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Effect of build direction on the microhardness and dry sliding wear behaviour of laser additive manufactured Ti-6Al-4V☆

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Abstract

This work presents micro structural and tribological behaviour of Ti-6Al-4V fabricated by direct metal laser sintering technique. The laser sintering was carried out at laser power of 170 W in an argon atmosphere. The microstructure, phase composition, micro hardness and wear study were determined. It has been found that specimens built vertically (VB) contained vanadium carbide (VC) and titanium oxide (TiO) phases in the present of α and β phases resulting in higher micro hardness as compared to horizontal build (HB) specimens. Wear volume loss was determined in a dry sliding wear configuration. An increase in applied load from 5 N to 25 N resulted in an increment in wear volume loss. The presence of delamination could be observed on the worn surface of HB specimen.

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*Keywords:*Laser; Titanium; Sintering; Hardness; Wear

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1. Introduction

Additive manufacturing (AM) is a process that builds components by depositing the material layer by layer. It combines the technologies such as powder metallurgy, solidification, CAD-CAM and rapid prototyping [1, 2]. There are various AM technologies in the past two decades like Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Laser Metal Deposition (LMD), Electron Beam Melting (EBM), Laser Engineering Net Shape (LENS) etc. These processes make use of thermal energy for melting either powder material or wire. Laser and electron beam are the major energy sources for melting [3, 4]. Direct metal laser sintering (DMLS) process, which is also referred to as SLM, is capable of producing parts geometries having complex shapes with high degree of geometric freedom [5].

Titanium alloys and more specifically Ti–6Al–4V find wider application in aerospace industry due to its high strength to weight ratio; biomedical fields due to its excellent bio-compatibility and superior corrosion resistance; food and chemical plants due to its excellent corrosion resistance. Its application also extends to various other sectors such as marine, offshore and defense industries [6]. More specifically, Ti-6Al-4V finds its application in orthopedic joint replacements, bone plates and dental implants which require superior mechanical properties mainly wear resistance [7]. Therefore, extensive wear studies on this material manufactured using DMLS technology become imperative in the current scenario. Obadele et al. [8] studied the dry sliding wear property of laser clad Ti-6Al-4V with commercially pure (CP) Ti under different counterface materials and reported a significant mass losses of the clad surfaces under WC and 302 steel counterface sliding against the CP Ti coating. In their work, Gu et al. [9] reported the formation of an adherent, plastically smeared tribolayer on the worn surface of selective laser melted commercially pure titanium. However, to the best of the authors' knowledge, there is scarcely any report focusing on the microstructure, phase constituents and wear performance of direct metal laser sintered Ti-6Al-4V which has wider potential applications.

This paper presents the effect of built orientation (horizontal and vertical) on Ti-6Al-4V laser as-sintered parts. The resulting phase constituents, microstructural evolution, microhardness and wear resistance at different built directions were assessed.

2. Materials and method

Rectangular shaped Ti-6Al-4V parts of size 100 x 30 x 15 mm were manufactured using direct metal laser sintering (DMLS) technology with average powder particle size of 45 µm in vertical and horizontal directions. An EOSINT M270 laser machine was used with the set parameters of laser power 170 W, scanning speed 1400 mm/s, layer thickness 30 µm, laser spot size 140 µm with high purity argon build atmosphere acting as a shield to Ti oxidation. One specimen was cut from horizontal built (HB) and five specimens were cut from vertical built (VB) parts starting from build platform end till opposite end and named as VB1, VB2, VB3, VB4 and VB5 respectively in this article.

Microhardness values were measured using Future-tech Vickers microhardness tester at a load of 0.98 N (100 gf) and dwelling time of 10 s. Five indentation were taken in all the specimens and the average value calculated. Tribological behavior of the Ti-6Al-4V parts built using DMLS technology were studied by conducting dry sliding reciprocating wear tests using a ball-on-disk wear tester under varying loads of 5 N, 15 N and 25 N. These tests were conducted at room temperature using a tribometer CETR UMT-2 (Bruker Nano Inc., Campbell, CA) with ball-on-disc configuration. Each test was repeated twice and the average wear scar size dimensions were taken to calculate the wear volume. The wear volume was calculated using the equation in ref [10].

