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Effect of Laser Power and Powder Flow Rate on Properties of Laser Metal Deposited Ti6Al4V

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***Abstract*—**Laser Metal Deposition (LMD) is an additive manufacturing process with capabilities that include: producing new part directly from 3 Dimensional Computer Aided Design (3D CAD) model, building new part on the existing old component and repairing an existing high valued component parts that would have been discarded in the past. With all these capabilities and its advantages over other additive manufacturing techniques, the underlying physics of the LMD process is yet to be fully understood probably because of high interaction between the processing parameters and studying many parameters at the same time makes it further complex to understand. In this study, the effect of laser power and powder flow rate on physical properties (deposition height and deposition width), metallurgical property (microstructure) and mechanical (microhardness) properties on laser deposited most widely used aerospace alloy are studied. Also, because the Ti6Al4V is very expensive, and LMD is capable of reducing buy-to-fly ratio of aerospace parts, the material utilization efficiency is also studied. Four sets of experiments were performed and repeated to establish repeatability using laser power of 1.8 kW and 3.0 kW, powder flow rate of 2.88 g/min and 5.67 g/min, and keeping the gas flow rate and scanning speed constant at 2 l/min and 0.005 m/s respectively. The deposition height / width are found to increase with increase in laser power and increase in powder flow rate. The material utilization is favoured by higher power while higher powder flow rate reduces material utilization. The results are presented and fully discussed.

***Keywords*—**Laser Metal Deposition, Material Efficiency, Microstructure, Ti6Al4V.

I. INTRODUCTION

LASER Metal Deposition (LMD) is an Additive Manufacturing (AM) process that builds part directly from three dimensional Computer Aided Design (CAD) model in layer-wise fashion [1]. LMD can be used to produce new part, build new structure on existing part and repair existing high valued part [2, 3]. The processing parameters greatly influence the properties of the deposited parts, these parameters include: laser power, scanning speed, powder flow rate and the shield gas flow rate. The properties of the deposit that these parameters influence include: the physical properties (deposition height, width and the surface finish), metallurgical property (macrostructure and microstructure) and the mechanical properties (hardness and strength) [4]. These process parameters interact in the LMD process making the process to be complex and difficult to understand. A lot of work has been reported in the literature to study the effect of these process parameters on the evolving properties [5-9], some of these works considered many process parameters at the same time. For a highly coupled system like the laser metal deposition with lots of interaction in the processing parameters require studying one or two parameters at the same time so that proper understanding can be achieved. Also, controlling one or two process parameters to achieve the required result is much easier than controlling many parameters that heavily interact.

Ti6Al4V is the most widely used aerospace alloy [10] because of its exciting properties that include: high strength to weight ratio, good corrosion resistance and excellent high temperature properties [11]. Despite these excellent properties, titanium and it alloys are difficult to produce using traditional fabrication methods [12] and the use of additive manufacturing method is promising in this regard. AM process builds layer by layer as against shaping by material removal in traditional process resulting in high material wastage. LMD is a very promising AM technology especially in the aerospace industry and it is capable of greatly reducing buy-to-fly ratio. It is expected that some of the unused materials during the deposition process can be reused but it is not possible to reuse Ti6Al4V because of high oxygen pick up at high temperature which contaminates the unused powders. Also, Ti6Al4V is very expensive and this makes it necessary to study the process parameter effect on the material utilization efficiency as well as the properties to fully take advantage of the laser metal deposition process. In this study, the effect of laser power and powder flow rate on microstructure, microhardness, deposition height and width, and material utilisation is fully studied. The aim of this present study is to be able to effectively control these resulting properties by controlling the laser power and powder flow rate.

II. EXPERIMENTAL PROCEDURE

Four different experiments were performed and these experiments were repeated three times each to establish the

