Fatigue properties of SLM-produced Ti6Al4V with various post-processing processes

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Abstract. Titanium and its alloys are very popular for various applications. They are the most widely used materials for biomedical applications. Titanium-based materials have shown excellent biocompatibility, as well as mechanical properties and corrosion resistance. The high fatigue life of this material is often demanded, therefore fatigue testing is necessary. Additive manufacturing (AM) is an innovative, widely investigated method for the production of metal components. AM allows the possibility of producing complex shaped components with near to net shape. Selective laser melting (SLM) is one of the most promising AM techniques. This research explores the fatigue behaviour of titanium alloy Ti6Al4V, produced by SLM. Different conditions and surface preparations for additive manufactured specimens were investigated by fatigue testing and then compared to each other. The aim of this research is to explore the influence of surface machining and processing by hot isostatic pressing (HIP) on the fatigue properties of the SLM produced components.

1 Introduction
The titanium alloy Ti6Al4V is the most frequently used Ti-based alloy; it is applied in more than half of all titanium alloys in the word [1]. It is a well-known fact that titanium and its alloys show good properties, such as low density, high specific strength, high fracture toughness, corrosion resistance and stability, and biocompatibility used for biomedical applications [1–3]. Despite its many advantages, there are also some disadvantages, such as high price of this metal and the difficulty of titanium processing. Titanium is highly reactive with oxygen, hydrogen and nitrogen at high temperatures [1,4]. Therefore, Ti has been used in applications that need proper material, despite the material cost [3].

Selective laser melting (SLM) is a type of an additive manufacturing process based on powder bed fusion. The concept of this method is based on depositing layer by layer until the whole component is built. This method allows producing from porous parts to parts with close to full density. Laser energy source melts the powder and subsequently fuses the required areas [5]. A deposition by SLM is carried out in an inert atmosphere. Post-processing including heat treatment and infiltration of printed components is also important [4].

Fatigue properties are very important values from the application point of view. The surface roughness and the presence of defects have the biggest influence on the fatigue properties of the material. The porosity and surface roughness provide stress concentration in their surroundings and can cause crack initiation. The sample roughness can be improved by surface treatment [3,6–8]. In
addition, many researchers explore minimization of the sample defects by the hot isostatic pressing (HIP) technique [9]. During the HIP treatment, products are heated at high temperatures and under high pressure. This creates plastic flow and prepares almost a fully dense structure. Generally, the lamellar or globular structure of grains α+β is desired, therefore temperature above the β-transformation is selected for the HIP processing of Ti6Al4V [10–12].

The purpose of this research was to investigate the differences in the fatigue life among machined, as deposited samples and the HIPed samples.

2 Material and Method

High cycle fatigue (HCF) properties of Ti6Al4V specimens at room temperature are investigated here.

2.1 Materials

The sample building was performed using an M2 Concept Laser machine under an argon atmosphere. The deposition was performed using the laser power of 200 W and the scanning velocity size of 1250 mm/s. The thickness of deposited layer was set to 30 µm and offset distance of 80 µm was used. The samples were produced by island scanning strategy in ZXY orientation [13]. The Ti6Al4V powder ELI grade 23 was used for deposition. A part of the specimens was subjected to recommended heat treatment to minimize residual stresses. The slow heating to 1093 K lasted 4 hours and was followed by hold at the temperature for another 1.5 hours; samples were then cooled slowly to 773 K and finally cooled to room temperature. The annealing was performed in vacuum furnace to avoid oxidation. The second part of the specimens was treated with HIP. Specimens were held for two hours under an argon atmosphere at the pressure of 1020 bar and the temperature of 1193 K. Annealed specimens and one half of HIPed specimens were machined by turning and polishing to the final surface roughness Ra = 0.2, with the direction corresponding to the building direction. The rest of the specimens was kept with the as-deposited surface.

The fatigue life of three different sample conditions was investigated, see Table 1. Each batch consisted of at least 12 samples.

| Sample condition                                      | Designation |
|------------------------------------------------------|-------------|
| As deposited specimens with HIP treatment            | AH          |
| Machined specimens with HIP treatment                | MH          |
| Machined specimens, no HIP treatment                 | M           |

2.2 Testing and evaluation of fatigue properties

The specimens were tested under high fatigue cyclic (HCF) conditions until failure or the endurance limit of 10 million cycles was reached. The aim of this testing was to obtain the Wöhler (S-N) curve for each processing condition at room temperature. The specimen geometry is depicted in Figure 1.