3. Results and discussions

3.1. Microhardness and microstructural study

Fig. 1 shows the average hardness of the horizontal build (HB) and vertical build (VB) as-sintered specimens taken at various locations from the built platform. It is clear that the both HB and VB specimens are almost in the same range except the VB middle specimens. The microhardness values of VB specimens at the extreme are less hard (310±10 $HV_{0.1}$) compared to the middle specimens were considerable higher microhardness value (405±5 $HV_{0.1}$) was obtained. This is basically due to the difference in the phases present.

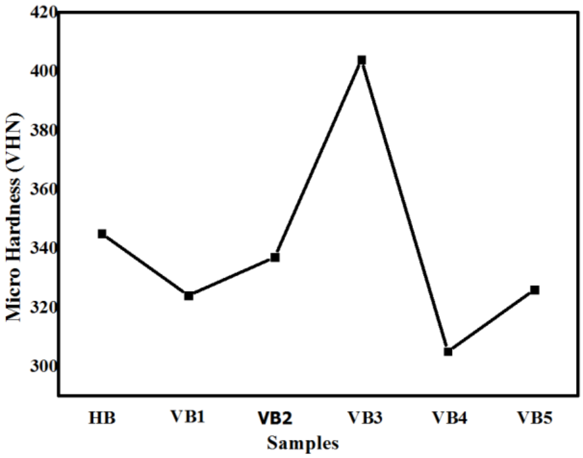

Fig. 1.Microhardness of horizontal and vertical built specimens

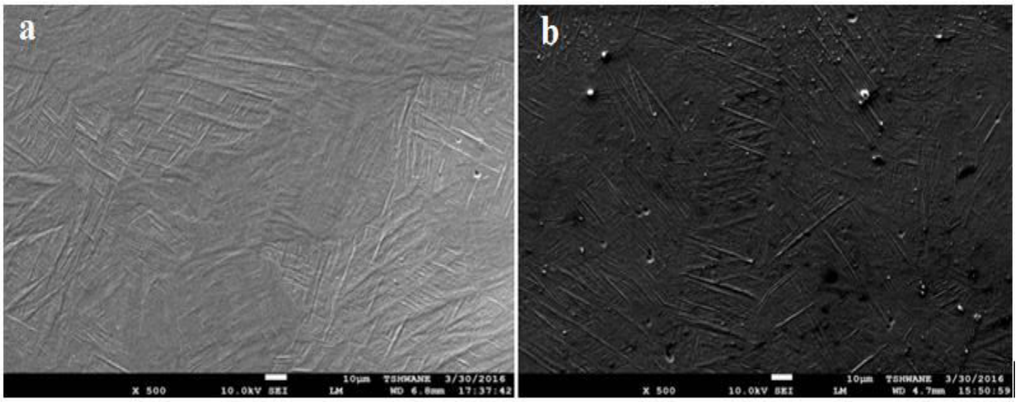

Fig. 2.(a) SEM images of HB; (b) SEM images of VB3 as-sintered specimens.

Fig. 2 shows the microstructures of HB and VB specimens. HB specimens are constituted by a mixed of α and β phases without the presence of martensite whereas VB specimens reveals the presence of martensite (α'). The higher hardness of the VB middle specimens could be attributed to the slow cooling rate due to the deposition of subsequent layers. On the other hand, the build platform in the opposite end, resulted in faster cooling rate. Fig. 3 shows the typical XRD spectra of DMLS-processed Ti-6Al-4V specimens obtained within a wide 2θ range (5-90º) for both HB and VB specimens. The results indicate the presence of α, ά and β phases. VC and TiO peaks were also observed only in VB specimens suggesting that the build direction during DMLS could influence phase(s) formation. These hard phases could be responsible for higher microhardness values recorded for VB specimens. The convective movement of the melt pool (Marangoni effect) and solidification rate during direct metal laser sintering could determine the phase change in the finally solidified materials.

