Material Efficiency of Laser Metal Deposited Ti6Al4V: Effect of Laser Power

Rasheedat M. Mahamood, Esther T. Akinlabi, Mukul Shukla and Sisa Pityana

Abstract— The economy of using Laser Metal Deposition (LMD) process in the manufacturing of aerospace parts depends on the right processing parameters. LMD is an additive manufacturing technology capable of producing complex parts directly from the CAD model data in one single step. LMD is also capable of repairing high value component parts; it is a promising technology for producing aerospace part that will reduce component weight as well as reducing the buy-to-fly ratio. Ti6Al4V is an important aerospace alloy and a very expensive material. This study investigates the influence of laser power on the overall economy of laser metal deposited Ti6Al4V. This was achieved by depositing Ti6Al4V powder on Ti6Al4V substrate at a varying laser power of between 0.4 and 3.0 kW while maintaining the scanning speed, the powder flow rate and gas flow rate at constant values of 0.005 m/s, 1.44 g/min and 4 l/min respectively. The substrate was sand blasted, cleaned with acetone and weighted before the deposition started. After the deposition process, the substrate containing the deposit was cleaned with wire brush and acetone to remove the unmelted powder particles on the surface of the deposit and the substrate, and then reweighed to know the mass of powder that was really deposited. Also, the width and height of the deposit were measured using the vernier caliper and the material efficiency was determined using the set of equations developed. The soundness of the deposits was studied using the optical microscope for the cross section of the samples prepared metallurgically and etched with Kroll's reagent. The study revealed that as the laser power is increased, the powder efficiency is also increased. The deposit width also increases as the laser power is increased. The deposit height on the other hand initially increases as the laser power is increased and started to decrease as the laser power is further increased. The results are presented and fully discussed.

Keywords— Deposition height, Laser metal deposition, Laser power, material efficiency, Microstructure, Titanium alloy.

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I. INTRODUCTION

Laser Metal Deposition (LMD) process belongs to the Directed Energy Deposition (DED) class of an Additive Manufacturing (AM) technique [1]. LMD produces complex parts directly from the three dimensional (3-D) CAD model of the part being produced in a layer wise manner and in one single step [2]. Of all the AM technologies, only the DED of which the LMD belongs can be used to repair high valued components which were usually discarded in the past [3] because of the way it repairs parts without causing damages to the part unlike the traditional manufacturing methods. LMD is a very important and promising technology for the aerospace industry among others. This is because, it can reduce parts weight since there will be no need to assemble parts as complex parts can be produced in one single step. It is also capable of reducing the buy-to-fly ratio [4], that is reducing scrap that can be as high as 80% in some complex aerospace parts when produced by traditional manufacturing method and this is one of the reasons why the cost of aircraft is very high.

Ti6Al4V is the most widely produced and the most widely used titanium alloy in the aerospace industry because of its unique light weight, with high strength and are structurally efficient and are useful in critical and high performance applications such as jet engine parts and air frame components [5,6]. Despite these exciting properties of the Ti6Al4V, they are difficult to process using traditional manufacturing techniques because of the way it reacts with the cutting tool during cutting operation that leads to generation of heat which results in eventual galling of the cutting tool [7]. Laser metal deposition provides an alternative manufacturing technique for processing such material because it is a tool-less manufacturing process and also very flexible.

A lot of research work on laser metal deposition has appeared in the literature [4, 6, 8]. Brandl et al., [4], studied the effect of laser power, scanning speed, and wire-feed speed on the resulting microstructures. They correlated the microstructure of the beads produced to the process parameters and they found that the cross sections of the deposit revealed fundamental microstructure of the laser deposited Ti6-Al-4V. Lu et al., [6] investigated the effect of annealing temperature and time on the microstructural characteristics of laser deposited Ti–6Al– 4V. They observed a unique bi-modal microstructure consisting of coarse primary alpha and fine lamellar transformed beta. Wu et al., [8] studied the effects of laser power, scan speed, powder feed rate on the microstructure of laser deposited Ti–6Al–4V and they discovered that the deposited Ti-6Al-4V long columnar grain structures dominate the microstructures especially at high laser power settings employed. They also found that the degree of the columnar

grain structure also increases with reducing scanning speed with other parameters kept constant.

