Effect of Laser Power on the Microstructural Behaviour and Strength of Modified Laser Deposited Ti6Al4V+Cu alloy for Medical Application

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ABSTRACT

The excellent biocompatibility property of Grade 5 titanium alloy has made its desirability largely increasing in the field of biomedical. The titanium alloy (Ti6Al4V) was modified with the addition of 3 weight percent (wt %) copper via a laser deposition process using the Ytterbium fiber laser with a wavelength of 1.047 µm. Therefore, this paper presents the effect of laser power on the microstructural behaviour and strength of the modified Ti6Al4V+Cu alloy. The laser powers were varied between 600 W and 1600 W respectively while all other parameters such as the scanning speed, powder flow rates and gas flow rates were kept constant. The melt pool and width of the deposited alloy increases as the laser power was increased. The α-lamella was observed to be finer at low laser power, and towards the fusion zone, Widmanstettan structures were fused and become smaller; and showing an evidence of α-martensite phases. The strength of the modified alloy was derived from the hardness values. The strength was observed to increase initially to a point as the laser power increases and afterwards decreased as the laser power was further increased. The improved Ti6Al4V+Cu alloy can be anticipated for biomedical application.

Keywords: Laser metal deposition, microstructure, microhardness, strength, Ti6Al4V+Cu alloy

1. INTRODUCTION

Today, laser is one of the technologies used commercially by most of the industries to solve different engineering problems. The process of laser technology is very energetic to the field of engineering, medical and in all walks of life. Most laser devices produce intense beams of low divergence light of an electromagnetic radiation ranging from 1 nm to 1000 µm in wavelength, 400 nm to 700 nm in visible spectrum, and 200 nm to 400 nm for ultraviolet light[1]. The modification and repair of most metals has been achieved through the use of laser especially in the aerospace, marine industrial, bio-medicals, chemical, and automotive industrial services. Ti6Al4V alloy is very relevant among other titanium alloys; since it demonstrates a combination of mechanical, physical and corrosion- resistance properties. This alloy is applicable in the emerging biomedical for bone repair, due to its excellent biocompatibility among metallic materials [2, 3]. The enhancements in the mechanical properties of the titanium alloys have generally been accomplished through the addition of one or two alloying compounds [4, 5, 6, 7]. On the other hand, Copper (Cu) has a low chemical reactivity and a greenish surface film coating called patina, which is largely formed on the surface in moist air to protect the metal from further attack [8]. The discovery of copper has shown that the risk of copper insufficiency is much higher that the excess of copper content in the body. It stimulates a warm flow of healing energy and improves the anti-oxidant defence in the body [9]. The addition of copper to titanium alloys allows the manipulation of the mechanical properties through age- hardening [10]. The effect of precipitation strengthening has been utilized in Ti-2.5Cu (in wt.%) over the commercially pure titanium [11]. The work was later extended to titanium alloys containing a variety of other alloying additions with minor composition modification. An experiment was conducted by replacing 4 weight percent (wt. %) of vanadium for copper with the same 4 wt.% of vanadium removed; and this yielded the same results. The Cu experienced the same influence on the β transus temperature as the vanadium; and it did not show direction what so ever on the β transus of Ti6Al4V [12]. The compressive strength and the hardness of titanium alloys were conducted to ascertain the performance of Ti-6Al-1.5V-2.5Cu in comparison to a standard titanium alloy Ti6Al4V by utilizing the precipitation hardening technique in the experiment; however the ductility value was marginally decreased [13]. The mechanical properties of cast Ti-Cu alloys was evaluated with the aim of producing an alloy for dental casting with better mechanical properties than the unalloyed commercially pure titanium. The cast Ti becomes stronger by alloying with Cu; and also showed an increment in the tensile strength and the yield strength over that of the commercially pure Ti [14]. The laser power is proportionally related to the rate of cooling during the solidification of the cladded alloy [15]. During the laser deposition operation, an increase in the laser power leads to a decrease in the layer height, and an increase in the layer width formed [16].

