Comparative Study of Microstructural Characterisation and Tensile Properties of Wrought and Additively Manufactured TI – 6Al – 4V Samples

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ABSTRACT

Titanium alloys are extensively applied in several engineering design due to their superior properties. The manufacturing of titanium products seems to be difficult when a traditional method is used because it is always time-consuming, waste high amount of material, coupled with the manufacturing costs. Selective laser melting (SLM), an additive manufacturing technique, has recently gained attention owing to its capability to produce near net shape components with little production time. SLM has been made known to be an attractive manufacturing method for the production of α/β titanium alloys particularly Ti – 6Al – 4V. A full understanding of the relationship between the process, microstructure and mechanical properties of the components manufactured by this technology is however critical for the establishment of SLM as an alternative manufacturing route. The purpose of this study is therefore to determine the microstructure, chemical composition, tensile properties and hardness for the wrought and additive manufactured SLM samples. Microstructure, mechanical properties and hardness were analysed in both longitudinal and transverse directions of wrought and SLM bar. It was established that the additively manufactured bar has higher yield strength, ultimate tensile strength and hardness than the wrought bar. The difference in the properties of SLM and wrought can be ascribed to the difference in microstructure due to processing conditions.

Keywords: Selective laser melting, titanium alloys, microstructure, mechanical properties, tensile properties

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1. INTRODUCTION

Titanium is a low-density element, and records show that approximately 60% of the density of steels, titanium and its alloys and other superalloys can be strengthened significantly by alloying and deformation processes. Titanium alloys are extensively used in aerospace, automotive, biomedical as well as chemical industry due to their excellent properties such as corrosion resistance and high-strength ratio (Lutjering and Williams, 2007). Ti – 6Al – 4V alloy is distinctive since it combines attractive properties with characteristic of workability that enables it to be produced in all types of mill products (in both large and small sizes), fabricability which allows the mill products to be made into complex shapes. Ti – 6Al – 4V became the standard alloy against which other alloy must be compared when selecting a titanium alloy for specific application (ASTM, 2014). Boyer (1996) explained that this titanium alloy is the most applied in aerospace engineering due to its high mechanical properties, low density and excellent corrosion properties.

Leyens and Peters (2003) also agreed that titanium alloys are used in aerospace application where the combination of weight, strength, corrosion resistance and or high temperature stability of aluminium alloys, high strength steels or nickel – based (Nb) superalloys are not enough. Owing to Ti – 6Al – 4V biocompatibility couple with excellent combination of mechanical and corrosive properties, it is the most popular titanium-based material in the production of biomedical components and other surgical instruments.

However, the mechanical properties of titanium alloys are largely determined by the chemical composition as well as the corresponding microstructure (Leyens and Peters, 2003). The metallographic preparation and subsequent microstructural examination are consequently of great interest. Titanium alloys microstructure is one of the significant factors controlling the tensile properties, fatigue strength and fracture toughness. As a result of thermomechanical processing, Titanium alloy could be equiaxed, lamellar or bi-modal microstructures (Shunmugavel, Polishetty, and Littlefair, 2015). Study of Filip et al., (2003) showed that bi-modal microstructure exhibits high yield stress, tensile stress, ductility and fatigue stress.

Recently, many manufacturing industrial sectors have embraced additive manufacturing (AM) technology. AM offers real prospects since it enables a flexible and cost-effective production of metallic components directly from 3D digital data model (Chanstand et.al, 2016). Manufacturing components layer by layer by AM technology allows a high freedom in design and the technology becomes interesting to reduce weight and add to functionalities in parts (Wohlers, 2013). The simplicity and high rate of production of AM technology is believed to have made it an attractive alternative manufacturing technique (Murr et al., 2012).

Although researches have been done to investigate the microstructures and tensile properties in fabricated materials by AM technology. Empirical studies on the microstructure characterization and tensile properties of Ti – 6Al – 4V seem to have received little attention as only a handful researches are conducted in this area. Regardless of the important of titanium alloys, the number of available article addressing the subject has been limited. This research will, therefore, extend its analysis on the microstructure characterization and tensile properties as studies in this area clearly indicate a gap and leaves a vacuum within the existing literature that need to be filled.