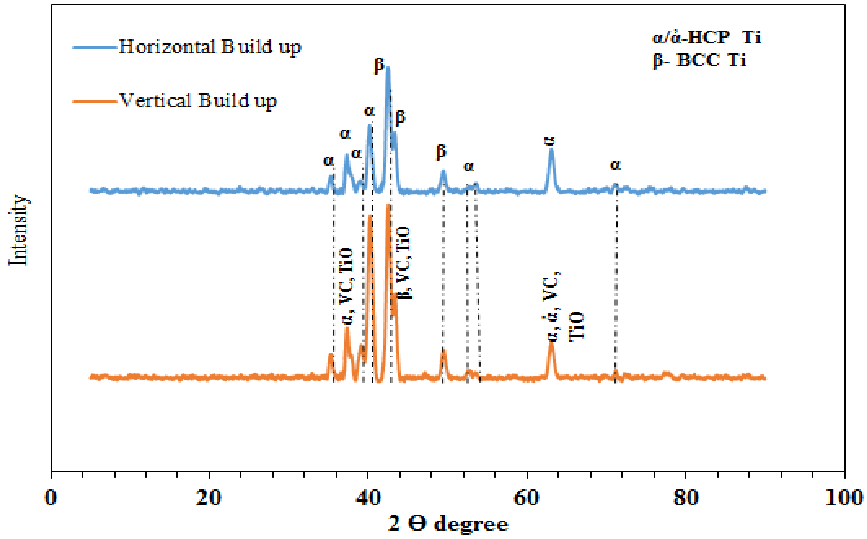

Fig. 3.XRD plots of horizontal and vertical built as-sintered specimens.

3.2. Wear analysis

Fig. 4 shows the wear performance of HB and VB specimens at 5 N, 15 N and 25 N applied loads in terms of wear volume loss. It can be noticed that wear volume loss is less in HB specimen for all the loads applied. In the VB specimens, wear volume loss of VB3 is relatively low while that of VB4 is higher at higher loads of 15 and 25 N. This observation is in agreement with the higher microhardness value measured at VB3 and subsequent lower value at VB4 as recorded in the Fig. 1. Generally, an increase in volume loss was observed as the load increases from 5 N to 25 N which suggest a gradual transformation from mild wear to severe wear at higher loads. Molinari et al.[11] reported that poor tribological properties of titanium alloys could be as a result of two main factors; the low work-hardening and low plastic shearing resistance, and also, the low protection exerted by the surface oxide due to high flash temperatures induced by friction during the dry sliding process.

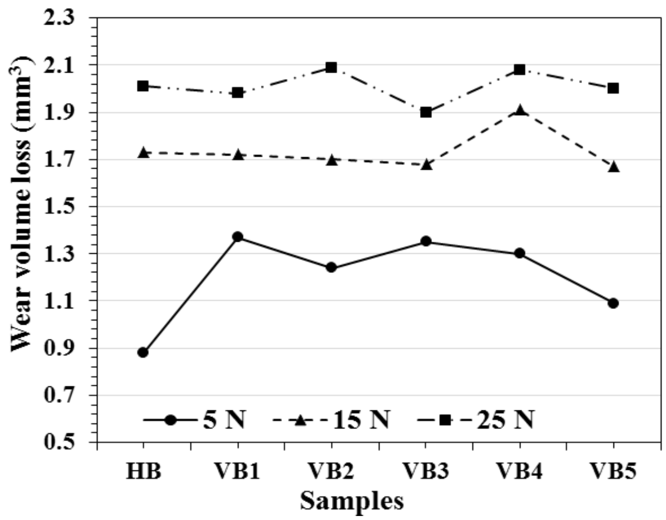

Fig. 4. Wear performance of horizontal and vertical built specimens at different loads.

Fig. 5 shows the SEM images of HB and VB3 worn regions for the applied load of 25 N. Parallel ploughs in the sliding direction can be noticed in both the specimens typical of abrasive wear mechanism. However, the worn area of VB3 specimen is relatively less and wear depth is shallow when compared with HB specimen. Presence of crack can also be found on the worn surface of HB which could lead to delamination (material removal) close to the crack tip. The higher microhardness value calculated for VB3 specimen could be a contributing factor as well as the formation of ά, VC and TiO phases as recorded in the XRD plots shown in Fig. 3.

