The heat treatment influence on microstructure and mechanical properties of TiAl6V4 parts manufactured by SLM

C Lancea*, S M Zaharia1, M A Pop2 and G R Buican1

1 Department of Manufacturing Engineering, Transilvania University of Brasov, Eroilor nr. 29, Brasov 500036, Romania
2 Department of Materials Science, Transilvania University of Brasov, Eroilor nr. 29, Brasov 500036, Romania

*E-mail: camil@unitbv.ro

Abstract. Nowadays titanium alloys are widely used for building various parts for the aeronautical or aerospace industries, in the energy field, petroleum industry, in medicine and recently in the automotive industry, the sporting goods industry, etc. In this paper is analysed the influence of the heat treatment on the microstructure and compressive strength of the TiAl6V4 alloy samples, having a Lattice structure. The analyses results indicate differences between the as-built samples and the heat-treated samples. In this regard, heat-treated samples have a much uniform and stable structure, a microstructure with fewer pores and better mechanical resistance to compression stress. These results confirm that the heat treatment favourably influences the microstructure of the samples, reduces the internal stress and their mechanical characteristics too.

1. Introduction
Additive manufacturing allows the fabrication of metal parts with complex shapes and high density that cannot be obtained through traditional manufacturing methods [1]. These structures allow obtaining of both strong and lightweight parts [2] that are highly demanded mostly in astro- and aeronautical industries (production of satellite parts, cabin accessories, jet engine components for Boeing and Airbus etc.) [3].

Lately, the interest for these kinds of parts increases in many other industries such as: automotive [4]–starting with high-performance Formula 1 racing cars and continued with the production vehicles [5] (Daimler AG, Ferrari, Mitsubishi Motors Inc. etc.); medicine (implantology, dentistry, surgery etc.) [6]; marine engineering (parts with a complex shape such as: engine blades, turbine impellers etc.) [7]; nuclear-power engineering (SLM parts for nuclear fusion reactors) [8]; chemical engineering etc.

In this regard, the lattice structures [9], which are three-dimensional closed or open celled structures, generated as a periodic arrangement of one or more unit cells, offer the best way to obtain lightweight structures with very good mechanical properties. The best material that meets these requirements has proven to be titanium, or to be more precise, titanium alloys [10]. That’s why nowadays, the most used material in SLM industry (also for building these kinds of structures) is TiAl6V4. This alloy is as much used (more than 50% of the market) because of its excellent properties in obtaining light, complex shapes having very good mechanical properties [11]. Besides this, another
The advantage of the TiAl6V4 alloys refers to a very good corrosion resistance and a highly biocompatibility [12].

The manufacturing of TiAl6V4 complex parts, through selective laser melting (SLM), decreases significantly the production costs by shortening the machining processes, no need of tools or devices and a very good material utilization [13]. Besides these advantages, the SLM process gives rise to some unwanted problems too. During the SLM manufacturing process the part is subjected to a high thermal stresses because of the high energy release in a very short time, followed by a rapid solidification and fast cooling [14]. These conditions can lead to some problems as segregation phenomena, a higher surface roughness, big internal porosity or the appearance of non-equilibrium phases [15].

Given this situation, after the SLM manufacturing a heat treatment is very necessary to relieve the cumulated stress, to stabilize the microstructure and finally to improve the mechanical properties of the part [16].

2. Material preparation and methods

A titanium Grade 23 powder (also known as TiAl6V4 ELI) was chosen to produce, through the SLM process, six specimens. All specimens have identical shapes, and were built as a Lattice structure. This structure was obtained as a three-dimensional pattern generated along three rectangular directions (figure 1-b) of a 3D cell (figure 1-a).

For determining heat treatment influence on microstructure and mechanical properties of the samples, three of them were not subjected to any heat treatment (figure 1-b), and the other three were subjected to a homogenization heat treatment (figure 1-c).