However, this work studied the influence of laser power on the microstructural behaviour and the strength of the modified laser deposited Ti6Al4V and Cu alloy. Here, the laser powers were varied between 600 W and 1600 W while the scanning speed and other parameters were kept constant.

2. EXPERIMENTAL SETUP AND PROCEDURES

The experiment was conducted on a fibre laser at the National Laser Centre, Council of Scientific and Industrial Research (NLC-CSIR), Pretoria, South Africa. The laser is a 2 kW Ytterbium system with a wavelength of 1.047µm and linked to a Kuka robot having a three way nozzle attached at its end effector. The laser system is a diode pumped laser incorporated with dual core fiber optic cables of 400 µm. This feature allows the laser beam to be delivered on the work piece through the delivery device.

2.1. Materials and methods

Two delivery jars were cleaned and prepared for the two powders (Ti6Al4V alloy and Cu powders). The particle sizes of the powders varied between 150 and 200 µm. The powders were fed from the two delivery jars and flow to the nozzle through some connecting hoses. An argon gas was supplied at 10 l/min to provide shielding against oxidation from the environment. Both the laser and the powders flow through the nozzle onto the substrate. The substrate is square plate titanium alloy with a dimension of 102 X 102 X 7.45 mm^3.The substrate was grit-blasted before the metal deposition to disinfect the surface from contaminants. Table 1 shows the experimental matrix used in this present study.

Table 1. Experimental matrix

Sample Label	Laser Power (W)	Scanning Speed (m/min)	Powder Flow Rate (g/min)		Gas Flow Rate (l/min)	
			Ti6Al4V	Cu	Ti6Al4V	Cu
A	600	0.3	4.175	0.32	3	1
B	800	0.3	4.175	0.32	3	1
C	1000	0.3	4.175	0.32	3	1
D	1200	0.3	4.175	0.32	3	1
E	1400	0.3	4.175	0.32	3	1
F	1600	0.3	4.175	0.32	3	1

The samples were labelled from A to F following the change in laser power. In this experiment, the scanning speed of 0.3 m/min and the powder flow rate of 4.175 g/min for Ti6Al4V and 0.32 g/min for Cu were kept constant while the laser powers were varied between 600 W and 1600 W respectively. The cross sections of the samples were mounted in poly fast prior to further characterization. The samples were ground (plain and fine grinding), polished and etched according to E3-11 ASTM standard guide for preparation of metallographic specimens [17].

2.2. Microstructure

Prior to microscopic observation, the Kroll's reagent was prepared for the etchant. It was a mixture of 100 ml H_2O, 2-3 ml HF and 4-6 ml HNO_3 respectively. Each sample was etched for 15 seconds, rinsed under a running tap water and dried off with a hand dryer. The microstructures of the laser deposited samples were observed under the BX51M Olympus microscope at low and high magnifications. The SEM of the two powders was also taken into account to show their morphologies.

2.3. Strength and hardness tests

The microhardness test was conducted on the cross section of each sample from the top of the deposit and towards the substrate. Eight indentations were made on the samples. A load of 500 g and a dwell time of 15 seconds were used throughout the hardness test according E384-11e1 ASTM standard [18]. The hardness values were converted to the strength using equation 1 [19].

$$S = HV \times 9.807 \quad (1)$$

Where S is the strength (MPa), HV is the Vickers hardness.