2. EXPERIMENTAL PROCEDURE AND MATERIALS

The original dimensions of the wrought rod were 70mm in diameter and a length of 600mm. The rod was received in rolled condition with a post annealing heat treatment at temperature of 730^{0}C for 2hrs followed by air cooling. A cylindrical rod of 60mm diameter with a length of 75mm was fabricated using selective laser melting, SLM 125HL. The rod was heat treated and stressed- relieved in vacuum furnace at 750^{0}C followed by furnace cooling to relieve the residual stresses developed during fabrication. The microstructural examination of SLM Ti – 6Al – 4V samples was sectioned using silicon carbide cutting blade at lower cutting speed 0.2mm/min with sufficient amount of water-based coolant. The sample was then mounted using Citropress machine and was mechanically subjected to series of abrasive grinding operations using Struers PEDEMAX -2 grinding machine. The polishing of the sample was carried out using 220, 400, 600, 800 and 1200 silicon carbide grit papers on METASERVE universal polishing machine.

The final polishing was then carried out on MD-Chem surface with OP-S solution as a suspension. The etchant used was Kroll's reagent that consists of 3ml HF, 6ml HNO_3 and 100ml of distilled water. The chemical composition of the sample was analysed using spectrometry methods on Leco table top optical emission spectrometer. Tensile sample of SLM Ti – 6Al – 4V were cut from the longitudinal and transverse sections of the cylindrical rod on wire-cut EDM machine having a gauge length of 20mm and width of 6mm. The tensile tests were performed on Instron testing machine (TTDL model with maximum load of 100Kg) having a displacement rate of 0.5mm/min and at a cross head of 5mm/min.

Tensile tests were carried out after the samples have been polished using grit papers 200, 400 and 1500 so as to remove surface irregularities. Vickers hardness machine was used to measure the micro hardness with a load of 150kgf while the indentations were made on both the longitudinal and transverse sections of the cylinder. A total of six (6) indentations were made randomly on locations.

3. Results and Discussions

Microstructure

The microstructure of SLM Ti – 6Al – 4V cylindrical bar in the longitudinal direction is as shown in Figure 1. It was observed that the microstructure of the SLM Ti – 6Al – 4V cylindrical bar was inhomogeneous and consisted of fine acicular α grains throughout the sample within the prior β grain boundaries after the solidification process. The microstructure and their inhomogeneity were as a result of uneven fast heating and cooling in the SLM process. In the longitudinal direction of the sample, the vertical prior β grains have grown almost parallel to the building direction with slight inclinations owing to scan rotation. The SLM sample presents a fully lamellar α + β microstructure after the stress relieving heat treatment. The size of α grains has increased to an average length and width of 9.2μm and 0.984μm. However, the wrought Ti – 6Al – 4V sample consisted of a completely equiaxed microstructure with intergranular β.

