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Microstructure and mechanical properties of wrought and Additive manufactured Ti-6Al-4V cylindrical bars

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Abstract

Titanium alloys are widely used in various engineering design application due to its superior material properties. The traditional manufacturing of titanium products is always difficult, time consuming, high material wastage and manufacturing costs. Selective laser melting (SLM), an additive manufacturing technology has widely gained attention due to its capability to produce near net shape components with less production time. In this technical paper, microstructure, chemical composition, tensile properties and hardness are studied for the wrought and additive manufactured SLM cylindrical bar. Microstructure, mechanical properties and hardness were studied in both the longitudinal and transverse directions of the bar to study the effect of orientation. It was found that additive manufactured bar have higher yield strength, ultimate tensile strength and hardness than the wrought bar. For both conventional and SLM test samples, the yield strength, ultimate tensile strength and hardness was found to be high in the transverse direction. The difference in the properties can be attributed to the difference in microstructure as a result of processing conditions. The tensile fracture area was quantified by careful examination of the fracture surfaces in the scanning electron microscope.

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Keywords: Selective laser melting,Titanium alloys,Mechanical properties,microstructure,hardness,tensile properties

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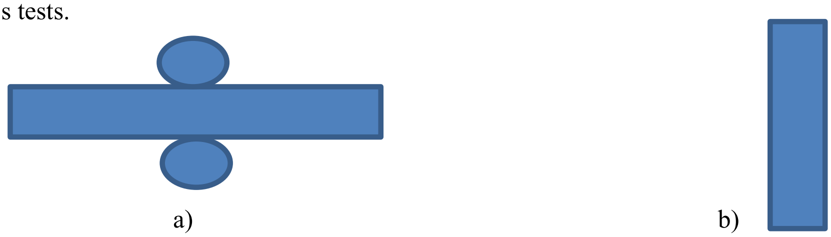
1. Introduction

Titanium alloys are widely used in aerospace, automobile, biomedical and chemical industries because of their superior properties like corrosion resistance and high strength to weight ratio(Leyens and Peters, 2003, Lütjering and Williams, 2007). Despite of their applications, manufacturing of titanium components is always challenging due to their high chemical reactivity and poor thermal conductivity. Casting, forging and machining are being traditionally used to manufacture titanium products and they have their own disadvantages like high material wastage and low production rate(Mitchell, 1998). Selective laser melting (SLM) has shown to be a promising additive manufacturing technology for a wide range of metal alloys. Using this technology, components with complex geometry can be manufactured with less product development cycle time. In the SLM process, the final component is obtained by selectively melting and solidifying layers of powders using a laser beam in an inert atmosphere. Due to the simplicity and high rate of production using this technology, it is believed that it can be an attractive alternative manufacturing method (Gibson et al., 2009, Murr et al., 2012). Therefore, it is necessary to study and ensure that the material properties of the components fabricated from this method are in acceptable standards. The microstructure of the titanium alloy is one of the important factors controlling its tensile properties, fatigue strength and fracture toughness. Based on the thermo mechanical processing titanium alloys can be of equiaxed microstructure, lamellar microstructure or bi modal microstructure. Bimodal microstructures have high yield stress, tensile stress, ductility and fatigue stress. Whereas fully lamellar microstructures have high fatigue crack propagation resistance and high fracture toughness. In lamellar microstructure the β-grain size, size of the colonies of α-lamellae and thickness of the α-lamellae determines the mechanical properties. Cooling rates affects the microstructure of titanium alloys to a great extent. Slow and intermediate cooling rates leads to a diffusion controlled nucleation and growth process of α-lamellae in to the β-grains. High cooling rates result in a martensitic transformation of the β-phase(Filip et al., 2003). During SLM fabrication of titanium alloys, rapid heating and cooling of components takes place in a concentrated area as a result of laser irradiation. This often result in the formation of acicular α'martensitic phase in titanium alloys due to the high cooling rate (approx.10-4 K/s4)(Murr et al., 2009). The main objective of this research is to study the microstructure, chemical composition and mechanical properties like yield strength, ultimate tensile strength, percentage elongation and hardness of the wrought and SLM fabricated Ti-6Al-4V rod. The effect of orientation on the mechanical properties are also studied.