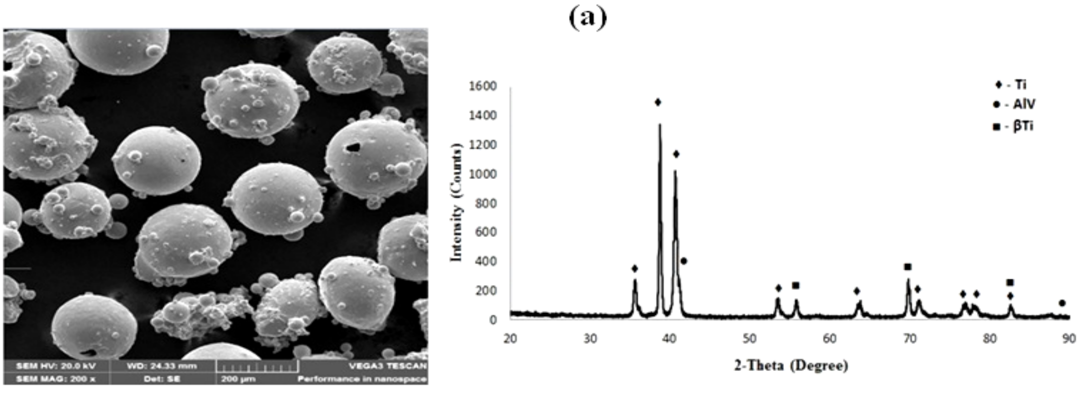
3. RESULTS AND DISCUSSION

The results and the discussion on the microstructure and the relationship between the hardness and the strength of the laser deposited alloys are presented in this section.

3.1. Microstructural evaluation

The SEM and the XRD analyses were conducted on the Ti6Al4V alloy and the Cu powders.

(a)



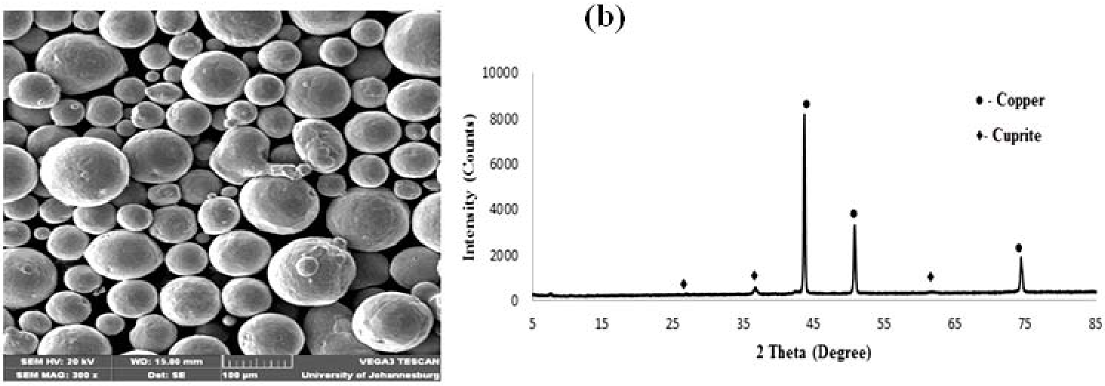
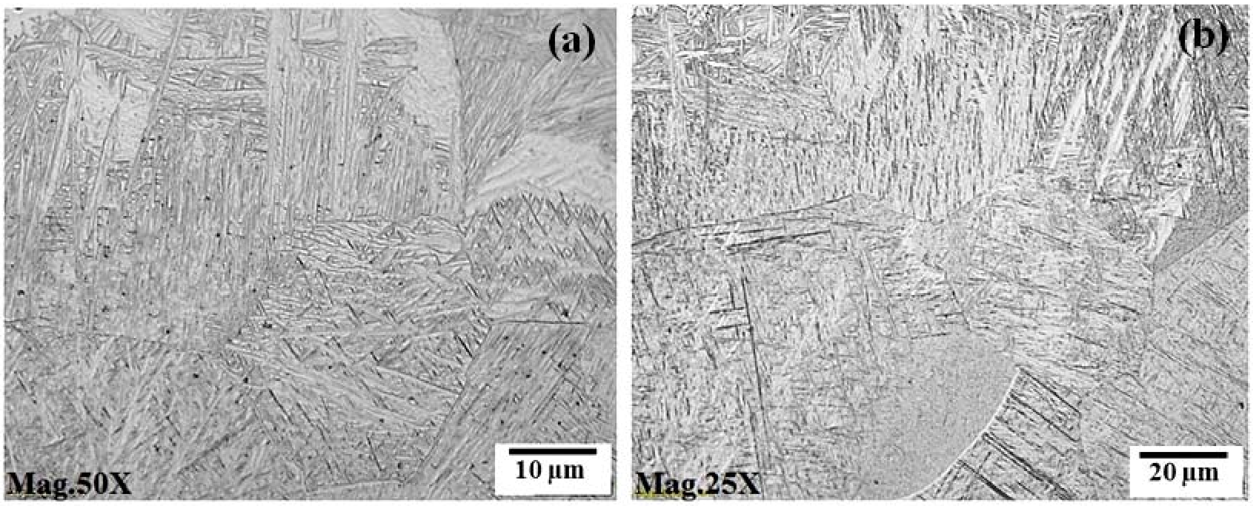