Material utilisation efficiency is very high in laser metal deposition process just like any other additive manufacturing process because the unspent powder particles can be recovered and reused. Ti6Al4V are very susceptible to oxygen pick up at high temperature [9], therefore the unspent Ti6Al4V in LMD process is not reusable due to contaminations. To fully benefit from the LMD process and also to reduce the cost of aerospace parts manufactured through LMD, there is need to study the influence of laser power on deposition height, deposition width and material utilization efficiency of laser deposited Ti6Al4V because the unspent Ti6Al4V powders are not recoverable due to environmental contamination.

This present study investigates the effect of laser power on the material utilisation efficiency of laser metal deposited Ti6Al4V powder. Also, studied is the effect of laser power on the deposit height and width to establish the optimum laser power that maximizes the powder efficiency and minimizes the degree of dilution for the set of processing parameters considered in this study.

II. EXPERIMENTAL PROCEDURE

Experimental procedure is subdivided into four parts namely: 1. The material preparation, 2. The experimental methods, 3. The weighing, measurements of the width and height of deposition, and the metallographic preparation of the samples for microstructural examinations. 4. Material efficiency determination

A. Material Preparation

Ti6Al4V powder used in this study is 99.6% pure and the particle size range is between 150 and 200 µm. The substrate is Ti6Al4V 5 mm thick square plate of dimension 72 X 72 mm^2 and of 99.6% purity. The shield gas used to carry the powder and to shield the deposit was an argon gas. The substrate was sand blasted and cleaned with acetone to remove the dirt and grease and to aid laser absorption prior to deposition.

B. Experimental Methods

The laser metal deposition process was achieved in this study through a Kuka robot carrying the high power Nd-YAG laser. Also, attached to the end effector of the robot are the coaxial nozzles for delivering the powder from the powder feeder. The laser power was focused on the substrate at a focal distance of 195 mm with a spot size of about 2 mm. The laser creates a melt pool on the surface of the substrate and the Ti6Al4V powder particle carried by the argon gas was delivered into the melt-pool and upon solidification, forms the deposit track. The schematic of the laser metal deposition process is shown in Figure 1.
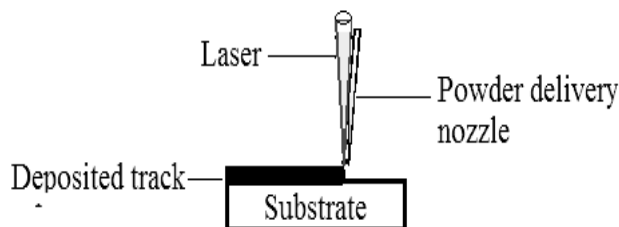

Fig. 1: Schematics of Laser Metal Deposition Process.

The scanning speed was maintained at 0.005 m/s, the gas flow rate at 4 l/min and the powder flow rate at 1.44 g/min. The laser power was varied between 0.4 and 3.0 kW, the sample designation and the processing parameter according to Mahamood et al., [10] is presented in Table 1.

Table 1. Processing parameters [10]

SAMPLE LABEL	LASER POWER (kW)	SCANNING SPEED (m/sec)	POWDER FLOW RATE (g/min)	GAS FLOW RATE (l/min)
A	0.4	0.005	1.44	4
B	0.8	0.005	1.44	4
C	1.2	0.005	1.44	4
D	1.6	0.005	1.44	4
E	2.0	0.005	1.44	4
F	2.4	0.005	1.44	4
G	2.8	0.005	1.44	4
H	3.0	0.005	1.44	4

C. Sample Preparation and Measurements

The substrate was weighed before the deposition process using a chemical balance. A single track of length 60 mm was deposited for each processing parameter. After the deposition process, the substrate was wired brushed and cleaned with acetone to remove all the unmelted powder that clung to the surface of the deposit and the substrate and then re-weighed to know the mass of the powder used up in the deposition process. The height of the deposit above the substrate and the deposit width were measured using the Vernier Calliper.

To observe the soundness of the deposits, the samples were sectioned to reveal the cross section, mounted, ground, polished and etched according to the standard metallurgical preparation of titanium. Optical micrograph by Olympus BX51M was used to observe the etched samples.

D. Determination of Material Efficiency

The difference in mass of the substrate before and after the deposition gives the mass of the powder that was used up during the deposition process and is designated as m_{pf} (g) and is given mathematically as:

$$m_{pf} = m_{sf} - m_{so} \qquad (1)$$

Where m_{sf} (g) is the mass of the substrate after deposition and m_{so} (g) is the mass of the substrate before deposition.

