

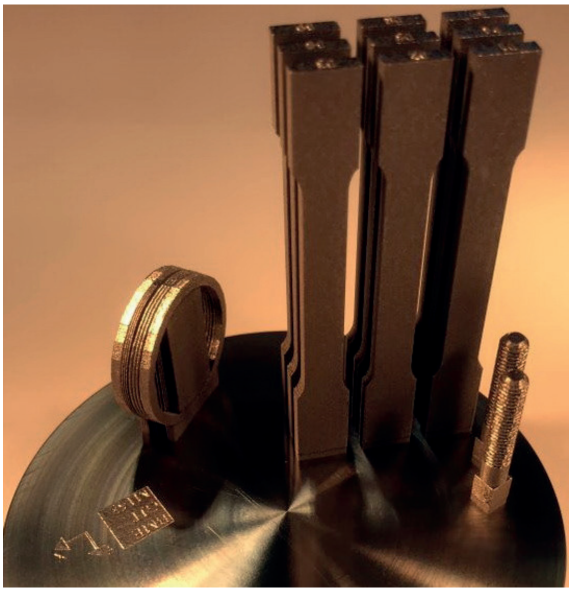

Figure 2 Tensile test sample manufacturing layout

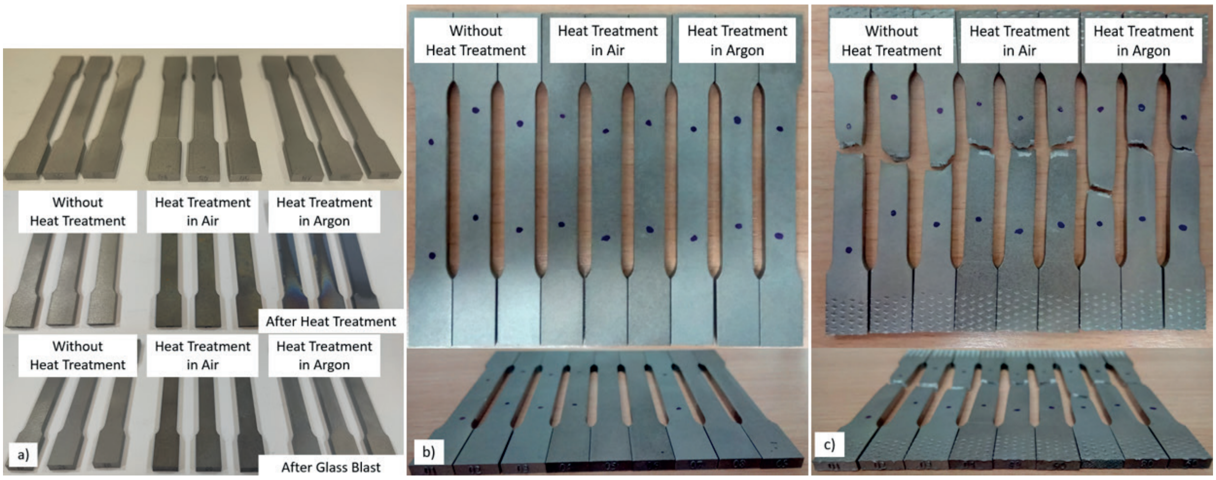

Figure 3 Ti-6Al-4V tensile test samples a) as manufactured, after the heat treatment, after the heat treatment and glass blasted, b) before the tensile test, c) after the tensile test

The heat treatment can improve Ti-6Al-4V parts microstructure and mechanical properties. Titanium is a particularly sensitive material to oxidation, so the heat treatment is carried out in an inert atmosphere or vacuum [8].

This study focuses on that how different heat treatments affect the additively manufactured Ti-6Al-4V tensile properties and how the cooling rates affect on the surface hardness of the samples.

2 Experimental materials

The static tensile test samples were manufactured with an EOS M100 DMLS powder-bed additive manufacturing equipment. The used Ti-6Al-4V powder was EOS Titanium Ti64 [9], which is the machine manufacturers' recommended stock material. The parts are manufactured with the basic parameter set recommended for this stock material from EOS. The spread layer thickness was 20 µm. The longest dimension of the tensile test samples was built in the Z direction, so the tensile force is parallel to the building direction, perpendicular to the layers. The shape of the tensile test samples and the layout is illustrated in Figures 1 and 2.