Figure 1. SEM morphology and XRD spectrum, (a) Ti6Al4V powder, (b) Cu powder

Figure 1 (a) show the morphology of Ti6Al4V alloy powder and the XRD spectrum. The SEM analysis shows that the powder was spherical with the agglomeration of dust particles called satellite.

The XRD spectrum of the Ti6Al4V powder, Ti is the major element in the constituent, having the highest peak of 54.2 %. Figure 1 (b) depicts the morphology and the XRD spectrum of Cu powder. The SEM morphology shows that Cu powder is also spherical in shape, and shows denser properties as compared with the Ti6Al4V powder. From the quantitative analysis, Cu shows the major phase within the spectrum; and it was almost 90 % in content.

Figures 2 show the microstructures of the entire laser deposited Ti6Al4V and Cu alloys from samples A to F deposited at laser powers between 600 W and 1600 W respectively.



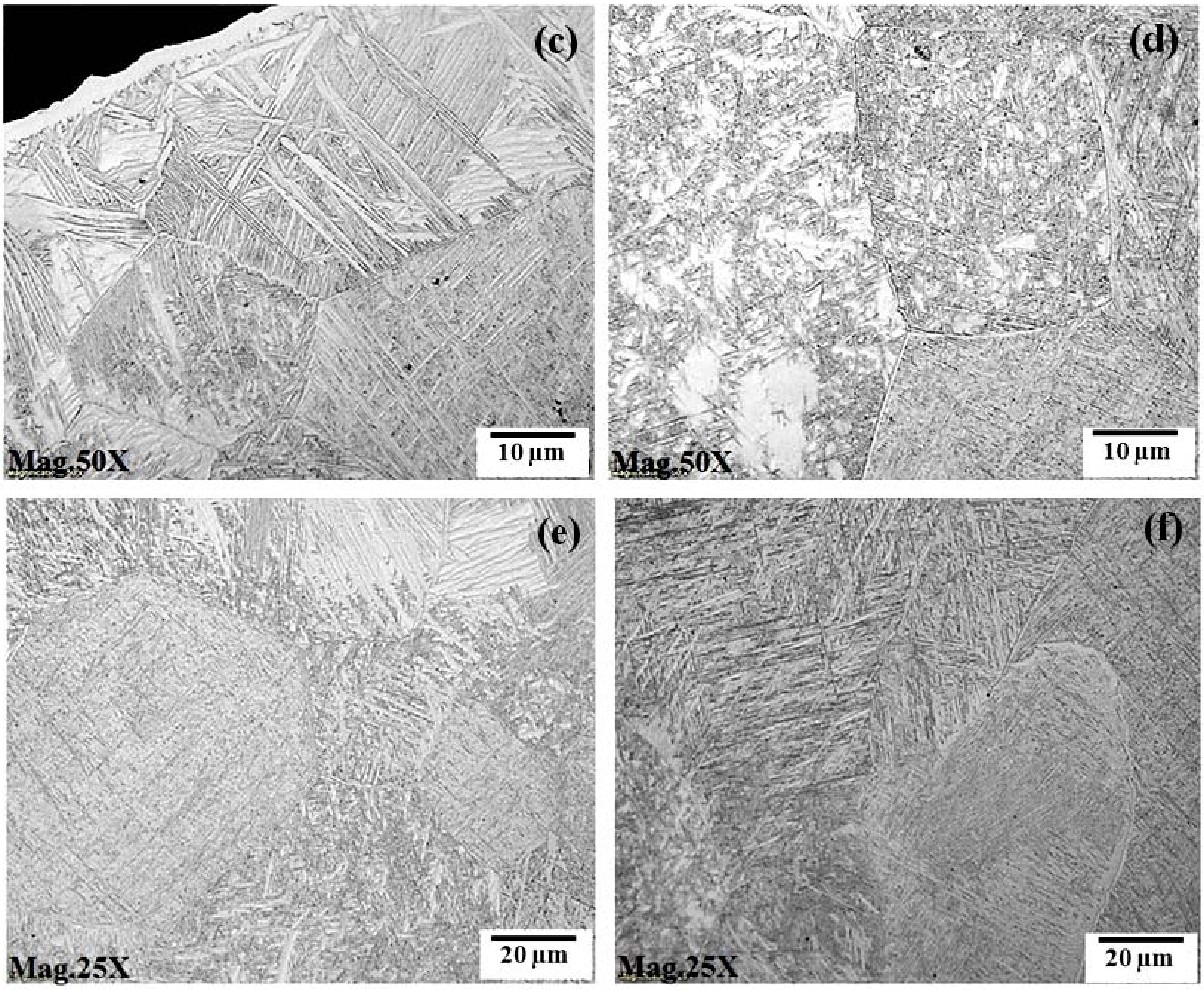
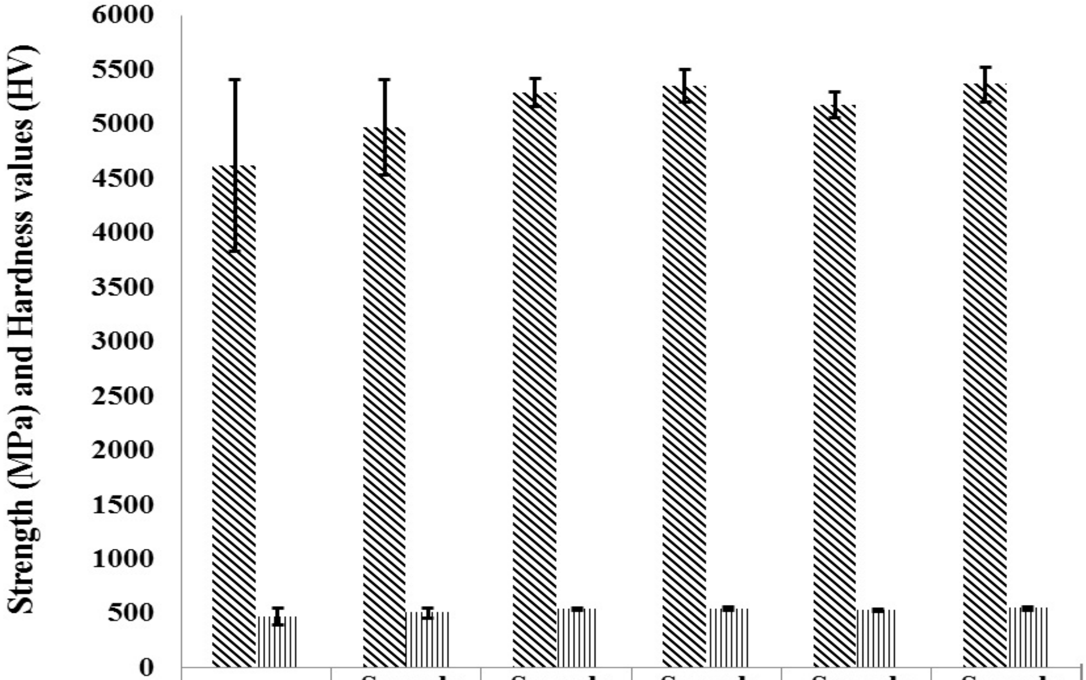


