Effect of Laser Power on Material Efficiency, Layer Height and Width of Laser Metal Deposited Ti6Al4V

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

Abstract— This paper reports the effect of laser power on the optimum utilization of the powder material, the layer height and the width of the laser Metal Deposited Ti6Al4V. The Ti6Al4V powder was deposited on Ti6Al4V substrate using an Nd: YAG laser of varying power between 0.4 kW and 3 kW. The other processing parameters; scanning speed, powder flow rate and gas flow rate were kept constant throughout the experiment. The effect of these laser powers on the layer height and width, the material efficiency and the metallurgical integrity were investigated. The weight of the substrate was taken before and after the deposition. Wire brush was used to remove the unmelted powder particles from the surface of the deposit and cleaned with acetone before it was re-weighed. The height of the deposit above the substrate and width of the layers were measured using the Vernier Caliper. The material efficiency was then determined. Metallurgical samples were prepared for macro and microstructural extermination to observe the soundness of the deposited tracks. All the deposited tracks are metallurgically sound except the sample produced at 400 w with poor bonding to the substrate. It was found that the width of the layer increases with increase in the laser power while the height increases initially then decreases as the laser power increases with the maximum increase occurring at the laser power of 1.6 kW. The powder efficiency also increases with the increase in the laser power with the optimum value at a laser power of 1.6 kW.

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

I. INTRODUCTION

Titanium and its alloys exhibit a very special combination of properties and corrosion resistance [1] that has made them desirable for critical and demanding industrial use. These include: aerospace, chemical and energy industry. Titanium alloy are unique lightweight, high strength alloy that are structurally efficient for critical, high-performance application such as aircraft, jet engine parts and airframe components [2, 3]. Despite these excellent properties, titanium alloys are difficult to machine and alternative manufacturing method is desired to process titanium to bring down the cost of the components produced from the material amongst other issues.

Laser Metal Deposition (LMD), an additive manufacturing technology is an excellent alternative manufacturing method for processing titanium alloys for aerospace application [4, 5]. LMD is a layer by layer process that produces components directly from the CAD data [6, 7]. This is different from the traditional manufacturing process that produces components through series of material removal. The use of traditional manufacturing process to produce aerospace product wastes lots of materials because only about ten percent of the material used are seen in the final product of some critical components. This is referred to as high buy-to-fly ratio [4, 5, 8, 9]; this is one of the reasons for the high cost of aircraft. LMD is a promising alternative because material utilization is on the high side as components are built through addition of material layer by layer. Also LMD can be used to repair high valued component parts that are prohibitive to be repaired and discarded in the past [6, 10]. There are still lots of knowledge required about the underlying physics of LMD process for example, there is need to fully understand the effect of laser power on deposition height above the substrate, the track width, the material efficiency and the metallurgical soundness.

There are considerable works in the literature about LMD process of Ti6Al4V [3-5, 7]. For the aerospace industry to fully benefit from the exciting technology that promises to reduce buy-to-fly ratio by at least 80%, so there is a need to fully understand the role laser power plays in the deposit height above the substrate which can be related to degree of dilution in fully dense deposit. In this study, the effect of laser power on height and material efficiency is investigated to determine the optimum power that maximizes the height and material usage without compromising the metallurgical integrity of Ti6Al4V, an important aerospace alloy using laser deposition of Ti6Al4V powder on Ti6Al4V substrate. The rest of the paper is arranged as follows: section 2 presents the experimental procedure while results and

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discussion are presented in section 3. The concluding remarks are given in section 4.

II. EXPERIMENTAL PROCEDURE

Experimental procedure is subdivided into four parts namely: 1. preparation of the material before deposition, 2. the deposition process, weighing and width and height measurement, 3. material efficiency determination and 4. Metallographic preparation of the samples for macro and microstructural examinations.