The actual mass of powder (m_{Po} (g)) delivered through the nozzle is given by:

$$m_{po} = p_{FR} \times t \qquad (2)$$

Where P_{FR} is the powder flow rate of 0.005 m/s which is constant and t is the time taken for the deposition.

To determine the time (t) taken for the deposition length (L) of 60 mm long track that were deposited in this study, the following equation was used.

$$S_s = \frac{L}{t} \quad ; \quad t(\text{sec}) = \frac{L}{S_s} \qquad (3)$$

Where S_s (mm/s) is the scanning speed. The material efficiency (μ) is given by:

$$\mu = \frac{m_{pf}}{m_{po}} \times 100 \, \mu \qquad (4)$$

III. RESULTS AND DISCUSSION

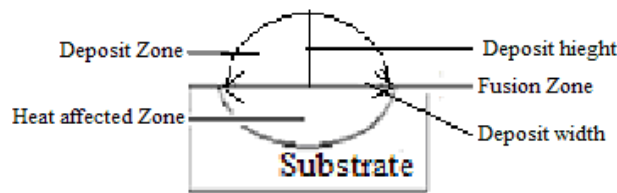The schematic of the deposit's cross section is shown in Figure 2

Figure 2: Schematic of cross section of the deposited track

The schematic shows the deposit height and the deposit width as it was measured by the Vernier Calliper. Figure 3 shows the micrograph of the substrate. The microstructure of the substrate is characterised by alpha (light) phase and beta (dark) phase with the beta phase finely dispersed in the matrix of alpha phase.
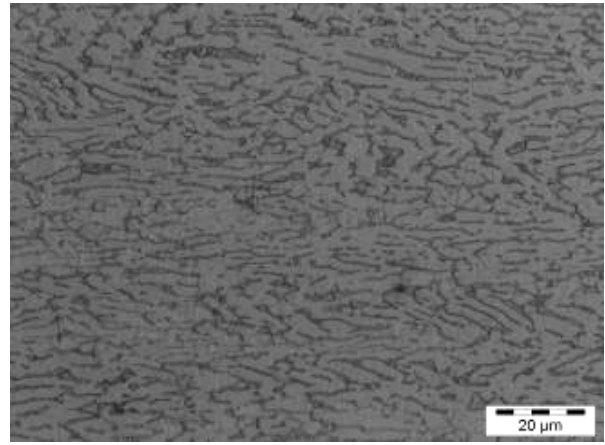

Figure 3: The micrograph of the substrate [10]

The morphology of the Ti6Al4V powder is shown in Figure 4. The particles are characterised as spherical shaped gas atomized powder particles.
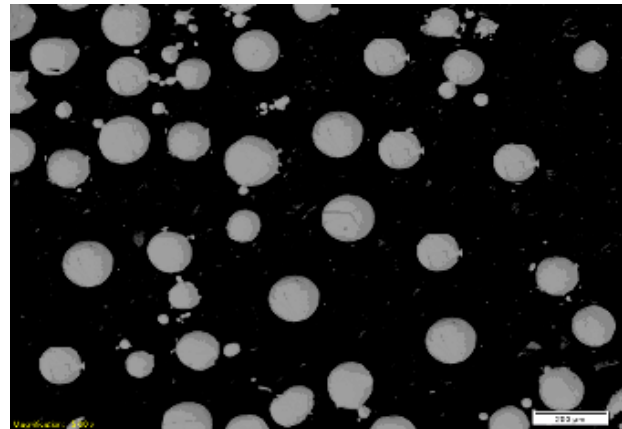

Figure 4: The micrograph of the Ti6Al4V powder

The results showing the measured deposit height and deposit width and the calculated material efficiency using equations 2 to 4 are presented in Table 2.

Table 2. Results showing the deposit height, deposit width and material efficiency [10].