Figure 2. Microstructures of the modified laser deposited Ti6Al4V+Cu alloys (a) sample A at 600 W; (b) sample B at 800 W; (c) sample C at 1000 W; (d) sample D at 1200 W; (e) sample E at 1400 W; (f) sample F at 1600 W

Figures 2 (a) to (f) show the microstructures of the etched samples observed under the microscope. The laser power is proportionally related to the rate of cooling during the solidification of the cladded alloy [15]. During the laser deposition process, an increase in the laser power leads to a decrease in the layer height, and an increase in the layer width formed [16]. However, the laser power is a function of the volume of deposited alloy. Widmanstettan microstructures were observed in almost all the samples. α-Ti lamellae were observed towards the top of the deposited alloy and grows prior the β-phase. Some α acicular microstructures were also observed in sample C deposited at a laser of 1000 W. The morphology and thickness of α lamella influence the mechanical properties of Ti6Al4V alloy [20, 21] . The increase in the laser power tends to create more melt pool and the heat input generated is also increased thereby widen the heat affected zone. The morphology of the α-phase can appear as equiaxed or acicular depending on the cooling rate and as such can lead to different features in the microstructures of the α-phase with different mechanical properties [22]. Thereby promoting the ductility of the alloy; since the cooling rate is at a slow pace, as a result of the high laser power.The different microstructural behaviour is dependent on the laser power, heat input and interaction time. At higher laser power, the Widmanstettan microstructure becomes coarser in combination with the slow cooling rate. Towards the fusion zone and the heat affected zone, the Widmanstettan microstructure becomes finer and fused and they show evidence of α-martensite phases [23].

3.2. Strength and hardness behaviour

Figure 3 shows the plot of the strength and Vickers hardness HV values of the laser deposited Ti6Al4V and 3wt.% Cu alloy.



	Sample A	Sample B	Sample C	Sample D	Sample E	Sample F
Strength (Mpa)	4619	4969	5291	5353	5176	5368
Hardness (HV)	471	507	540	546	528	547

Figure 3. Plot of strength and hardness value of the deposited alloys.

The hardness values of the modified alloy varied between HV 471±81 and HV 541±16. Sample A deposited at laser power of 600 W and scanning speed of 0.3 m/min exhibits the lowest HV value of 471±81 while sample F deposited at laser power of 1600 W and scanning speed of 0.3 m/min displays the highest HV value of 541±16 respectively. As the laser power increases, the HV was also increased up to sample D and later showed a decrease in the HV value. The HV values are almost 10 times the strength of the deposited Ti6Al4V+Cu alloy. The strength is varied between 4619±791 MPa and 5368±160 MPa respectively. A high density boundary generates more plastic deformation that leads to a decrease in the material hardness. The hardness at the fusion zone and towards the heat affected zone is always higher than the hardness at the middle of the deposited alloys. This phenomenon can be attributed to the α-martensite phases present at this region.

4. CONCLUSION

The deposition of the modified titanium and copper alloy through the laser metal deposition process was achieved successfully. The increase in the laser power has an influence in the heat input and the melt pool created in the substrate. α-Ti lamellae were observed to grow from the top of the deposited alloy and towards the β-phase. The morphology and thickness of the α lamella have an influence on the mechanical properties of Ti6Al4V+Cu alloy. Sample F deposited at a laser power of 1600 W exhibits the highest hardness value and strength of HV 541±16 and 5368±160 MPa respectively. This work will be extended to additive manufacturing by building a bone implant prototype for medical application.

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