A. *Material Preparation*

A commonly used aerospace alloy, Ti6Al4V was used in this study. 72 x 72 x 5 mm Ti6Al4V plate substrate of 99.6% purity was used. Ti6Al4V powder of particle size of 150-200 µm and of 99.6% purity was also used. The substrate was sandblasted and washed with acetone to remove grease and dirt and also to reduce laser reflection and aid absorption of the laser power.

B. *Laser Metal Deposition Process*

The deposition process was carried out using a 4.4 kW Nd-YaG laser that was fitted with a coaxial nozzle for powder delivery. The laser spot size was maintained at approximately 2 mm on the substrate at a distance of 195 mm focal length. The powder was delivered by argon gas at a flow rate of 4 l/min. Figure 1 shows the schematic of the laser metal deposition process. The laser scanning speed was maintained at 0.005 m/sec and the powder mass flow rate at 1.44 g/min. The laser power was varied between 0.4 kW and 3 kW. The processing parameters are presented in Table I. The substrate was weighed before deposition, a single track of length 60 mm was deposited each for each processing parameter. After deposition, wire brush was used to remove all unmelted powder particles that is attached to the surface of the deposit. The surface was also cleaned with acetone and re-weighed to know the weight of actual powder deposited. The height of the deposit above the substrate and the layer width were measured using the Vernier Caliper.

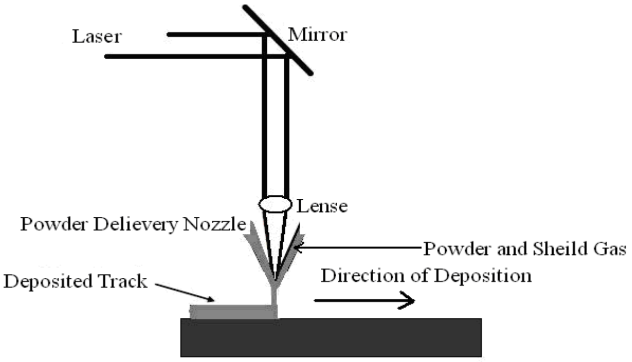


Fig. 1: Schematics of Laser Metal Deposition Process.

Table 1. Processing parameter

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. *Determination of Material Efficiency*

The mass of powder delivered through the nozzle was determined using the following equations.

$$m_{P_f} = m_{S_f} - m_{S_0} \text{ --- (1)}$$

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

The scanning S_S (m/sec) speed is given by:

$$S_S = L/T_D \text{ and } T_D = L/S_S \text{ ---------------------- (2)}$$

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

$$m_{P_0} = (P_{FR} \times T_D) \div 60 \text{ ---------------------------------- (3)}$$

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 given by:

$$\mu = (m_{P_f} / m_{P_0}) \times 100 \text{ --------------------------------- (4)}$$

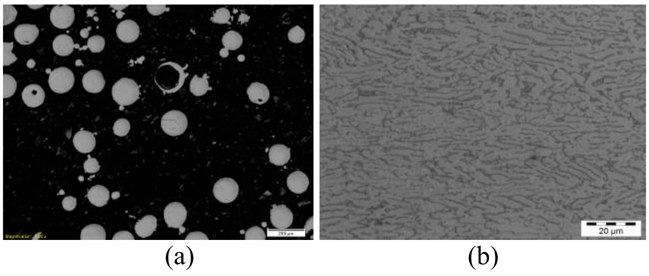
D. *Metallographic Preparation for Morphology and Microstructural examination*

After the deposition process, the samples were cut and laterally sectioned. The cut samples were mounted and metallographically prepared for macrostructure and microstructure observation: ground, polished, cleaned, dried and etched according to standard metallographic preparation technique. Optical Microscope (OM) was used to study the prepared samples.

The following observations were carried out on the prepared samples: macrostructural examination to study the size of the deposited track and porosity if any. Microstructural examination was conducted to further confirm the soundness of the deposited tracks.