2.1. Samples material
TiAl6V4 ELI is the high purity version of TiAl6V4 (Grade 5), the world most used titanium-based alloy. The chemical composition of this titanium-based alloy, expressed as a percentage, is given in table 1:

| Element | Ti | Al | V | C | O | N | Fe | H | other |
|---------|----|----|---|---|---|---|----|---|--------|
| Balance | 5.5–6.5% | 3.5–4.5% | 0.08% | 0.13% | 0.03% | 0.25% | 0.0125% | 0.5% |

2.2. Geometry of the samples

The cell is composed of three rectangular isosceles triangles (figure 1-a), placed in three rectangular planes, having base and high of 25mm. The cylinder has a 5mm diameter. The cell was three times patterned along rectangular directions so that the sample dimensions become 75mm x 75mm x 75mm (figure 1-b).

After manufacturing the dimensions of the physical samples were compared with the dimensions of their CAD model and the results showed a difference of about 0.03 mm along all the three rectangular axes.
2.3. Fabrication of samples
Samples were produced at SLM Solutions Group AG headquarters, in Lübeck, Germany on a SLM125 3D printer machine with a single (1x 400 W) IPG fibre laser. The scanning speed was set to 2 m/s, with a total laser power of 250 W, 140 μm hatch spacing and a 40 μm layer thickness. In order to obtain fully dense and good quality samples [15], the layers were scanned using a zigzag pattern, which was rotated with 90° after exposing each layer. The laser spot size was 80 μm and the building process was performed in an inert atmosphere (argon). The building platform was preheated and maintained at 35°C during the entire building process.

2.4. Microstructure and surface feature analysis
For analyzing microstructure, two sets of samples: heat-treated and as-built were cut with a diamond cutting disk, followed by grinding. The samples were cold-mounted in Dentacril resin and polished with 60, 30 and 15 μm grit magnetic discs on a Buehler Phoenix Beta Grinder (figure 2-a).

![Buehler Phoenix Beta Grinder (a) and the Nikon Eclipse MA 100 optical microscope (b).](image)

After polishing on felt and 0.05μm alumina paste a mixture of 30 ml HCl + 10 ml HNO3 was used for etching the specimens.

The microstructural analysis was conducted using a Nikon Eclipse MA 100 optical microscope (figure 2-b).

2.5. Influence of temperature and tensile properties
To homogenize structure and to increase the mechanical properties [17], three of the specimens were heat-treated after the following schedule: homogenization treatment at 850°C, for 2 hours, followed by furnace cooling in a Nabertherm N 41/H/P300 furnace.

![Microstructure of the as-built samples (magnification 200X).](image)

![Microstructure of the heat treated samples (magnification 200X).](image)

A metallographic analysis was performed to study the microstructural changes that appears after the heating treatment. The as-built samples (figure 3) has a fine acicular martensitic structure (α' phase); as a result of the high cooling rate, given by the SLM process [18]. The small spherical pores
(figure 3) indicate a good scanning speed within the SLM process. The heat treated samples have an improved structure, much uniform where the α' martensite was transformed into more stable α+β phases with white regions (given by the α phase) and dark areas (given by the β phase) (figure 4).

The compression properties were analysed on as-built and stress relieved samples. For determining the compression resistance the fixture bearing blocks and the ends of the samples were cleaned with acetone and subjected to a quasi-static uniaxial compression.

The tests were made on a WDW-150S universal testing machine with a crosshead displacement speed of 2 mm/min, according to ASTM standards [19]. The obtained strain-stress curve is shown in figure 5.

A comparative study regarding the compression properties of the samples were made also using the ANSYS Workbench 19 R3 finite element analysis software, (figure 6). For meshing the model were used TET10 type elements of 5 mm. The mesh was composed of 1244206 nodes and 616852 elements.

By comparing the results it is shown that FEA results are very similar to the experimental results (figure 5 and figure 6).

![Figure 5](image5.png)  
**Figure 5.** Compression testing results for: as-built samples (a) and heat treated samples (b).

![Figure 6](image6.png)  
**Figure 6.** Compression testing results after FEA.

3. Conclusions
After analyzing the differences between the as-built samples and the heat treated samples the following conclusions can be drawn:

- The heat treatment lead to a structure where the α’ martensite was transformed into more stable α+β phases;
- Microstructure of the heat treated samples is much uniform;
- The heat treated samples have less pores;
- Compression resistance of the heat-treated samples was improved.

In this regard was concluded that heat treatment improves the microstructure of the samples by reducing the internal stress that occurs during the building process. By decreasing the internal stress a better mechanical stress resistance was obtained too.

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