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THE MICROSTRUCTURAL EVOLUTION OF TI-6AL-4V SPECIMENS FABRICATED BY SELECTIVE LASER SINTERING OF PRE-ALLOYED POWDERS

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Abstract. Selective laser sintering (SLS) is known as a cutting-edge technique to manufacture complex geometry products. Among various kinds of materials, Ti-6Al-4V is one of the most popular materials for the SLS process. The as-built Ti-6Al-4V products were widely applied in many applications such as aerospace, automobile, and especially in medical and implant parts. The purpose of this research is to investigate the microstructure and other properties of Ti6Al4V samples produced by selective laser sintering technique. Through this research, the direct fabrication of Ti6Al4V metal object by SLS machine has been carried out using MetalSys250 machine. Different parameters of the SLS process were used to produce 1cm x1cmx1cm cubic samples and then microstructure as well as mechanical properties of the as-built samples were investigated. Powder particles are fully dense, possess a spherical shape and are composed of acicular α phase. The as-built sample shows the oriented acicular martensitic phase with the defined columnar grain structures.

Keywords: Ti-6Al-4V, 3D-printing, Selective laser sintering, Laser patterns, microstructure.

Classification numbers: 2.9.1, 2.10.1, 2.10.2.

1. INTRODUCTION

Selective laser sintering (SLS) is a type of additive manufacturing (AM) technique which has been widely used to produce 3D objects from metal, polymer, and ceramic powders recently [1]. It was also known as a promising manufacturing process compared to conventional methods due to their remarkable features in term of fabricating very complicated parts even with high melting point materials, reduce the production time, and provide good mechanical properties to products. Therefore, the SLS has been applied in many applications such as aerospace, medical and implant manufacturing, and many other industrial fields [2]. The SLS has become possible to reliably manufacture dense parts for a number of materials, including steel, copper, aluminum, and titanium. Among these materials, Ti-6Al-4V powder has been widely used for high-performance engineering solutions in aerospace motor cases, aircraft turbines, pressure vessels, and marine components. Recently, many studies have invested in using SLSed Ti-6Al-4V products for biomedical applications such as implant parts in surgery [3]. In the SLS process, the microstructure as well as the quality of products is affected by a large number of different process parameters [4, 5] such as laser powers, laser scanning speeds, laser scanning strategies (pattern), laser hatches distance and layer thickness [6, 7]. Thus, one of the most interesting advantages offered by the SLS technique is that it allows tailoring of the as-built microstructure by accommodating the process parameters in a strategic presentation. For example, the quantity of the energy deposited to the metallic powders, (the energy density) plays an important role in the formation of the microstructure of the as-built components. In the case of Ti-6Al-4V, it is concerned with the question of whether the as-built Ti-6Al-4V products could have mechanical properties comparable to the conventional products. One of the ways to clarify this matter is the investigation of the origin and the evolution of the microstructure of the sample produced by the applied process. In fact, the AM process in general and SLS technique, in particular, is a complicated process related to complex physical and metallurgical phenomenon during processing with a wide range of non-equilibrium phenomena taking place depending on a large number of parameters such as laser power, scanning speed, hatch spacing, and layer thickness [1, 2, 8, 9]. It was found that the microstructure of AM parts is a result of the complex thermal cycle, and a rapid solidification [9, 10]. Therefore, all the materials processed by AM process exhibit a very fine-grained, non-equilibrium structure in comparison to the products from conventional processes like casting or wrought. In addition, the different AM methods also yield different microstructures due to their specific mode of operation. This makes the modeling, controlling of microstructures and composition in AM products rather difficult and challenging. Hence, the investigation on the microstructure, mechanical and physical properties of the as-built objects as well as the effects of parameters process on the characteristics of the final products become very important.

Herein, we report a study on the fabricate Ti-6Al-4V samples using the SLS process with the aim of understanding the evolution of the microstructure of Ti-6Al-4V parts produced by SLS.

2. MATERIALS AND METHODS

2.1. Materials and experimental process

Gas-atomized Ti-6Al-4V powders (Grade.5, VTECH-china) with spherical shape and particle size of under 45 μm were used as the feeding material in the SLS process. All the samples investigated in this work was built in the cubic shapes with dimensions of 10×10×10 mm using an SLS machine (MetalSys250) with the parameter conditions as shown in Table 1. A zig-zag pattern of scanning strategies with the rotation angle of about 67 degrees of the next layer to the previous layer during the SLS process was used (Fig. 1). The parts were built in a controlled nitrogen atmosphere to avoid any possible oxygen contamination. The substrate was kept at a temperature of about 200 ^{o}C in order to reduce the residual stresses that might increase during the SLS operation.