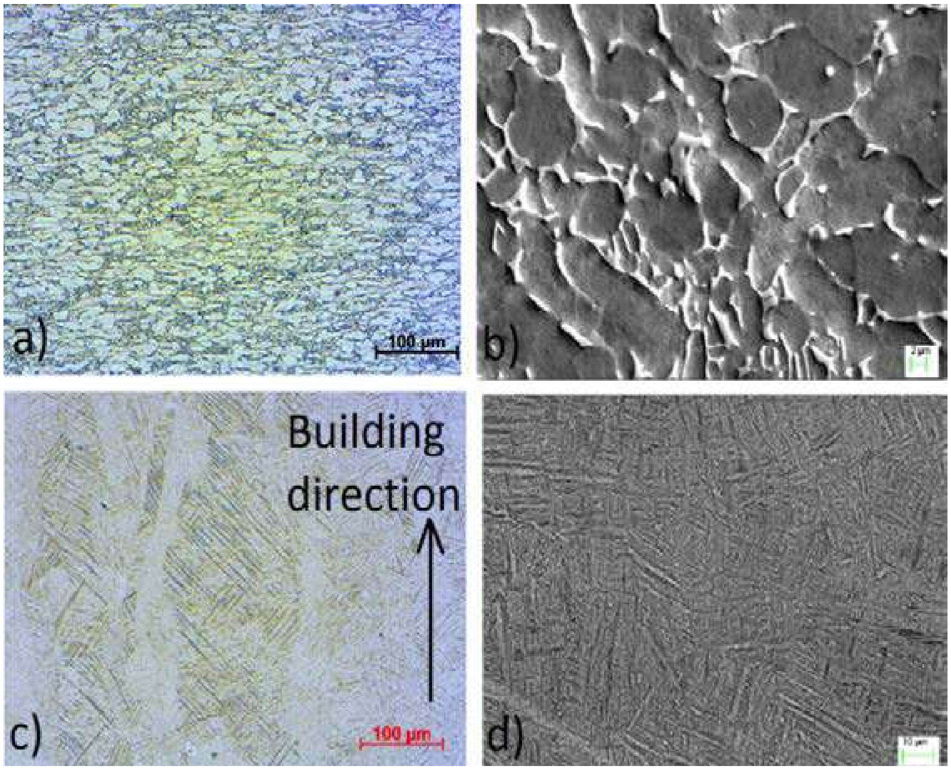

Figure 1 Optical image and SEM image displaying the microstructure in longitudinal direction for wrought (a,b) and SLM (c,d) Ti – 6Al – 4V samples.

The β phase in the SLM part reveal a bright contrast in the α – lath boundaries as shown in Figure 2. The microstructure of the alloy was somewhat different in the longitudinal and transverse directions. The microstructure of the alloy in transverse directions is as shown in Figure 2.

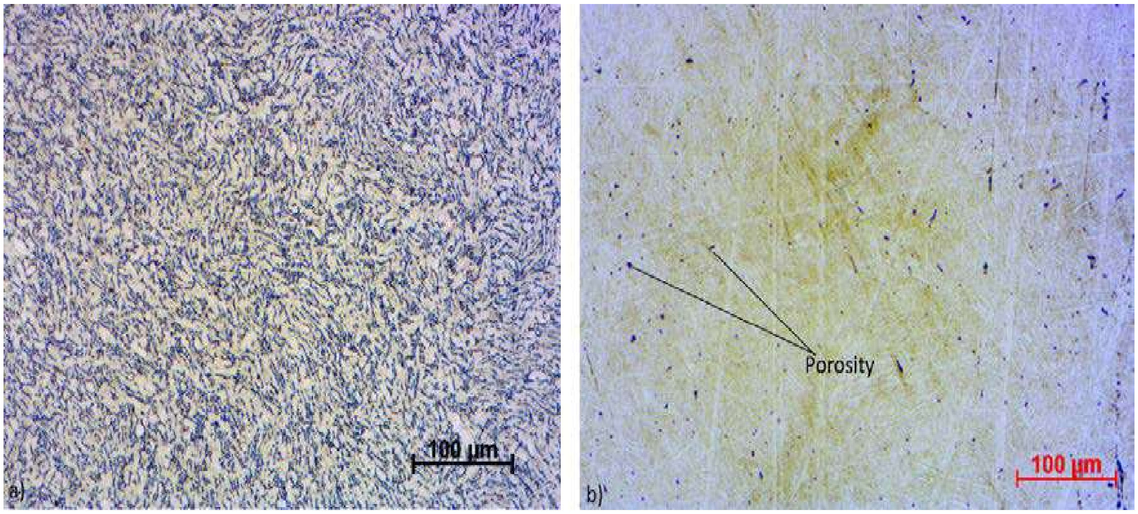

Figure 2 Microstructure of wrought (a) and SLM (b) Ti – 6Al – 4V

Chemical Composition

The chemical composition of the wrought and SLM Ti – 6Al – 4V cylindrical bars is shown in Table 1. During fabrication of SLM pars, the inert gas environment resulted in less elemental pick- ups of oxygen, hydrogen, nitrogen and carbon. The chemical composition analysis of SLM part conformed with the ASTM standards. However, 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

Chemical composition	Al	V	Fe	C	O	N	H	Ti
Wrought Ti-6Al-4V	6.46	4.38	0.170	0.017	0.17	0.03	-	Bal.
SLM Ti-6Al-4V	0.82	4.20	0.326	0.026	0.20	0.041	0.0047	Bal.