Static tensile tests were performed on a Zwick Z250 testing machine at room temperature according to EN 10002 standard, with a test rate of 2 mm/min, clamping distance 47 mm. The optical strain gauge was a Mercury Monet DIC and the gauge length under test was 26 mm.

Three types of tensile test samples were examined (3 pieces in each condition), shown in Figure 3. There were samples in as manufactured condition, samples that were heat treated in air and samples that were heat treated in Argon (inert gas) atmosphere.

The heat treatment profile was the same in both atmospheres. The peak temperature of the heat treatment was 650 °C, the heating rate was 230 °C/h

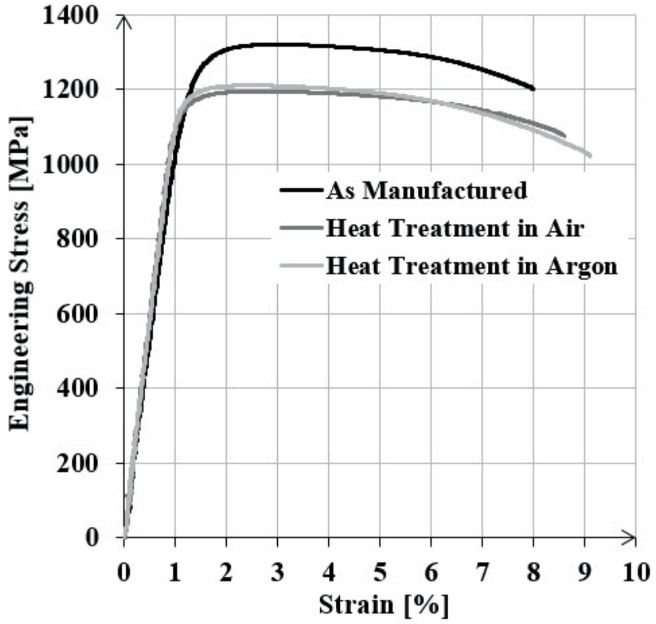

Figure 4 *Engineering stress-strain curves of as manufactured and heat-treated Ti-6Al-4V*

Table 1 *Average of measured mechanical properties of as manufactured and heat-treated Ti-6Al-4V*

Condition	R_m [MPa]	$R_{p0.2}$ [MPa]	A [%]	E [MPa]
As Manufactured	1318 ± 6	1178 ± 40	7.5 ± 0.5	114 ± 8
Heat Treatment in Air	1190 ± 7	1136 ± 10	7.6 ± 0.7	116 ± 3
Heat Treatment in Argon	1202 ± 10	1151 ± 12	8.4 ± 0.2	119 ± 4

and the soaking time was 3 h. The samples were let to cool down freely in air or in continuous Argon ventilation. According to the literature, the used heat treatment results in stress relieving, the strength and elongation remain unchanged, while the internal stresses are relieved [5-6, 8-9].

After the heat treatment, the samples were micro-glass blasted. With this procedure, any powder particles attached to the samples during the manufacturing and oxidised surfaces formed during the heat treatment process, have been removed from the surface of the samples. Figure 3 shows the samples as manufactured, after the heat treatment and after the micro-glass blast. The colour of the heat-treated samples in the air atmosphere became darker grey than of the as manufactured samples. After micro-glass blast this colour change remained.

According to the manufacturers data in the case of a part made of EOS Ti64 powder in vertical direction as manufactured state has the tensile strength (R_m) 1240 ± 50 MPa, the yield strength ($R_{p0.2}$) 1120 ± 80 MPa, elongation at break (A) 10 ± 3%, modulus of elasticity (E) 110 ± 15 GPa, Vickers Hardness 320 ± 12 HV5 [9].

To get information about the hardness differences due to different heat treatment cooling rates, samples were cooled down to room temperature after the heat treatment in the furnace or removed from the furnace and cooled in the open air.