III. RESULTS AND DISCUSSION

The morphology of the Ti6Al4V powder used in this research study is shown in Figure 2a. Figure 2b shows the microstructure of the substrate. The material efficiencies for the samples A to H were determined using equation 4. The results are presented in Table II with the processing parameters and the measured width and height above the substrate of samples A to H.The plot of efficiency against laser power is shown in Figure 3.



(a) (b)

Figure 2: (a) Morphology of Ti6Al4V powder (b) Microstructure of the substrate

Table 2. Results showing track heights, widths and material efficiency

Sample Designation	**Laser Power (kW)**	**Scanning Speed (m/Sec)**	**Powder Flow Rate (g/min)**	**Gas Flow Rate (l/min)**	m_{P_0} **(g/sec)**	m_{P_f} **(g/sec)**	**Deposited Track Width (mm)**	**Deposited Track Height (mm)**	**Powder Efficiency μ (%)**
A	0.4	0.005	1.44	4	0.288	0.10	1.9	0.17	34.72
B	0.8	0.005	1.44	4	0.288	0.17	2.9	0.38	59.02
C	1.2	0.005	1.44	4	0.288	0.24	2.94	0.42	83.33
D	1.6	0.005	1.44	4	0.288	0.26	3.36	0.45	90.28
E	2.0	0.005	1.44	4	0.288	0.27	4.60	0.40	93.75
F	2.4	0.005	1.44	4	0.288	0.27	5.74	0.34	93.75
G	2.8	0.005	1.44	4	0.288	0.28	6.06	0.30	97.22
H	3.0	0.005	1.44	4	0.288	0.28	7.84	0.26	97.22