![Figure 1. Drawing of specimen geometry](image-url)
The fatigue tests were performed in accordance with ASTM E466-7 standard under force controlled constant amplitude at room temperature in the air. The HCF tests were carried out with asymmetry ratio $R = -1$ at a frequency of 50 Hz. The fatigue limit $\sigma_c$ was evaluated as the stress level under which the specimens survived $10^7$ cycles. The testing setup is shown in Figure 2.

2.3 Microstructure analysis
The microstructure characterization was carried out on the microscope OLYMPUS PME3. The specimens for microstructural characterization were grinded on the silicon carbide paper and subsequently polished on the diamond paste. Final chemical-mechanical treatment was performed in colloid silica polishing suspension containing 20 vol. % of $\text{H}_2\text{O}_2$. Porosity was determined from micrographs using the image analysis by ImageJ.

3 Results and Discussion
Three S-N curves were constructed for different surfaces and process conditions of the titanium alloy at room temperature, as shown in Figure 5, Figure 4 and Figure 5. Orange symbols represent the specimens that withstood $10^7$ cycles, blue dots represent failed samples. In the graphs fitted curve that represents the reliability of the results is plotted. Very high scattering of the results was obtained because of the random presence of defects. More considerable dispersion of the results was revealed for as deposited samples. In this case surface defects influenced the fatigue behavior and decreased the value of fatigue limits.

![Figure 2](image1.png)

**Figure 2.** The test setup of HCF

![Figure 3](image2.png)

**Figure 3** S-N curve of as deposited HIPed specimens
Table 2. Fatigue endurance limits

| Sample       | Fatigue endurance limit $\sigma_c$ (MPa) |
|--------------|----------------------------------------|
| HIP          |                                        |
| As deposited | AH                                     | 230 |
| Machined     | MH                                     | 350 |
| without HIP  | M                                      | 220 |

Table 2 represents fatigue endurance limits of all the tested batches. No significant change in values of fatigue limit has been obtained between the M and AH samples. However, a significant difference was observed for the HIPed and machined samples. The fatigue limit of these samples reached an increase by nearly 40 % in comparison with the others. All of these points to the fact that the large inner defects strongly affect the fatigue properties of the AM titanium alloy. At the
same time, the surface treatment of the material has major impact on the results. The shape of the curves in the graph in Figure 6 demonstrates the above-described facts. Eliminating high surface roughness and inner defects plays a key role in the fatigue of the titanium alloy processed by SLM. Only removal of the surface roughness by machining is insufficient as internal defects become exposed to the surface. Conversely, eliminating porosity does not pronounce significantly if as built surface is kept.

![Graph showing S-N curves](image)

**Figure 6.** Comparison of all S-N curves for all investigated samples

The microstructure of the tested samples is depicted in Figure 7. In other studies, it has been shown that the sample fracture is caused by a lack of fusion or present porosity in AM products when compared to the HIP processed samples [14]. A distinctive porosity of samples without HIP treatment was found in comparison to HIPed samples. Image analysis revealed that HIP decreased the porosity significantly, from 0.67 ± 0.30 % to 0.01 ± 0.01 %. In Figure 7 can be noticed finer lamella thickness of specimens without HIP.

![Microstructure images](image)

**Figure 7** Microstructure of: a) HIP treated sample, b) sample without HIP treatment

4 Conclusions
Fatigue properties were investigated for three surface and processing conditions of the titanium alloy at room temperature. High scattering in the results is caused by defects of various amount, size, dimension or place in the specimens. No significant differences in fatigue life limit were observed between as deposited HIPed samples and machined samples without HIP post-processing. Additional HIP processing significantly increased the fatigue endurance limits of material. There, it can be stated that post-processing by HIP leads to effective increment of the endurance limit. The results revealed
that it is need to eliminate inner pores and high surface roughness in case of as deposited samples. The defects and surface roughness are initiators of fracture during cyclic loading.

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