3 Results and discussion

Figure 4 shows the engineering stress-strain curve for each examined condition of Ti-6Al-4V tensile test samples and Table 1 shows the results data of the tensile tests. The tensile strengths show that without the heat treatment the Ti-6Al-4V has bigger tensile strength and that applied stress relieving heat treatment causes 9.2% reduction. Smaller reduction can be seen in the yield strength. The elongation at break shows a minimal increase as a result of the heat treatment but it is to the margin of deviations. The examination shows that the heat treatment atmosphere has no effect on the mechanical properties of the tensile test samples. In this measurement, the orientation of samples had no effect on the results. All the samples were manufactured in the same conditions.

All of the measured samples were glass blasted so the adhesive powder particles which stuck to the surface and partially melted by laser due to insufficient laser energy had no effect on the measured properties. Those bonded powder particles could form sharp corner transition regions, which act as stress concentrators, which could lead to decreased ductility.

Figure 5 shows the Vickers hardness values of different types of Ti-6Al-4V samples. The Vickers hardness, according to the material datasheet is 320 ± 12 HV5 [9]. On the as manufactured type,

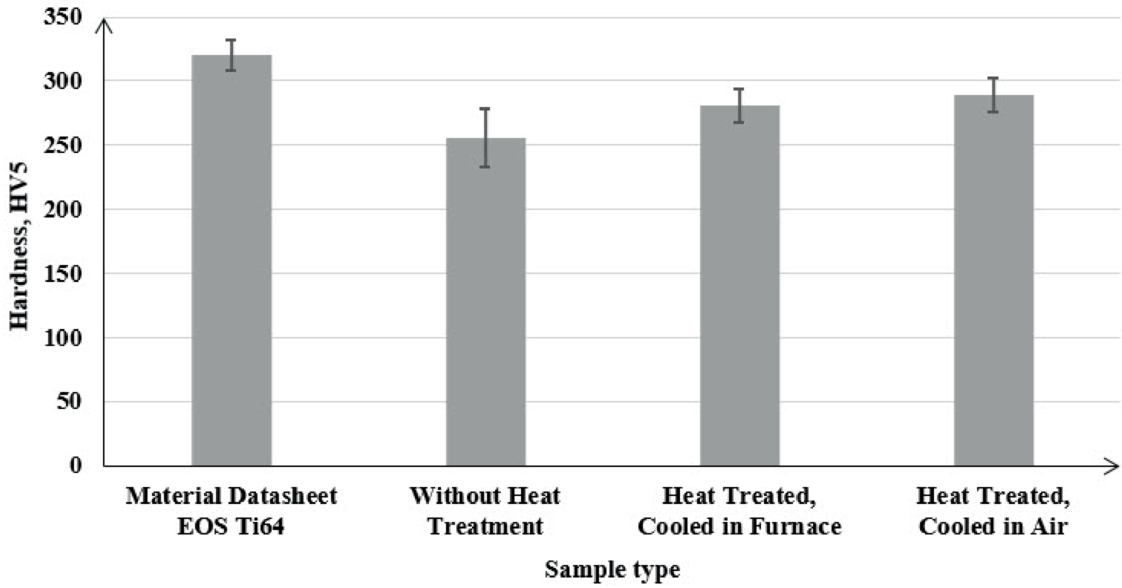

Figure 5 *Vickers Hardness (HV5) of Ti-6Al-4V AM samples with and without the heat treatment*