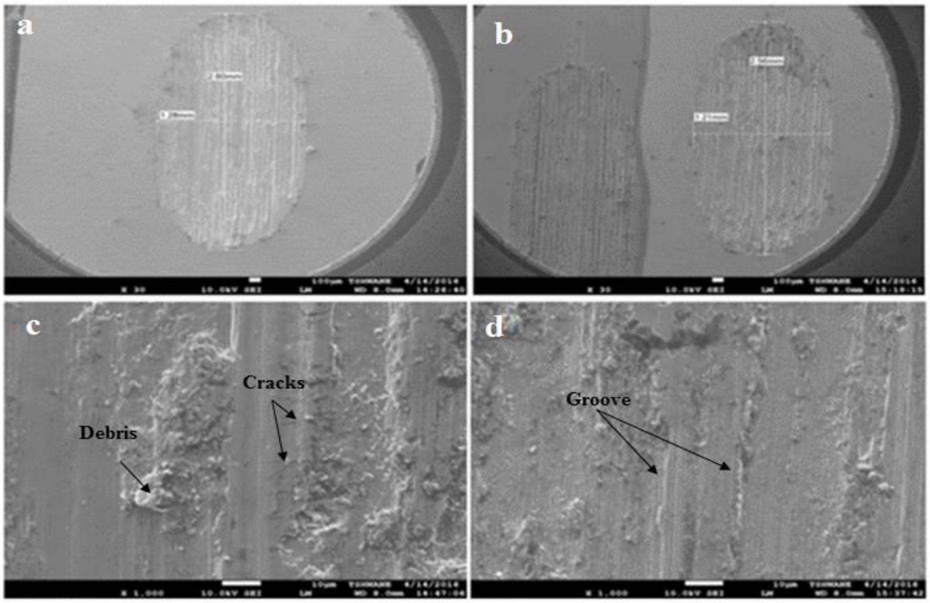

Fig. 5 - Wear track of HB and VB 3 specimens at 25N load (a, b) Lower magnification (c, d) Higher magnification.

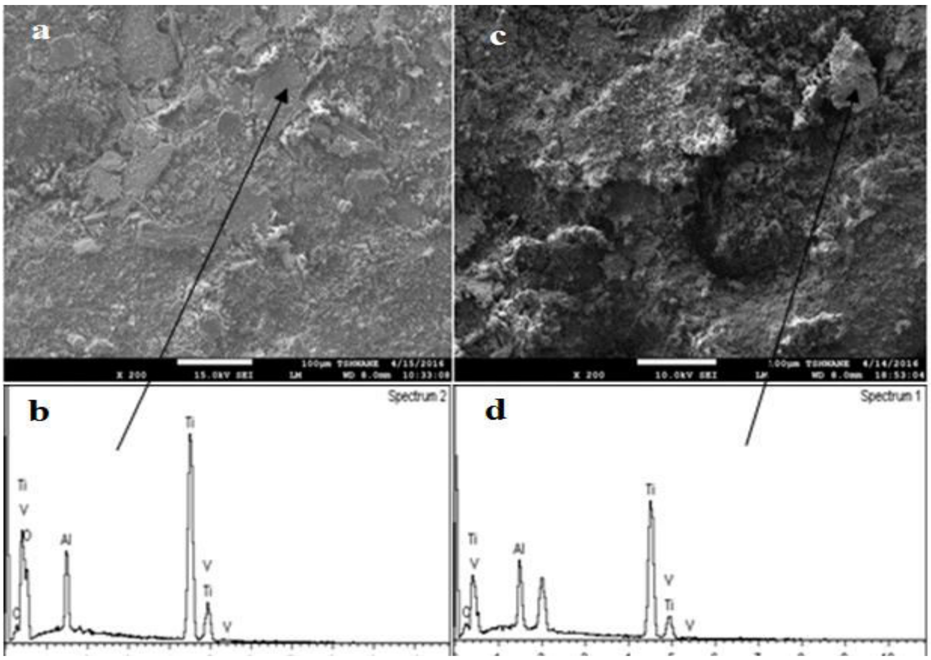

Fig. 6.(a, b) Wear debris and EDS of HB; (c, d) VB specimens at 25 N load.

Figure 6 shows the SEM analysis of wear debris generated under a load of 25 N in HB and VB3 specimens. The debris consist of loose tiny powder debris and mostly consists of flaky chips. Energy dispersive spectroscopy (EDS) analysis of both specimens debris (Fig. 6b and 6d) also confirm that the powder debris and the flaky chips are Ti-rich with no trace of the WC counterface ball. This can only suggest that the wear debris were from the DMLS specimens. The presence of large size flaky chips in the debris could be related with the severity of adhesive wear [12].

4. Conclusion

The phase constitutions and microstructural features of DMLS-processed Ti parts experienced a change from α+β phase typical of Ti-6Al-4V to α, ά, β and presence of TiO and VC. Vertically build (VB3) specimen gave the highest microhardness values and relatively low volume loss at higher applied loads. The wear mechanism is a combination of both abrasive and adhesive with transformation from mild to severe wear.

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