Sample	m_{P_0} (g/sec)	m_{P_f} (g/sec)	Deposited Track Width (mm)	Deposited Track Height (mm)	Powder Efficiency μ (%)
A	0.288	0.10	1.9	0.17	34.72
B	0.288	0.17	2.9	0.38	59.02
C	0.288	0.24	2.94	0.42	83.33
D	0.288	0.26	3.36	0.45	90.28
E	0.288	0.27	4.60	0.40	93.75
F	0.288	0.27	5.74	0.34	93.75
G	0.288	0.28	6.06	0.30	97.22
H	0.288	0.28	7.84	0.26	97.22

The detail of the material efficiency calculation according to Mahamood et al., [10] is given below:
The deposition time (t) is first determined from equation (3). The scanning peed (S_S) of 0.005 m/s (5 mm/s) is constant for all the deposit and the track length (L) of 60 mm is also constant for all the samples. Therefore;

$$t = 60 / 5 = 12 \text{ s} = 0.2 \text{ min}$$

The actual mass of the powder delivered by the powder feeder through the nozzle (M_{so}) is calculated using equation 2.
P_{FR} =1.44 g/min , t = 0.2 min

$$M_{Po} = 1.44 \text{ X } 0.2 = 0.288 \text{ g}$$

Finally, the powder efficiency is calculated using equation 4

$$\mu = (M_{Pf} / 0.288) \text{ X } 100 = 347.2 \text{ } M_{Pf}$$

An important objective of the laser metal deposition process is to have a sound deposit that is fully dense and has a minimum degree of dilution. There is a relationship between the dilution rate and the deposition height, if during the deposition process and the deposit height is reducing instead of increasing, it can be linked to the dilution rate. Dilution occurs when the substrate material mixes with the deposited powder. The dilution is needed for proper bonding to occur between the substrate and the deposit but it needs to be kept minimal so as not to degrade the deposition process. Figure 5 shows the graph of laser power, material efficiency and the deposition height. The powder efficiency is found to increase as the laser power is increased. This is because as the laser power is increased, more powder is melted thereby increasing the powder utilisation efficiency. The deposition height increases initially as the laser power is increased and then started to reduce as the laser power continues to increase. This can be explained thus: at lower laser power, melted powder solidified faster and there is less time for dilution to take place. As the laser powder is further increased, the melt pool gets bigger and the solidification becomes slower causing more substrate material to melt deeper making more mixing of the substrate and the deposited material causing the deposit height to reduce. Therefore, instead of the deposit height to continue to increase as the laser power, it continues to reduce at a very high laser power. The same thing is responsible for the deposit width, the deposit width increases as the laser power is increased.
Figure 5 shows the plot of material efficiency and deposit height against laser power. It can be seen from the graph that the optimum laser power is around 1.5 kW
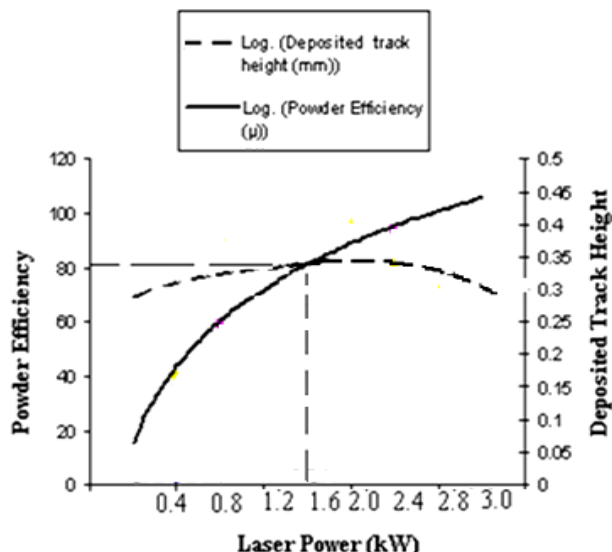

Figure 5: The plot of powder efficiency and deposited height against the laser power

The micrograph of the fusion zone of sample at 400 W is shown in Figure 6. The bonding is not very sound at this low laser power and there is porosity in the fusion zone. The reason for this observation is that at the laser power of 400 W, the melt pool is very small and the solidification is very rapid, not allowing more time for the substrate and the powder to mix properly. This shows that too low laser power with the combination of other processing parameters considered in this study, will result in porous and less sound deposit.
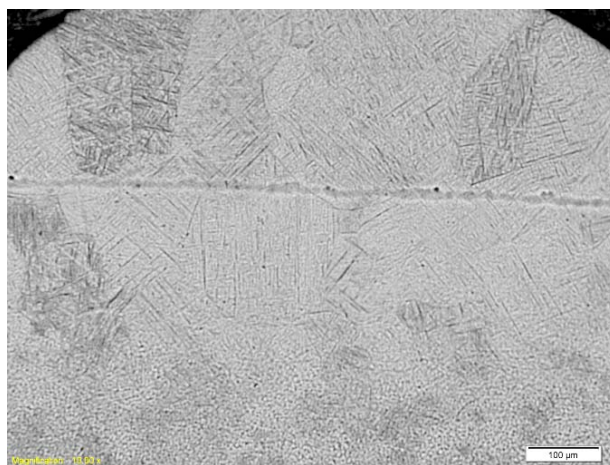