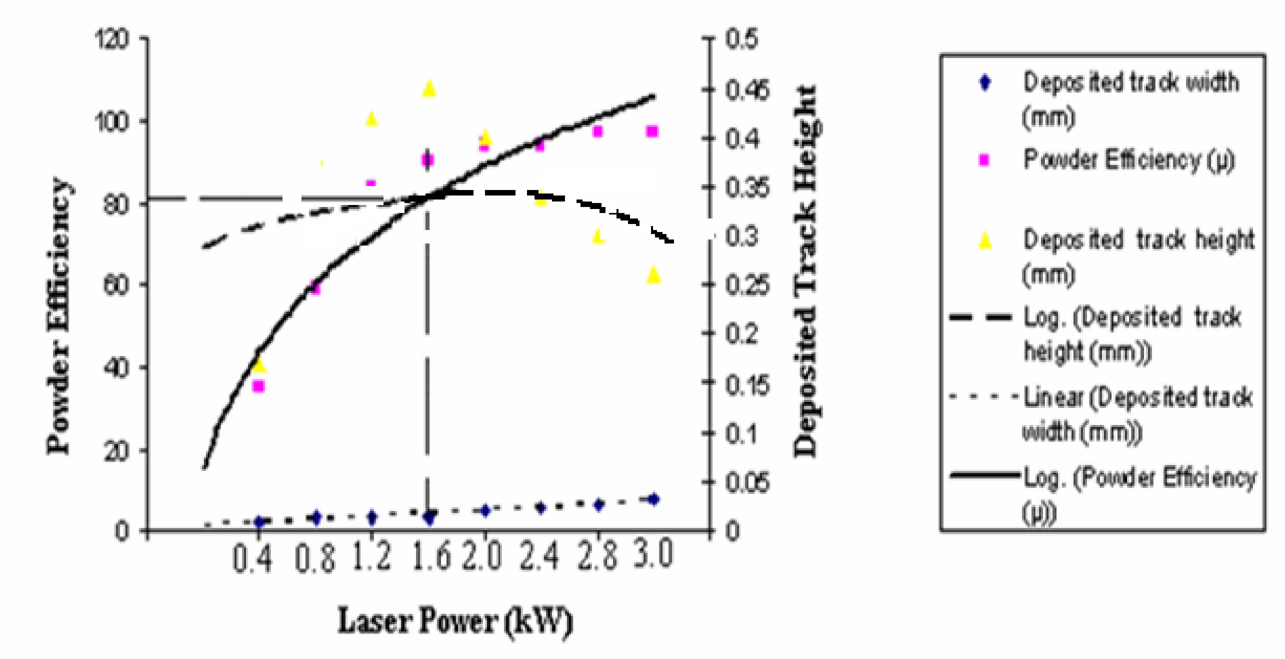
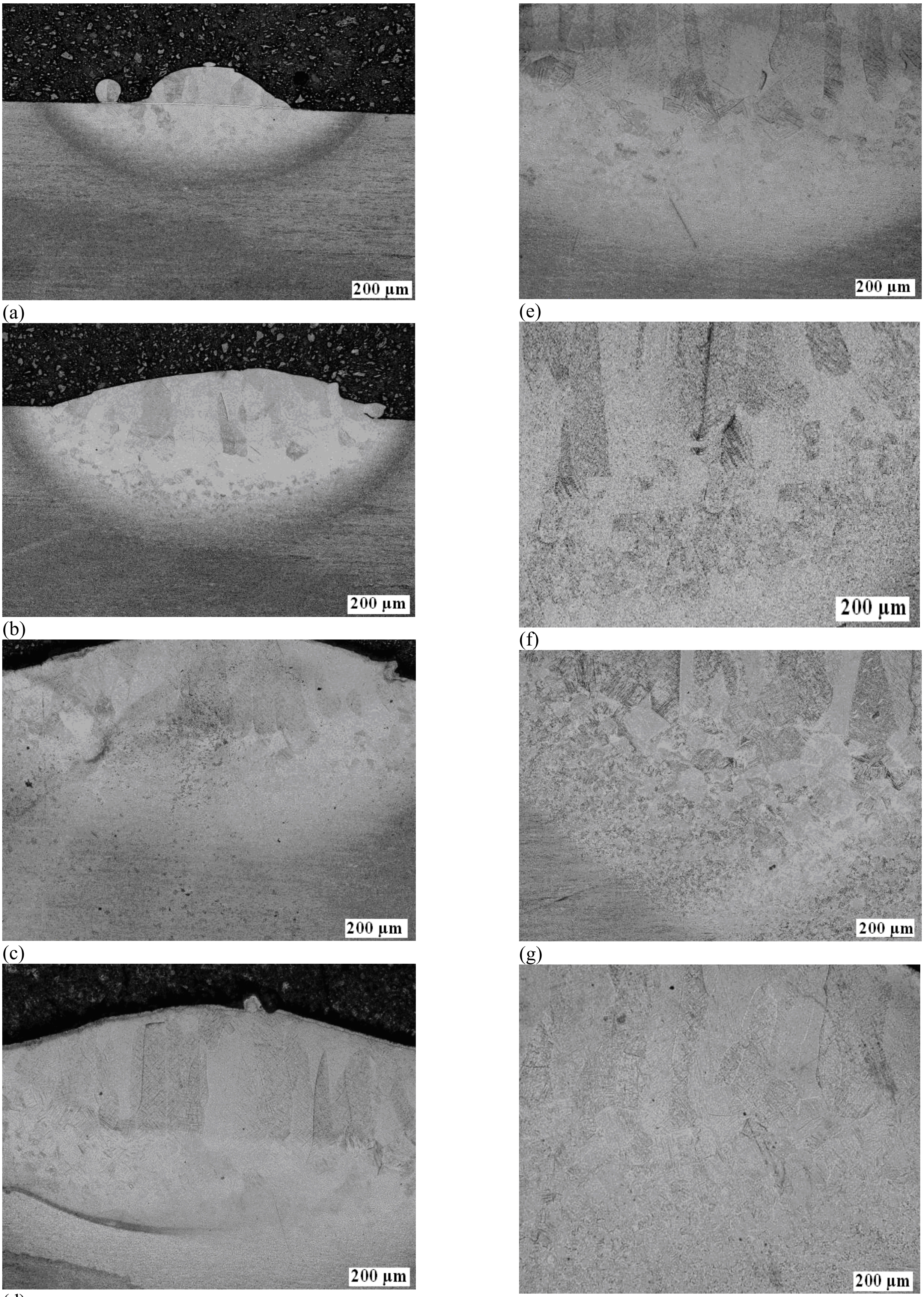