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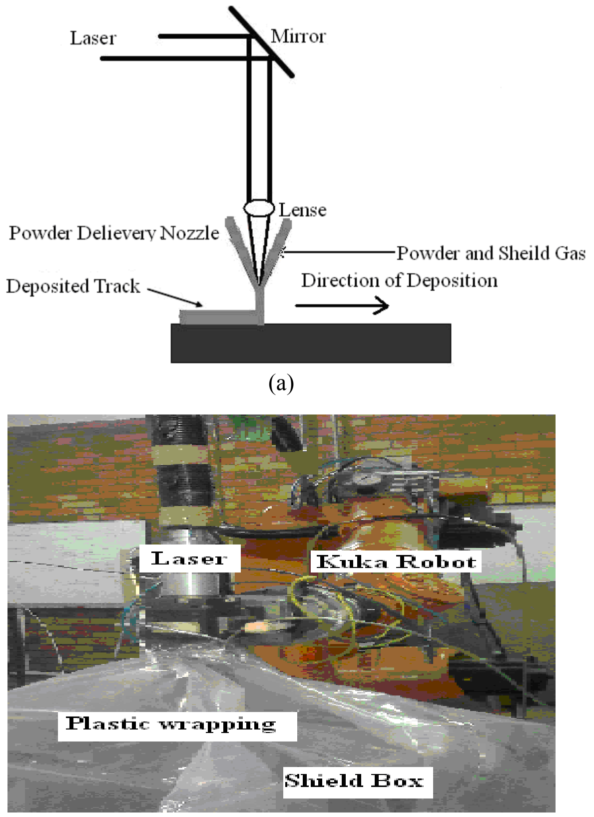
Open Science Index, Mechanical and Mechatronics Engineering Vol:6, No:11, 2012 publications.waset.org/4310.pdf

experimental repeatability making a total of twelve samples produced. 72 x 72 x 5 mm Ti6Al4V plate of 96% purity was used as the substrate and Ti6Al4V powder of particle size ranging between 150-200 µm of 96% purity was deposited on the substrate. The substrate was sandblasted using the Guyson sandblaster and cleaned with acetone to remove dirt and grease.

The laser metal deposition was achieved by using a Kuka robot carrying the 4.4 kW Nd-YAG laser available at the National Laser Centre (NLC) in CSIR Pretoria, South Africa. The robot was attached with coaxial nozzle for powder delivery. The powder was delivered by shielding with argon gas. The deposited surface was protected from environmental attack using glove box fitted with plastic wrapping and filled with argon gas. The schematic of the laser metal deposition process and the experimental set-up is shown in Fig. 1a and 1 b respectively. The laser spot size was maintained at a diameter of 2 mm at a focal distance of 195 mm above the substrate. The scanning speed and the argon gas flow rates were maintained at 0.005 m/s and 2 l/min respectively. The processing parameters are presented in Table I. 60 mm single track each was deposited at each set of the processing parameter.



(a)

(b)

Fig. 1 (a) Schematics of Laser Metal Deposition Process (b) Experimental setup

TABLE I
PROCESSING PARAMETERS

Sample Designation	LASER POWER (kW)	SCANNING SPEED (m/sec)	POWDER FLOW RATE (g/min)	GAS FLOW RATE (l/min)
A	1.8	0.05	2.82	2
B	1.8	0.05	5.64	2
C	3	0.05	5.64	2
D	3	0.05	2.82	2

After the deposition process, the deposits were laterally sectioned, ground and polished according to standard metallographic sample preparation of Titanium [13]. The microstructures were studied using the optical microscope and the microhardness were measured using the Vickers hardness indenter with a load of 500g, dwell time of 15 seconds and a spacing of 15 µm. The substrate was weighed before deposition and after deposition; it was cleaned with wire brush to remove the un-melted powder particles and washed with acetone, and then reweighed using the chemical balance to know the mass of the powder that took part in the deposition. The material utilisation efficiency was determined using the set of equations 1 to 4 according to Mahamood *et al* [14]. The deposition height and width were measured using the Vernier Calliper.

Mass of powder delivered through the nozzle is:

$$m_{P_f} = m_{S_f} - m_{S_0} \tag{1}$$

Where:

m_{P_f} (g) is the mass of powder deposited, m_{S_0} (g) is the mass of the substrate before deposition process and m_{S_f} (g) is the mass of the substrate after deposition.

The scanning S_S (m/sec) speed is:

$$S_S = L / T_D \quad \text{and} \quad T_D = L / S_S \tag{2}$$

Where: T_D (sec) is the time taken for the deposition, L (mm) is the length of each track which is 60 mm.

Mass of powder delivered m_{P_0} (g/sec) during deposition is:

$$m_{P_0} = \left(P_{FR} \times T_D\right) \div 60 \tag{3}$$

P_{FR} is the powder flow rate in g/min and the 60 in equation 3 is a conversion factor for the powder flow rate to g/sec.

The powder efficiency (µ) is:

$$\mu = \left(m_{P_f} / m_{P_0}\right) \times 100 \tag{4}$$

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III. RESULTS AND DISCUSSION

The microstructure of the substrate is shown in Fig. 2 with the alpha and beta grains in hot rolled state. The Ti6Al4V powder were gas atomized spherical shape powder with sizes ranging between 150 and 200 µm. The morphology of the Ti6Al4V powder and the particle size analysis is shown in Fig. 3a and 3b respectively.