2.2. Analytical methods

The phases and morphology characteristics of the as-built samples then were evaluated using analysis methods like the optical microscope (OM), field emission-scanning electron microscope (FE-SEM, JSM-6500, JEOL Ltd.) and X-ray diffraction method (X-ray diffraction, Ultima IV, Rigaku Corp.). Before microstructural observation, the specimens were ground using a SiC grinding paper with the fine grit size up to 1500, polishing and etching with a suitable solution. Mechanical properties of the samples were also observed by using a Vickers-Hardness tester. For each sample, an average of 5 measurements is given out.

Table 1. Parameter conditions of SLS process used in this work.

Laser power (W)	**Scan speed (mm/s)**	**Laser beam diameter (µm)**	**Nitrogen**	**Hatch Distance (µm)**	**Layer thickness (µm)**
100 ÷120	600 ÷ 1000	90	99.9 %	70	80

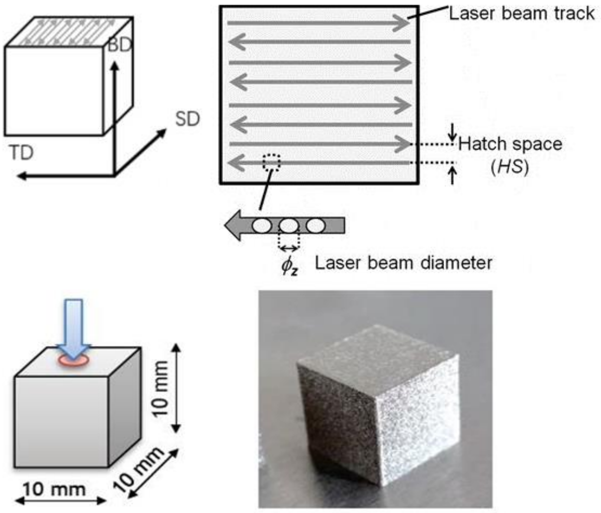

Figure 1. The schematic of laser pattern in SLS process.

3. RESULTS AND DISCUSSION

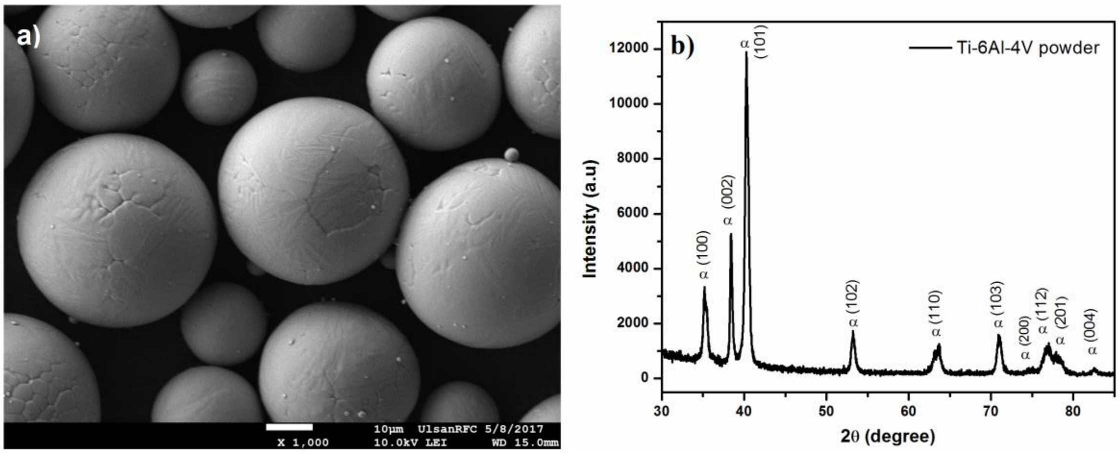

Figure 2. The initial Ti-6Al-4V powders (a) and its XRD pattern (b).

The Ti-6Al-4V powder used in this work was produced by the atomization process, has a spherical shape, smooth, and fully dense as shown in Fig. 2 (a). The particle size of the powder was within 15 and 45 µm. The SEM micrograph also reveals characteristic micro-dendritic features on the surface of the powder particles. The XRD pattern of the powder exhibits only primary α phase peaks which are the characteristic of hexagonal close-packed (hcp) structure of Ti without obvious peaks of β phase [11] (Fig. 2(b)).