Figure 3: Plots of Powder efficiency, track width and deposit height above the substrate

Height and width were also plotted against the laser power on the same graph to be able to compare and determine the optimum laser power.Appropriate curve fitting techniques were used to draw the graphs in Microsoft excel. It can be seen from the graph that width of the deposited tracks increase with increase in laser power, this is as a result of increase in the melt pool size as a result of increase in laser power [4]. The height of the deposit above the substrate increases at low power as the power increases and begin to decrease when power reaches 1.6 kW. These decreased in height is directly proportional to the degree of dilution between the substrate and the deposited powder as a result of increasing power, increasing melt pool size and decreasing cooling rate thereby causing the substrate material to melt deeper and absorbs more deposited material. This is in agreement with Kodryn and Semiatin [9]. This is also responsible for the increased layer width. Powder efficiency on the other hand tend to increase with increase in laser power, this is due to more powder being completely melted as power increases but this melting continue to increase the melt pool size thereby causing the substrate to also melt more because of slower cooling rate. So instead of the deposited height to increase above the substrate, it is absorbed into substrate thereby increasing the width at the expense of the height above the substrate. The optimum power for the settings used in this study is 1.6 kW as can be seen in Figure 3 which also corresponds to the highest deposit height above the substrate.

The micrographs in Figure (4a) to (4h) show the morphology of all the samples at 50x magnification. All the samples show columnar prior β grains as a result of temperature gradient towards the substrate which is consistent with the literature [8]. Only Figure 4a shows poor bonding of the deposit to the substrate, other samples are fully bonded and fully dense. The poor bonding in Figure 4a can be attributed to low power but the deposit part is fully dense without porosity. Figures 4b to 4h shows sound metallurgical bonding and full dense deposit. The micrographs are taken at the interface of the deposited layer and the substrate. It is can be seen that there is no porosity in all the deposits except for sample A with little porosity at the interface between the deposit and the substrate. The microstructure at the interfaces further confirm that the cooling rate was reducing as the power increases as a result of increased melt pool sizes [4]. The acicular α decreases with increasing power and some appearance of colony α at higher laser power further confirms the lower cooling rate as the power increases which caused the increase in layer width.