2. Experimental Design

The initial dimensions of the conventionally made (here on referred as wrought) rod was 70 mm in diameter and 600 mm in length. The rod was received in rolled condition with a post mill annealing heat treatment at 730°C (2 hrs) followed by air cooling. This material will be addressed as wrought Ti-6Al-4V throughout the paper. A cylindrical rod of 60 mm diameter and 75 mm length was fabricated using SLM 125HL in an inert nitrogen environment using optimum parameters. The fabricated cylindrical rod is then heat treated and stress relieved in vacuum furnace at 750°C followed by furnace cooling to relieve the residual stresses developed during fabrication. This material will be addressed as SLM Ti-6Al-4V in the fore coming sessions. For the microstructural examination of wrought and SLM Ti-6Al-4V, samples were sectioned using silicon carbide cutting blade at lower cutting speed 0.2 mm/min with ample amount of water based coolant. The samples were then mounted using citropress machine and was then mechanically polished using 220,400,600,800 and 1200 silicon carbide grit papers. After plane grinding with grit paper, the samples are grinded on MD-Largo surface with DiaPro Allegro suspension solution. Then final polishing was carried out using MD-Chem surface with OP-S solution as a suspension. Then Krolls reagent that consists of 3ml of HF, 6ml of HNO3 and 100 ml of distilled water was used as an etchant. The chemical composition of the wrought and SLM Ti-6Al-4V were analysed using spectrometry methods. The metallic elements were analysed using Leco table top optical emission spectrometer and the non-metallic particles were analysed using carrier gas hot extraction methods by melting the material in the graphite crucible. Tensile samples each were cut from the longitudinal and transverse sections of the wrought Ti-6Al-4V and SLM Ti-6Al-4V cylindrical rod using wire-cut EDM with a gauge length of 20 mm and width of 6mm. Tensile tests were carried out after polishing the samples using grit papers 220,400 and 1500 to remove surface irregularities. Tensile tests were carried out in a servo hydraulic Instron 5586 machine at a cross head speed of 4mm/min. Micro hardness was measured using Vickers hardness tests.



a) b)

Figure 1 a) Rolled Ti-6Al-4V bar (wrought bar) b) Additive manufactured Ti-6Al-4V bar (Selective laser melting)

The micro hardness indentations were made on the longitudinal and transverse sections of the cylinder and a totally 6 indentations were made at random locations. The hardness measurements were performed on a vickers hardness testing machine with a load of 150gf and a dwell time of 15 seconds.

3. Results and Discussions

3.1 Microstructure

Figure 2 shows the microstructure of wrought and SLM Ti-6Al-4V cylindrical bar in the longitudinal direction. The wrought Ti-6Al-4V bar consisted of a fully equiaxed microstructure with inter granular β. The average size of the equiaxed α grains, which determines the mechanical properties of titanium alloys, was about 14µm approximately. On the other hand, microstructure of the SLM Ti-6Al-4V (as built) cylindrical bar was inhomogeneous and consisted of fine acicular α’ grains throughout the sample within the prior β grain boundaries after the solidification process. This microstructure and their inhomogeneity was the result of uneven fast heating and cooling in the SLM process. In the longitudinal direction of the cylinder, the vertical prior β grains have grown almost parallel to the building direction with slight inclinations due to scan rotation. After the stress relieving heat treatment, SLM parts consists of a fully lamellar α+β microstructure. After heat treatment, the size of α grains has grown to an average length and width of 9.2µm and 0.984µm.The β phase in the SLM part is present as bright contrast in the α-lath boundaries as shown in Figure 2d. The microstructure of both the alloys was quite different in the longitudinal and transverse directions. The grain size was small in the transverse section in both wrought and SLM fabricated bar. The microstructure of the alloys in the transverse direction is shown in Figure 3.

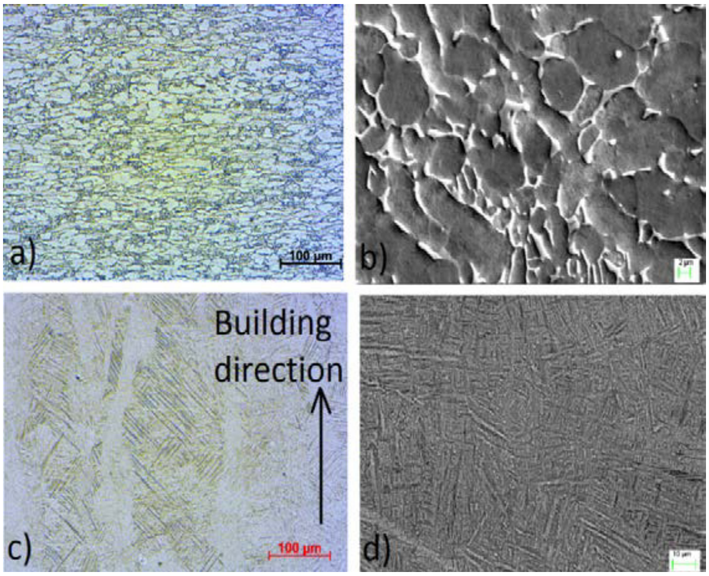


Figure 2 Optical image and SEM image showing the microstructure in the longitudinal direction of (a,b) wrought and (c,d) SLM Ti-6Al-4V rod