Mechanical Properties

Tensile tests were conducted on the flat tensile samples at room temperature taken from longitudinal and transverse sections of SLM fabricated cylindrical rod. The result of which was presented in Table 2. It was established that SLM rods have higher yield strength and ultimate tensile strength compare to wrought part. However, SLM parts lacked considerably in ductility compare to wrought part. Usually, titanium alloy's mechanical properties are strongly influenced by its microstructure. Plastic deformation is as a result of dislocations. The larger α grain size in the wrought titanium alloys enables the deformation with fewer pile up, while the smaller α grain size in SLM parts increases pile up of dislocation. Consequently, resulting in higher yield strength, ultimate tensile strength and poor ductility. The SLM rod has elongated grains in the longitudinal direction due to layer by layer heating. The transverse direction grains were refined as compared to the longitudinal direction. Accordingly, this difference in the microstructure occasioned in both the high yield strength and tensile strength in the transverse specimens compared to longitudinal specimens.

Table 2: Tensile properties of the tested cylindrical rods

Material	Young's modulus Gpa]	Yield strength[Mpa]	Ultimate tensile strength[Mpa]	Percentage elongation[%]	Percentage reduction in area[%]
Wrought Ti – 6Al – 4V (Longitudinal)	106	948	995	22	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	11

Subsequently, scanning electron microscope (SEM) was used to examine the fractured surface of the samples. The fractured surface of SLM parts reveals terrace- like feature with small size shallow dimples and transgranular surface showing their brittle nature. Additionally, concentric features due to porosity and un-melted powder particles were also found during fabrication of SLM parts. The fractures of the longitudinal sample which display weak surface due to layer by layer build up during the process is as shown in Figure 3.