Figure 6: The micrograph of sample at a laser power of 400 W [10]

Figure 7 shows the micrograph of the fusion zone of the sample at a laser power of 0.8 kW. The bonding is very sound when compared to that seen in Figure 6 and there is no porosity because the laser power was high enough to cause proper bonding and fully dense deposit.
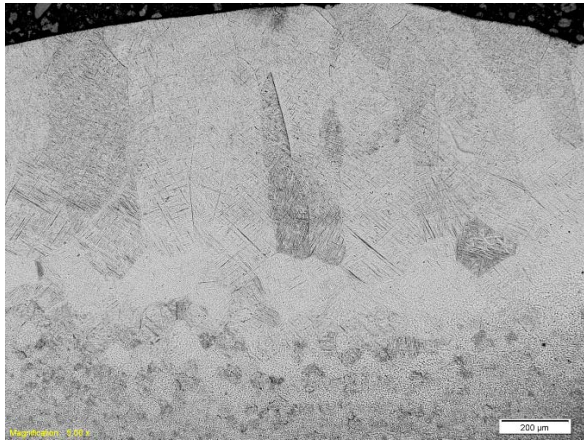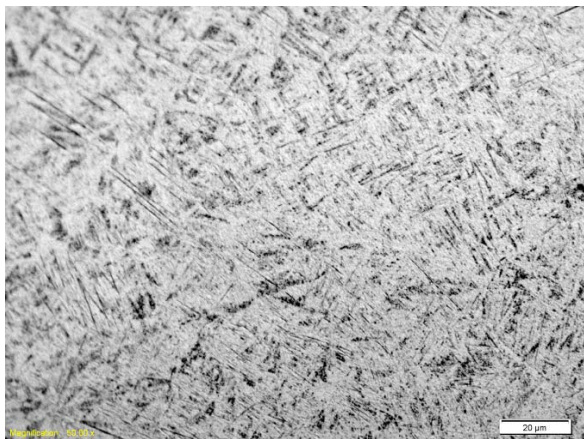
Figure 7: The micrograph of sample at a laser power of 800 W [10]

The micrograph of sample at a laser power of 1 .6 kW is shown in Figure 8a, and that of the sample at the laser power of 2.8 kW is shown in Figure 8b. It can be observed that the cooling rate decreases as the laser power is increased because of the appearance of colony α (see Figure 8b) which is characterised by low cooling rate of Ti6Al4V [4]. Also the density of the acicular α alpha is less in Figure 8b when compared to the one seen in Figure 8a which further confirms that the cooling rate at higher laser power is slower than that at lower laser power.

(a)

(b)

Figure 8: Micrograph of sample at laser power of (a) 1.6 kW (b) 2.8 kW

I V. CONCLUSSION

The Ti6Al4V powder has been successfully deposited on the Ti6Al4V substrate at laser power varied between 0.4 and 3.0 kW while maintaining the scanning speed, the powder flow rate and the gas flow rate at 0.005 m/s, 1.44 g/min and 4 l/min respectively. The effect of varying the laser power on the material efficiency and the degree of dilution has been studied extensively and the following conclusions were drawn from this study.

1. The laser power has influence on the material efficiency. As the laser power is increased, the material efficiency is increased.

2. As the laser power is increased, the deposit width is increased and the degree of dilution is also increased due to more energy input during the deposition process.

3. As the laser power is increased, the deposit height increases initially until the laser power reached the value of about 1.6 kW and the deposit height began to drop as the laser power is further increased in combination of the other processing parameters considered in this study.

4. Optimum laser power of 1.5 kW is achieved in this study that maximized the deposit height, minimized the dilution and maximized the powder efficiency at scanning speed of 0.005 m/s, powder flow rate of 1.44 g/min and the gas flow rate of 4 l/min.

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