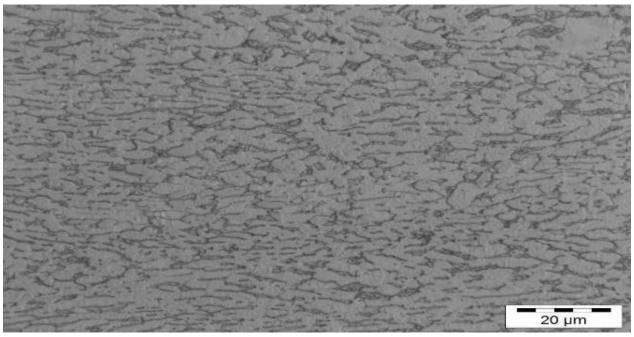
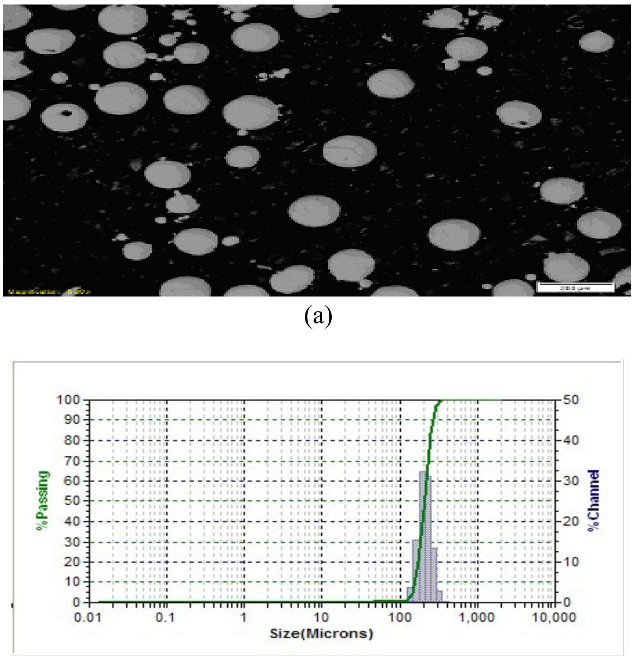


Fig. 2 Microstructure of the substrate



(a)

(b)

Fig. 3 (a) The Morphology and (b) the Particle size analysis of the Ti6Al4V powder [14]

The results of the deposition height, width and the material utilization efficiency calculated using equation 4 are presented in Table 2.

Similar results were obtained for the three sets of the experiments with very little variations which can be attributed to the variation in the atmospheric condition during the experiment. The results presented in Table 2 are the average values. The macrograph of samples A and D and the micrographs of the samples B and C are presented in Fig. 4 and 5 respectively. The graphs of the microhardness are shown in Fig. 6 to be able to compare the microhardness of each sample with that of the parent material.

(a) Sample A at 1.8kW power, and 2.82g/min powder flow rate

(b) Sample D at 3kW power, and 2.82g/min powder flow rate

Fig. 4 The macrograph of the samples A and D showing the deposit layer and the substrate

It was observed that the depositions were fully dense (see Fig. 5) as there is no pore and the binding is metallurgically sound, this was observed in all the samples. From Table 2, the deposition height and width increase as the laser power interesting to note that the material utilization increases as the laser power increases but it decreases as the powder flow rate powder flow rate causes the deposition width and height to increase as a result of more powder being delivered. It is increases; this is because at higher laser power, more powder is melted at constant powder flow rate. So also, the increase in increases. With higher laser power, more powders are completely melted while as the powder flow rate is increased more powder is delivered than can completely be melted resulting in more wastage of material.

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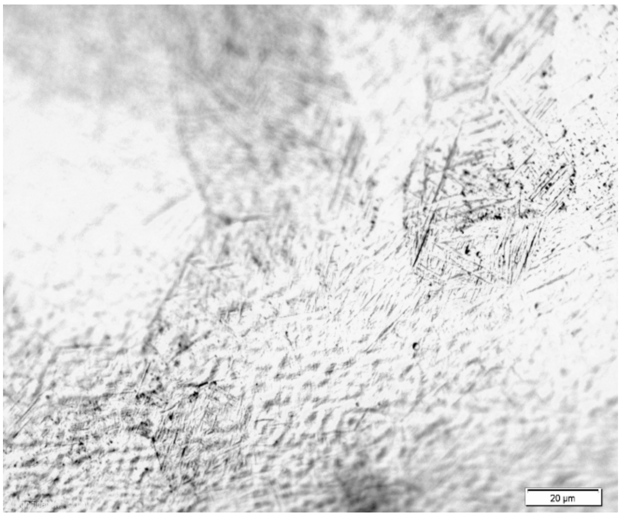
TABLE II
TABLE OF RESULTS SHOWING THE TRACK HEIGHTS, WIDTHS AND POWDER EFFICIENCY