After printing, as-built samples were separated out of the substrate part for each one and their properties were investigated. In this work, the attention was focused on the evolution of the microstructure of the as-built specimens during the SLS process. Nine samples were built with different conditions and the optical microscope images of them are presented in Fig. 3.

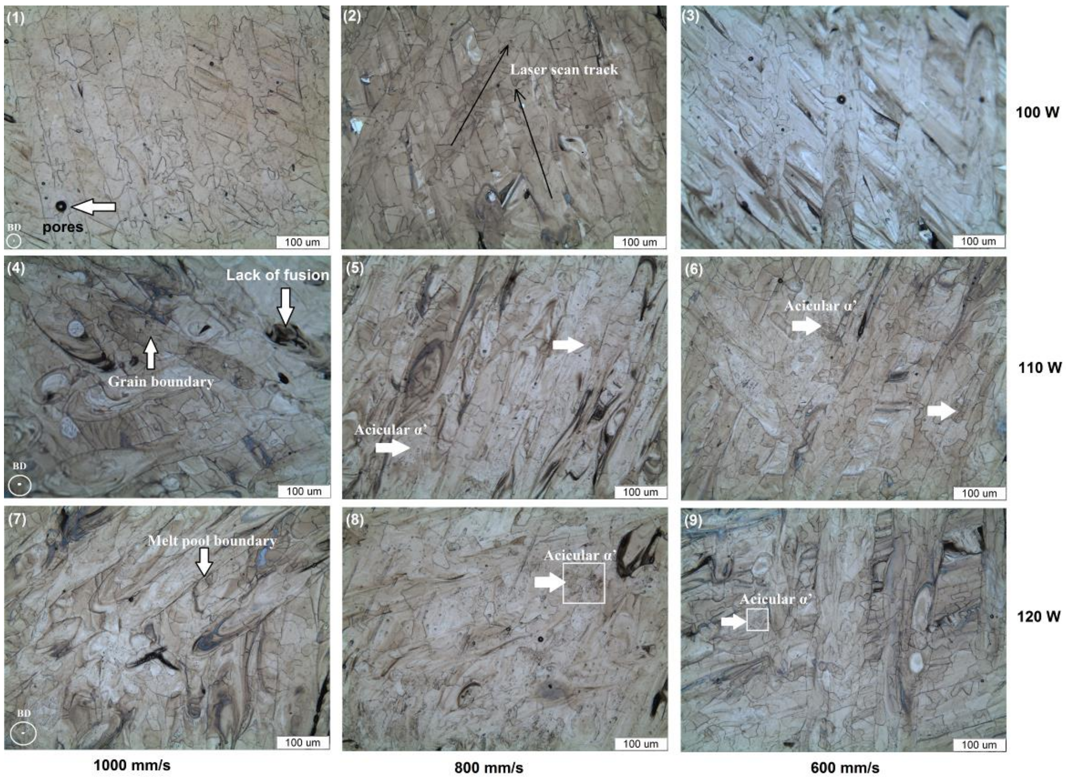

Figure 3. OM images of Ti-6Al-4V samples built with different parameter conditions.

Generally, the typical microstructure of the Ti-6Al-4V as-built samples on the top-view surfaces are shown in Fig.3. It could be recognized that the microstructures of the as-built specimens show a similar microstructure to each other, they reflect the pattern parameter conditions and expose the typical characteristics of SLS samples including the lack of fusion, pores and melt pools on the surfaces [4, 7]. Thus, the top-view images exhibited the track of melt pools and its borders which stood for the scanning strategy in the SLS process (Fig.3). It is observed more clearly in the Fig. 4 (a, b) and Fig. 4 (c, d) which represent for sample number 8 and number 6 (Fig. 2) printed at 120/800 and 110/600 of power/speed conditions, respectively. The width of the melt pool tracks is about 70 µm, corresponding to the hatch spacing of 70 µm used to produce the object. The grains were observed inside the melt pool area with the various oriented direction however they become smaller when the samples were processed at high power and low scanning speed parameters. In addition, the samples also exposed the region consisted of the fine acicular martensitic α' as shown in Fig. 3 and more clearly in Fig. 4. It is noted that this type of microstructure is significantly different compared with the microstructure of conventional products such as wrought and cast Ti-6Al-4V [12, 13]. Indeed, in the conventional products like as-cast Ti-6Al-4V, the microstructure consisted of transformed β containing acicular α as well as α at prior-β grain boundaries. In the case of the wrought products, the microstructure consisted of a fully equiaxed microstructure with inter-granular β phase [14] whereas the as-built samples consisted of fine acicular martensitic α' as presented in Fig. 4(b), Fig. 4(d). Furthermore, as examined in the SEM, a high-resolution SEM image reveals that the top surfaces microstructure consists of martensites α' in which the acicular laths cross on another and the grain boundary was hard to distinguish (Fig. 5).