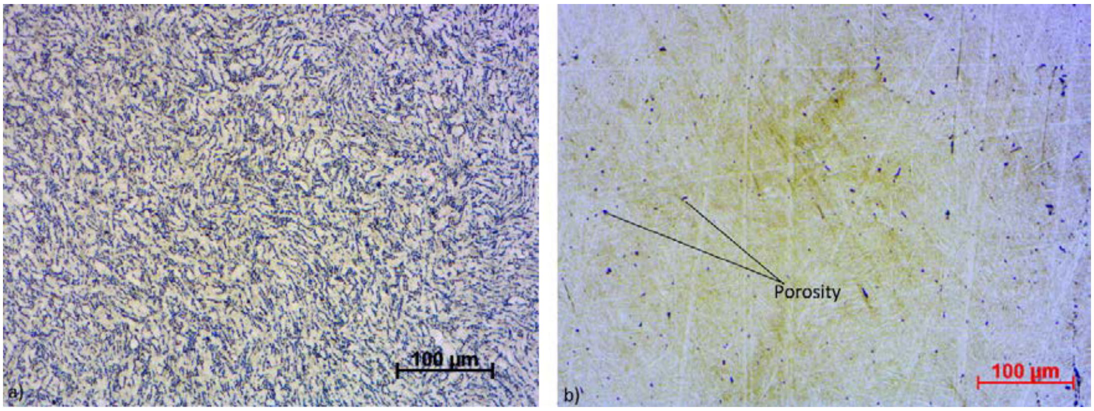


Figure 3 Microstructure of a) Wrought Ti-6Al-4V rod and b) SLM Ti-6Al-4V rod in the transverse direction

3.2 Chemical composition

Table 1 shows the chemical composition of the wrought and SLM Ti-6Al-4V cylindrical bars. The inert gas environment during fabrication of SLM parts has resulted in less elemental pick-ups of oxygen, hydrogen, nitrogen and carbon. The chemical composition analysis of SLM parts are in agreement with the ASTM standards. There was no significant change in the chemical composition of wrought and SLM rod.

Table 1 Chemical composition of wrought and SLM Ti-6Al-4V bar

Chemical composition	Al	V	Fe	C	O	N	H	Ti
Wrought Ti-6Al-4V	6.48	4.37	0.170	0.016	0.17	0.03	-	Bal.
SLM Ti-6Al-4V	6.82	4.20	0.325	0.025	0.20	0.041	0.0047	Bal.

3.3 Mechanical properties

Room temperature tensile tests were conducted on the flat tensile samples taken from longitudinal and transverse sections of the wrought and SLM fabricated cylindrical rod. The results from the tensile tests are shown in Table 2. It was found that SLM rods have higher yield strength and ultimate tensile strength compared to its wrought counter parts. But SLM parts lacked significantly in ductility unlike the wrought part. This difference in their material behaviour can be explained in terms of the difference in microstructure as titanium alloy's mechanical properties are strongly influenced by its microstructure. In the wrought Ti-6Al-4V, the size of the equiaxed α grains determines the mechanical property whereas in SLM Ti-6Al-4V the colony size and size of the α laths determines its property. Plastic deformation is movement of dislocations. The larger α grain size in the wrought alloys facilitates the deformation with less dislocation pile up, whereas the smaller α grain size in SLM parts increases the dislocation pile ups. Thus results in the higher yield strength, ultimate tensile strength and poor ductility of SLM parts. The stress strain curve of the wrought and SLM Ti-6Al-4V is shown in Figure 4. The wrought titanium rods has elongated grains in the longitudinal direction as a result of rolling and whereas the SLM rod has elongated grains in the longitudinal direction as a result of layer by layer heating. In both the cases, the transverse direction grains were refined as compared to the longitudinal direction. Thus this difference in the microstructure resulted in the high yield strength and tensile strength in the transverse samples as compared to the longitudinal samples.