Sample Designation	LASER POWER (kW)	SCANNING SPEED (m/sec)	POWDER FLOW RATE (g/min)	GAS FLOW RATE (L/min)	Deposit width (mm)	Deposit height (mm)	TD	MP (g)	MD (g)	Powder Efficiency
A	1.8	0.05	2.82	2	2.16	0.14	1.2	0.0564	0.03	53.19
B	1.8	0.05	5.64	2	2.22	0.3	1.2	0.1128	0.04	35.46
C	3	0.05	5.64	2	3.24	0.42	1.2	0.1128	0.07	62.06
D	3	0.05	2.82	2	3.0	0.4	1.2	0.0564	0.04	70.92



(a) Sample B at 1.8kW power, and 5.64g/min powder flow rate

(b) Sample C at 3kW power, and 5.64g/min powder flow rate
Fig. 5 The micrograph of the samples B and C showing the deposit layer, the fusion zone, the heat affected zone and the substrate

The macrostructure seen in Figs. 4(a) to 4(d) for samples A to D shows culumnar grains in all the four samples but their population reduces as the laser power increases. This is due to the lower cooling rate at higher laser power resulting in larger globular grains in the heat affected zone on which the columnar prior beta grains grow epitaxially. Also, at low cooling rate, there are fewer neucleation sites leading to fewer culumnar grains as the laser power is increased. The micrographs in Fig. 5(a) to 5(d) for samples A to D also confirms the lower cooling rate as the laser power increases because of the accicular α which appeared more at higher laser power and the matensite decreases as the laser power is increased showing that there is slower cooling rate at a higher laser power. The Vickers microhardness profiles of the substrate and the deposits are presented in Fig. 6.

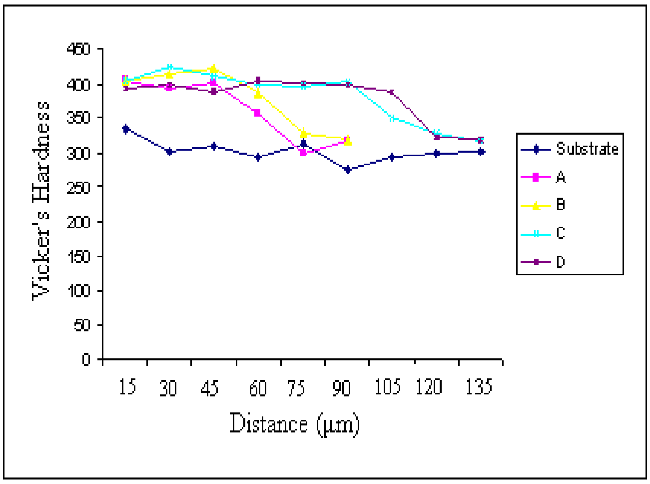


Fig. 6 Graph of the micro hardness of samples A to D and the substrate

The microhardnes results shown in Fig. 6 shows that the microhardness increases with an increase in the laser power especially very close to the substrate because at higher laser power what is happening very close to the substrate is similar to quenching due to wide temperature difference between the sustrate and the deposit and the middle of the deposit is softer because of the low cooling rate at that region that resulted in accicular α (see Fig. 5a to 5d).

IV. CONCLUSION

The effect of laser power and powder flow rate on physical, metallurgical, mechanical properties and material utilisation efficiency of laser deposited Ti6Al4V was studied. An increase in the laser power was found to result in higher material utilisation and higher hardness while an increase in the powder flow rate resulted in a decrease in the material utilisation efficiency. The columnar prior beta grain is also found to decrease with increase in the laser power. The deposit height and width both increased with an increase in the laser power and the powder flow rate. This study revealed that there is limit to which the powder flow rate could be

Open Science Index, Mechanical and Mechatronics Engineering Vol:6, No:11, 2012 publications.waset.org/4310.pdf

increased in order to achieve a higher material utilisation. This will make the laser metal deposition to leave up to its promise of reducing the buy-to-fly ratio of aerospace parts.

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