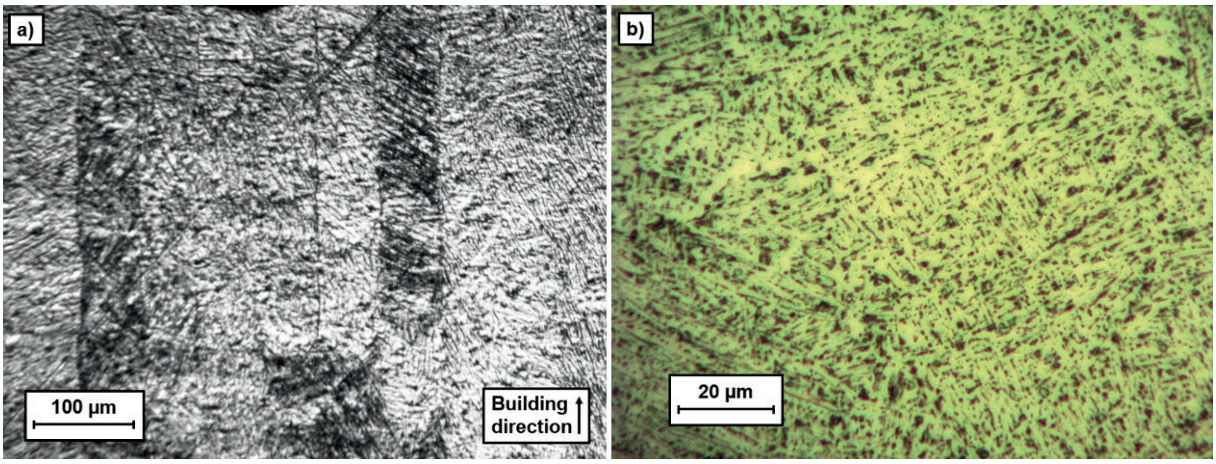

Figure 6 *Microstructure of as-built Ti-6Al-4V AM sample*

without the heat treatment, samples from the same Ti64 powder manufactured with EOS M100 machine had the average hardness value of 255 ± 22 HV5. After the heat treatment the samples cooled in the furnace or removed from the furnace and cooled in the open air. The measured average hardness value is 281 ± 13 HV5 in the case of cooling in the furnace and 289 ± 13 HV5 in case of cooling in open air. The hardness in the datasheet is 20% higher than the manufactured samples without the heat treatment. This difference also occurs for parts manufactured in different regions of the production area. The effect of the heat treatment can be noticeable. The measured hardness after the heat treatment is 10-13% higher than the as manufactured state. The difference between the different cooling rates shows a little bit higher hardness in the case of the faster cooling rates, but this average hardness difference can be compared to the standard deviation of the measurement.

During the DMLS process, the created melt pool is tiny and the cooling rate is thought to be within the range of 10^3-10^5 °C/s and faster than the crucial cooling rate of 410 °C/s that is necessary for martensitic transformation (β to α') in Ti-6Al-4V. The additively manufactured Ti-6Al-4V typically consists of acicular α' martensite rather than equilibrium α and β phases [10]. In Figure 6(a) columnar grains, the common microstructure characteristic of additively manufactured samples, can be seen. The building direction is parallel to the grain growth direction due to the thermal history of the layer-by-layer fabrication. The as-built phase composition, α' martensite needles, are shown in Figure 6(b). During the heat treatment, when the temperature is higher than the martensite dissolution temperature (T_{Mdiss} 400 °C), the α' martensite needles can dissolute partially or completely [11], which depends on the temperature. During the stress relief heat treatment, the decomposition of the α' martensite possibly creates fine (α + β) lamellar structure. The reduction of strength values and higher elongations hint to these structural modifications, which are more likely partial because of the applied temperature. The literature is not uniform on the issue of whether the decomposition of martensite takes place completely in this temperature range [10-12].

4 Conclusions

Based on the results, it can be stated that for the Ti-6Al-4V samples, the applied heat treatment reduced the tensile strength by 9.2% compared to without the heat treatment condition and the atmosphere applied during the heat treatment had no detectable effect on the mechanical properties of samples. After the heat treatments, the samples' surface discoloured when the heat treatment was in air atmosphere and after the micro-glass blast, this colour change remained. The geometry of the tensile test samples did not change by more than 0.01 mm after the micro-glass blast. The results found are based on a static examination. Further dynamic tests on samples can be used to investigate the effect of heat treatment atmosphere on fatigue properties.

Examination of the hardness of the heat-treated samples shows that no significant change in the examined cases can be measured. The differences are comparable to the standard deviation of the measurement results. After the heat treatment, it seems that in this case, the cooling rate had no to effect on formation of the structure, which would affect the hardness.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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