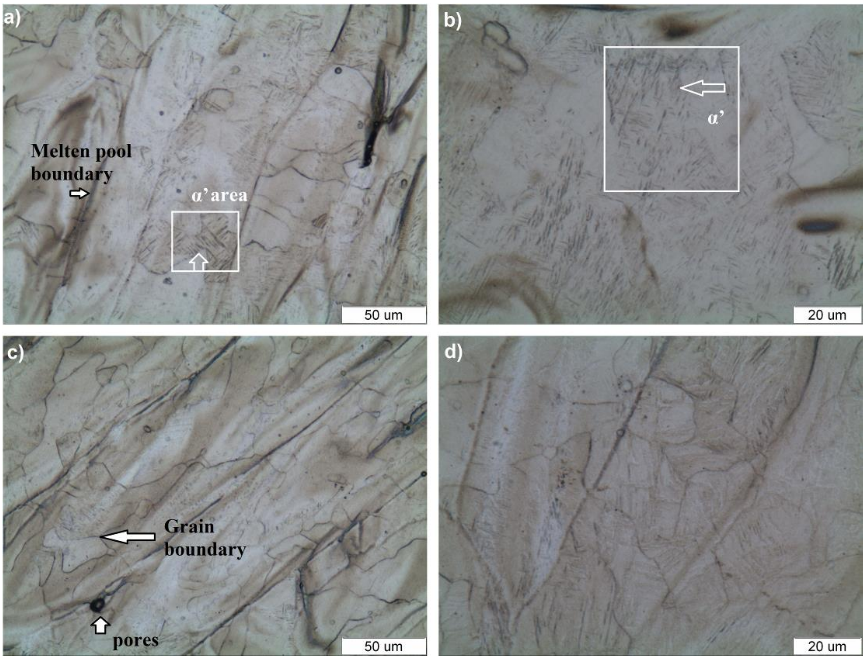

Figure 4. Optical microscope images of the top-view surfaces of the samples processed at 120/800 (a, b) and 110/600 (c, d) of power/speed condition at high magnification.

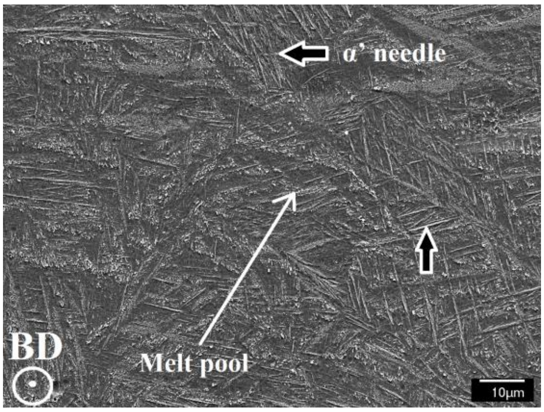

Figure 5. SEM image shows the acicular martensitic microstructure (α') on the top side surface of the SLS Ti-6Al-4V specimen printed at 120/800 of power/speed condition.

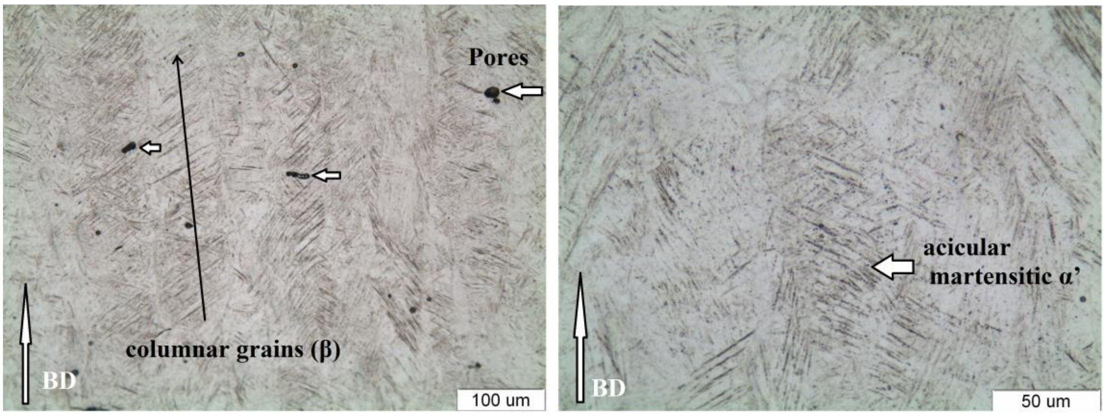

Figure 6. OM images on the side-view surface of the as-built sample printed at 120/800 of power/speed condition.

