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Microstructure and tensile properties of Ti-6Al-4V alloys manufactured by selective laser melting with optimized processing parameters

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Abstract. Selective laser melting (SLM) is a precise additive manufacturing process that the metallic powders without binder are melted layer by layer to complex components using a high bright fiber laser. In the paper, Ti-6Al-4V alloy was fabricated by SLM and its microstructure and mechanical properties were investigated in order to evaluate the SLM process. The results show that the microstructure exists anisotropy between the horizontal and vertical section due to the occurrence of epitaxial growth, and the former microstructure seems equal-axis and the latter is column. Moreover, there is little difference in tensile test between the horizontal and vertical sections. Furthermore, the tensile properties of fabricated Ti-6Al-4V alloy by SLM are higher than the forged standard ones. However, the fatigue results show that there are some scatters, which need further investigation to define the fatigue initiation.

1. Introduction

Additive Manufacturing (AM) is a process in which parts are built up by progressive consolidation of raw materials, such as powder or wire, in a layer-by-layer fashion [1-4]. This is a different approach to traditional fabrication methods such as machining from block or plate, where the final part geometry is produced by subtracting or removing material. All additive layer manufacturing technologies share the layer additive approach: a three-dimensional CAD model is sliced into thin layers and the particular AM process builds the physical part layer by layer. With this additive approach, parts of greater complexity can be economically produced. Manufacturing near-net-shape components in a layer-bylayer fashion offers a great potential for time and cost savings in comparison to conventional manufacturing technologies. Especially aerospace components that are machined from costly wrought material at a low fly-to-buy ratio represent interesting applications [5-7]. Recently, there exist some reports dealing with microstructures of Ti-6Al-4V alloy fabricated by AM processes, but none of them is related to evaluating the SLM process in microstructure and mechanical properties in different locations in order to satisfy the industrial requirements [8-10]. In the present paper, Ti-6Al-4V alloy was deposited by commercial SLM processes, and its microstructure and tensile properties were investigated for aeronautical industry application. The material investigated is the titanium alloy Ti-6Al-4V, the most commonly produced titanium alloy and one of the most common aerospace alloys.

2. Experiment

Ti-6Al-4V alloy powder was provided by Falcon Rapid Fabrication Technology Corporation. The powder was produced by the gas atomization process and was spherical with a maximum particle size 53 µm (98.7% less than 53 um). Ti-6Al-4V alloy samples were fabricated on an EOS M280 machine

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including a laser unit delivering a continuous single mode laser power of 400 W which produces a laser beam with a wavelength of 1070 nm and an intensity distribution of Gaussian. The laser spot diameter was 100~500 μ m and the maximum scanning speed was 7 m/s. In addition, the layer thickness can be selected between 20~100 μ m and the deposition was carried out on a 30 mm thick Ti-6Al-4V alloy plate. During the SLM process, the processing chamber will be filled with argon in order to maintain the oxygen level during the process. The schematic principle of SLM process is shown in Figure 1.

The horizontal and vertical section microstructures of the samples were examined using a Leica optical microscope. The chemical composition was carried out with the Oxford INCA energy dispersive X-ray (EDX) microanalysis software. The element concentration conforms to AMS4998 regulation. Two post heat treatments were applied. Stress relieving at 800 $^{\circ}$ C for 2 hours followed by furnace cooling (FC) to reduce residual stresses without substantial change to microstructure.

The sample location was shown in Figure 2 and the room temperature tensile property was tested according to ASTM E8/E8M. Samples were taken from middle point and four corners of the base, the specimens size were $\Phi 10 \times 70$ mm for vertical samples and $10 \times 10 \times 70$ mm for horizontal samples. A schematic drawing of the test pieces is shown in Figure 2.



3. Results and Discussions

3.1. Microstructure

Figure 3 shows the microstructure features of Ti-6Al-4V alloy fabricated by SLM in the X-Z and X-Y sectional directions. The microstructure shows morphology as macrostructure of columnar prior-grains that are growing epitaxially across many layers vertically in Figure 3(b). This type of microstructure is a typical of additive manufacturing processes, which involve partial re-melting of the previous layers. Indeed, when the laser beam scans the layer of powder, it remelts the top of the columnar grains, which results in the epitaxial growth of the strongly textured grains. Moreover, the time the melting pool remains liquid before a complete solidification in the β domain, depending essentially on the solidification rate and the thermal gradient, acts on the epitaxial growth and especially the number of nuclei formed. When a layer of the former microstructure seems equal-axis and the latter one is column. It seems to mean that this unidirectional grain growth may also influence the anisotropy of properties of the SLM as-built alloy. However, the electron back scatter diffraction technique shows that there is no obvious texture in both sections as shown in Figure 4.

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3.2. Tensile properties

Table 1 and Table 2 show that the tensile properties of Ti-6Al-4V alloy fabricated by SLM in the X-Y and X-Z sections at room temperature. It can be seen that the SLM tensile strength is similar in both transverse and longitudinal sections, no matter the sample location is in the middle part or in the corner position during the processing, which is higher than the as-forged standard one (the tensile properties of forged Ti-6Al-4V alloy is yield strength of forged 828MPa, ultimate tensile strength 895MPa and elongation 10%). However, the fatigue test results, as shown in Figure 5, show that there are some scatters between the two sections in spite of the limited data, due to some defects occur during the processing or the powder.

 Table 1. Tensile properties of Ti-6Al-4V alloy fabricated by SLM in X-Y direction at different

 location of the base

No.	UTS (MPa)	Standard Deviation (MPa)	CV (%)	YS (MPa)	Standard Deviation (MPa)	CV (%)	E (%)	Standard Deviation (%)	CV (%)
c1h	1037	5.77	0.56	980	5.00	0.51	15.5	0.87	5.58
c2h	1040	0.00	0.00	982	2.89	0.29	15.83	1.26	7.95
c3h	1067	15.28	1.43	1018	20.21	1.98	16.83	0.76	4.54
c4h	1053	5.77	0.55	988	7.64	0.77	14.17	1.04	7.35
mh	1057	11.55	1.09	997	12.58	1.26	16.17	1.04	6.44

Table 2. Tensile properties of Ti-6Al-4V alloy fabricated by SLM in X-Z direction at different location of the base.

No.	UTS (MPa)	Standard Deviation (MPa)	CV (%)	YS (MPa)	Standard Deviation (MPa)	CV (%)	E (%)	Standard Deviation (%)	CV (%)	
c1h	1033	11.55	1.48	977	14.43	1.12	15.83	1.04	6.57	
c2h	1037	5.77	1.64	983	16.07	0.56	15.83	0.76	4.82	
c3h	1037	5.77	1.30	967	12.58	0.56	16.17	1.76	10.86	
c4h	1047	5.77	1.47	982	14.43	0.55	15.83	0.29	1.82	
mh	1067	5.77	1.14	1013	11.55	0.54	13.83	0.58	4.17	



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4. Summary

(1) The microstructure of fabricated Ti-6Al-4V alloy by SLM shows anisotropy between the X-Z section and X-Y section. The former microstructure is column and the latter seems equal-axis owing to epitaxial growth. In addition, there is no obvious texture occur between the X-Z section and X-Y section.

(2) The tensile strength and ductility of fabricated Ti-6Al-4V alloy by SLM are quite uniform on the different process position, showing the higher value than that of the forged standard ones.

(3) The fatigue test results of fabricated Ti-6Al-4V alloy by SLM show some scattering due to some defects occur during the processing or the powder.

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