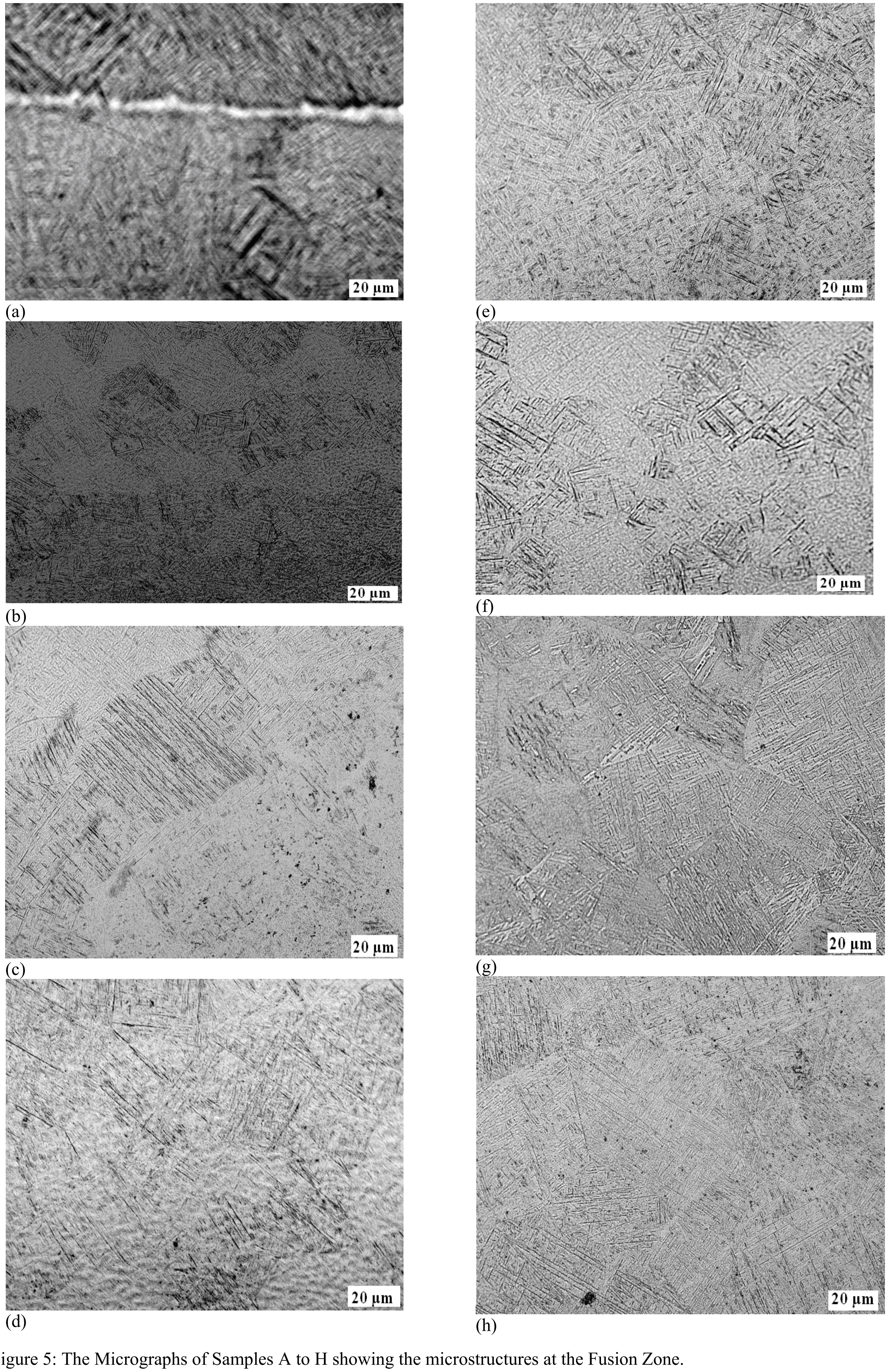
(a) (e)

(b) (f)

(c) (g)

(d) (h)

Figure 4: The Macrographs of Samples A to H: (a) to (d) Showing Deposit area, Fusion Zone and Substrate of Sample A to D (e) to (h) Showing part of the deposit area, the fusion zone and the substrate of samples E to H.



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 5: The Micrographs of Samples A to H showing the microstructures at the Fusion Zone.

IV CONCLUSSION

Ti6Al4V, an important aerospace alloy was deposited on Ti6Al4V substrate at varying laser power between 0.4 kW and 3.0 kW while keeping other processing parameters i.e: the scanning speed, powder flow rate and gas flow rate ,constant using laser metal deposition technique. The effect of the laser power on the width, height of the deposit above the substrate and material efficiency was extensively studied. Laser power has significant effect on the material efficiency as well as the height and width of the deposited tracks. As the laser power increases the track width increases so the efficiency also increases but on the other hand, the height of the deposit above the substrate initially increases as the power goes up and start to decrease from laser power of 1.6kW. Decrease in height is proportional to the degree of dilution taken place as laser power increases leading to deeper penetration of the deposit into the substrate. An optimum power for the set of processing parameter used in this study is found to be at a laser power of 1.6kW.

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