Figure 6 shows the microstructure on the side-view surfaces of SLS Ti-6Al-4V specimen processed at 120/800 of power/speed condition as examined in the OM which is represented for all the samples. It could be revealed that the microstructure consists of columnar grains containing the colonies of martensitic α' needles. These columnar grains which are identified as prior β grains elongated almost perpendicular to the layer deposition direction, extending over multiple layer cross-sections and slight inclinations due to the alternating scan pattern during the SLS process (Fig. 6). The average width of the β grains is about 50-60 µm, which is smaller than the hatch distance. By using SEM observation, it could be seen that the acicular martensitic α' inside the elongated-prior-β grains are arranged at ± 45^0 to the building direction (Fig.7). These microstructure features of the AM Ti-6Al-4V products are the result of the extremely rapid heating and cooling rates during the solidification in the AM process, which can reach 10^4-10^5 Ks^{-1} and the martensitic needle is transformed from the β phase and the martensite starts to nucleate at the temperature 850 ^oC [15-19].

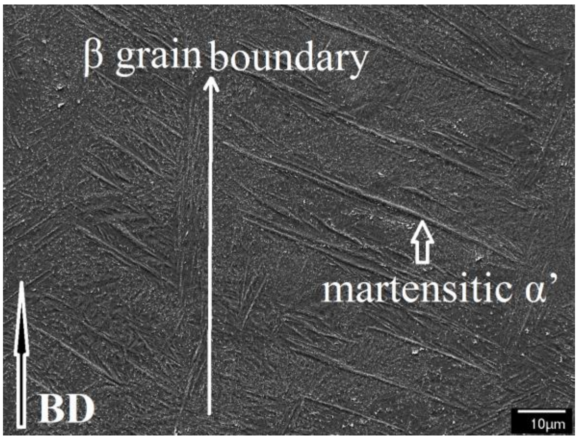

Figure 7. SEM image showing the elongated–prio-β-grains and α' laths.

The measured Vickers microhardness values of the specimens are listed in Table 2. The as-built samples show a great variation in Vickers microhardness (~350 ÷ 390 Hv). However, most of them are higher than that of conventional products (~340 ÷ 350 Hv) [12, 20, 21]. It seems that the high speed of laser scanning resulted in low hardness value that the samples got. The enhancement on the hardness of the as-built parts in comparison to the conventional products is attributed to the formation of the fine microstructure and the acicular martensitic α’ phase under the rapid cooling condition. However, the hardness value fluctuates without certain rule, therefore, it needs to study more about this matter to achieve a full understanding of the effect of SLS parameter on the hardness of the as-built samples.

Table 2. Microhardness of the as-built samples printed at different parameters.

Micro Hardness (Hv)			
Power/Speed	**1000(mm/s)**	**800(mm/s)**	**600(mm/s)**
100 (W)	343.667	371.467	369.733
110 (W)	358.467	374.867	378.250
120 (W)	354.9	393.833	378.0

4. CONCLUSIONS

According to the results which have been figured out about, there are some following conclusions for our study:

Ti-6Al-4V alloy components were fabricated successfully by using the SLS process, showing a high potential application of this method in manufacturing of the net-shape and complex geometry parts.

Because of the line- and layer-by-layer building, the microstructure of a sample produced by SLS was differed in the two views. The top-view surface of the specimen showed the presence of the grains with the acicular martensitic α’ phase while the side-view exhibited the columnar structure with acicular mixture phases inside. This is attributed to the extremely rapid heating and cooling rates during the solidification in the SLS process.

Due to the difference in microstructure (the presence of the acicular martensite α’ phase), mechanical properties (hardness) was found to be higher in the SLS samples as compared to the conventional parts.

The as-built samples showed solidification tracks, melt pools on the macro-scale which is related to scanning strategy of SLS process. Therefore, it could be used as useful data for optimization of AM manufacturing process by selecting and adjusting the parameter conditions

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