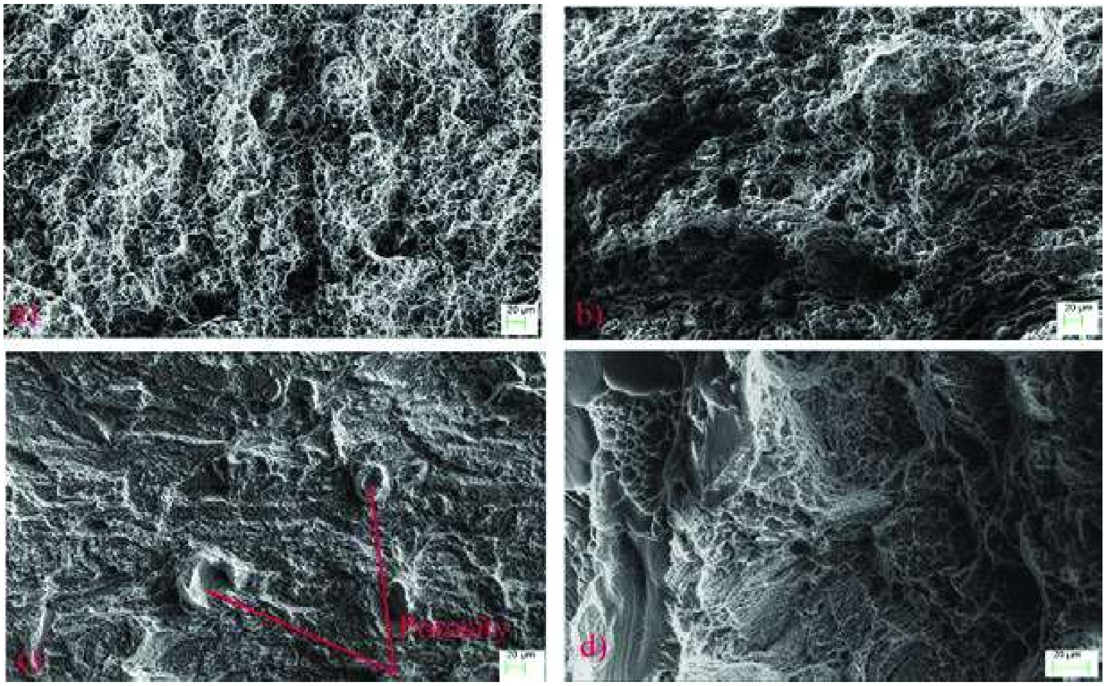

Figure 3 Fracture surface of tensile specimens from the longitudinal direction (a) and transverse direction (b) for Wrought Ti – 6Al – 4V. SLM specimens Ti – 6Al – 4V (c) longitudinal direction and (d) SLM Ti – 6Al – 4V transverse direction.

4. CONCLUSION

The microstructure, chemical composition, tensile properties and hardness were studied for wrought and additive manufactured Ti – 6Al – 4V. The evidence in this study suggests that there are several processing techniques under which it is possible to fabricate near fully dense SLM Ti – 6Al – 4V. However, the following conclusions were established from this study.

- SLM Ti – 6Al – 4V had elongated grains due to epitaxial growth as a result of layer by layer build up during the process. The grains had a high aspect ratio in the longitudinal section as compared to the transverse section in the rod.
- The SLM rod chemical composition was similar to that of the wrought rod and was in the range of the ASTM standards.
- As a result of the difference in microstructure, the yield strength and ultimate tensile strength was found to be higher in the SLM rods compared to the wrought sample. The samples oriented in the transverse direction had higher yield strength and tensile strength than the longitudinal specimens.
- The mechanical properties are economical to cast material and components manufactured by other additive manufacturing methods.
- The ultimate tensile strength (UTS) varies between 995 and 1114 MPa, subject to orientation and location of the samples.
- Fatigue properties of Ti – 6Al – 4V components manufactured by SLM are comparable to casting after stress-relieved and like wrought processes after heat treatment.

REFERENCES

1. American Standard for Testing and Material International (2014) Standard specification for Additive Manufacturing Titanium-6 Aluminium -4 Vanadium with Powder Bed Fusion
2. Boyer, R. (1996) An overview on the use of titanium in the aerospace industry. Material Science and Engineering 213(1), pp. 103 – 114
3. Chastand, V., Tezenas, A., Cadoret, Y., Quaegebeur, P., Maia, W and Charkaluk, E. (2016) Fatigue characterization of titanium Ti - 6Al – 4V samples produced by additive manufacturing. Procedia Structural Integrity. pp. 3168 – 3176
4. Filip, R., Kubiak, K., Ziaja, W. and Sieniawski, J. (2003) The effect of microstructure on the mechanical properties of two-phase titanium alloys. Journal of Materials Processing Technology, 133 pp. 84 – 89
5. Leyens, C and Peters, M (2003) Titanium and titanium alloys. Wiley GmbH.
6. Lutjering, G and Williams, J.C (2007) Titanium. Springer
7. Murr, L.E., Gaytan, S.M., Ramirez, D.A., Martinez, E., Hernandez, J., Amato, K.N., Shindo, P.W., Medina, F.R., and Wicker, R.B. (2012) Metal fabrication by additive manufacturing using laser and electron beam melting technologies. Journal of Material Science and Technology, 28 pp. 1 -14
8. Shunmugavel, M., Polishetty, A. and Littlefair, G. (2015) Microstructure and mechanical properties of wrought and additive manufacture Ti – 6Al – 4V cylindrical bars. Procedia Technology, pp. 231 – 236
9. Wohlers, T. (2013) Wohlers report: Wohlers Associates.