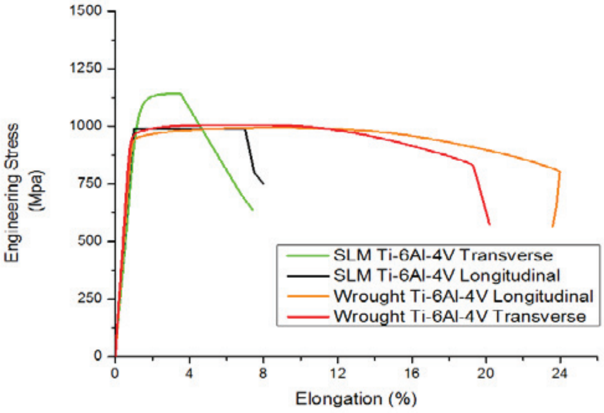


Figure 4 Stress-strain curve for the wrought and SLM Ti-6Al-4V

Table 2 Tensile properties of the tested cylindrical bars

Materials	Young's Modulus [Gpa]	Yield Strength [Mpa]	Ultimate tensile strength [Mpa]	Percentage of Elongation [%]	Percentage of reduction in Area [%]
Wrought Ti-6Al-4V f (Longitudinal)	105	948	994	21	40
Wrought Ti-6Al-4V (Transverse)	107	962	1008	19	38
SLM Ti-6Al-4V (Longitudinal)*	113	964	1041	7	13
SLM Ti-6Al-4V (Transverse)	109	1058	1114	3±2	11

After tensile tests, scanning electron microscope was used to study fractured surface of both materials. The samples were cut parallel to the fractured surface and were viewed under the SEM. The fractured surface profile of wrought titanium exhibited deep dimples that indicate the ductile behavior of the material. On the other hand, the SLM parts exhibits terrace like feature with small size shallow dimples on quasi cleavage surface and transgranular facets indicating their brittle nature.

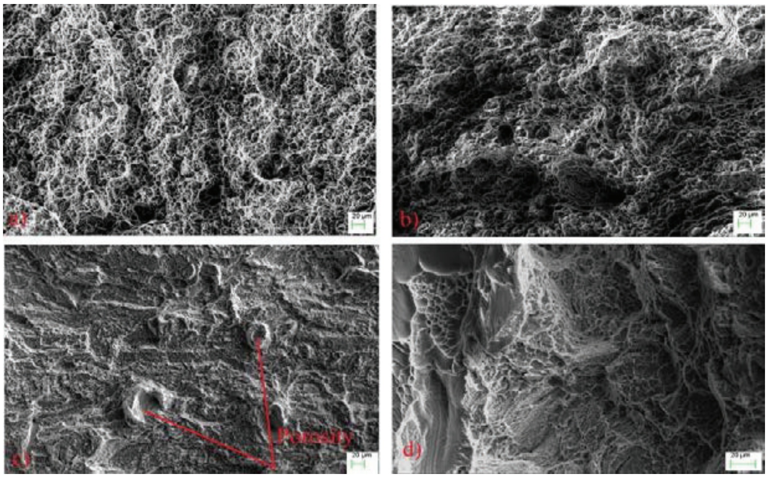


Figure 4 Fracture surface of tensile samples from the longitudinal direction a) wrought Ti-6Al-4V longitudinal samples b) wrought Ti-6Al-4V transverse samples c) SLM Ti-6Al-4V longitudinal samples d) SLM Ti-6Al-4V transverse samples

In addition concentric features as a result of porosity and unmelted powder particles during fabrication of SLM parts were also found. The fractures of the longitudinal specimen shows weak surface as a result of the layer by layer build up during the process as shown in Figure 5.

4. Conclusion

Microstructure, chemical composition, tensile properties, hardness were studied for the wrought and additive manufactured Ti-6Al-4V rod. The following conclusions were made from this research:

- The wrought Ti-6Al-4V has an equiaxed microstructure with elongated grains in the direction of rolling whereas SLM Ti-6Al-4V had elongated grains as a result of epitaxial growth due to layer by layer build up during SLM process. The grains had a high aspect ratio in the longitudinal section as compared to the transverse section in the SLM rod.
- The chemical composition of the SLM rod was more similar to that of the wrought rod. The chemical composition was within the range of the ASTM standards.
- Due to the difference in microstructure, the yield strength and ultimate tensile strength was found to be higher in the SLM rods as compared to the wrought counterpart. The samples oriented in the transverse direction had higher yield strength and tensile strength than the longitudinal samples.
- Percentage of elongation was lower in the SLM rod as compared to the wrought rod and the longitudinal specimens had higher elongation as compared to the transverse specimens.
- The wrought rod exhibited deep dimple fracture revealing the ductile nature whereas the SLM rod exhibited transgranular fracture as a result of their brittle nature.

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