Powder Flow Rate Influence on Laser Metal Deposited TiC on Ti-6Al-4V

Esther T. Akinlabi, *IAENG, Member,* and Stephen A. Akinlabi, *IAENG, Member*

***Abstract*— Laser metal deposition (LMD) presents a suitable substitute for conventional machining of titanium products. It is an additive manufacturing technology used to build prototypes, models, tools, dies and end products. The process is used to manufacture components from materials, which are difficult to machine through conventional methods. Titanium and its alloys are one of the difficult materials to machine since they cause galling on the cutting tool. This paper reports on the material characterization of Laser Metal deposited TiC on Titanium alloy grade 5 and the effect of varying the powder flow rate on the evolving properties of the material. The clads were characterized through microstructural analysis, hardness and degree of porosity. The physical appearances of the samples appeared sound without defect. However, the surfaces of the samples were rough. Furthermore, the average microhardness decreased as the powder flow rate was increased. The microstructural evaluation revealed that the grain size in the deposit zone becomes shorter as the powder flow rate was increased. The microstructure in the heat-affected zone had smaller grain sizes relative to the grain sizes in the deposit zone. In addition, the porosity characterization revealed that the number of pores increases when the powder flow rate increases.**

***Keywords*— Powder flow rate, TiC, and Ti-6Al-4V**

I. INTRODUCTION

Titanium (Ti) has exceptional properties, which makes it desirable to use in manufacturing titanium components especially in the aerospace industry, biomedical, chemical, sports etc. It is currently the most attractive and widely used metals for different industrial applications [1]. Titanium has strength similar to steel but with a weight nearly half that of steel. It is highly reactive with oxygen, nitrogen, carbon and hydrogen [2], and highly difficult to extract, this explains its tendency to explode. However, it is known to have unique excellent properties such as high corrosion resistance especially in sea water, erosion resistance particularly in aggressive environments, capacity to operate under very high temperatures, low specific gravity, high specific strength and stiffness [2].

Titanium is hard to cut which makes conventional machining of titanium difficult to perform. Moreover, conventional machining results in material wastage and in addition Titanium is very expensive. Given that titanium is hard to machine and that it is expensive, an alternative method to manufacture titanium components is required. The significant benefits of Additive Manufacturing (AM) make it a suitable alternative. AM is a manufacturing process of building components in a layer-by-layer fashion or additive layer manner from a CAD model. Additive manufacturing was established in 1987 [3], during the early period, the technology only included the production of prototypes, tools, molds and dies. Nonetheless, since its invention the technology has improved and has since then find different industrial applications [3]. There are many different AM processing techniques, one of which is the Laser Metal Deposition (LMD). Laser metal deposition is not only used for the creation of new parts, it is also used to repair components or to add a structure to a structure of an existing component. The benefits of laser metal deposition involve rapid production of tools, molds and dies. It is also very relevant to surface engineering. Moreover, laser metal deposition is beneficial for the repair and restoration of damaged components. Due to these advantages, LMD has improved from making only prototypes, models, tools, molds and dies, but now used in the production of end products. LMD is also responsible for producing components with complex geometries, which are otherwise impossible to manufacture using conventional machining processes [4]. Figure 1 is a schematic of the laser metal deposition process.

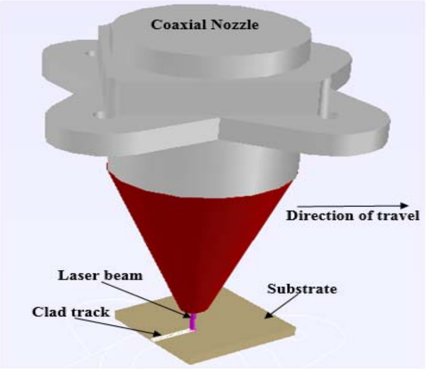

Fig. 1: Schematic of laser metal deposition process

Titanium alloys are widely utilized in the aerospace industry because they form part of the lightweight metals. Ti-

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Esther T. Akinlabi is an Associate Professor and Head of Department with Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa, 2006. (Phone: +275592137; E-mail:etakinlabi@uj.ac.za).

Stephen A. Akinlabi is with the Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa. (E-mail: stephenakinlabi@gmail.com).

6Al-4V is the most frequently used titanium alloy and has a variety of applications. However, like all titanium alloys, Ti-6Al-4V is difficult to machine because of its low thermal conductivity and volume specific heat resulting hence, cutting at high temperature during machining [5]. Ti-6Al-4V maintains strength at high temperature as such requires high machining forces. Hard tools are not suitable for machining titanium alloys due to chemical similarities, which causes chemical reaction and wear in the cutting tool [5]. One of the ways to combat machining challenges related to Ti-6Al-4V is additive manufacturing.

The advent of the AM process as an alternative manufacturing technique is of immense and significant benefits over the conventional approach of manufacturing process, made academics and researchers to closely study the possibility of improving the process and the operation parameters. Akinlabi *et al.*, [6] investigated the effect of scanning speed on material efficiency while keeping other process parameters constant. The scanning speed was varied between 0.01 and 0.1 m/s. The investigation revealed that the optimum scanning speed exists at 0.01 m/s with an efficiency of 90.43% below and above this scanning speed the powder efficiency will drop. Similarly, Pityana *et al.*, [7] conducted an investigation on the effects the gas flow rate and powder flow rate on properties of laser deposited Ti-6Al-4V. The gas flow rate was varied between 2.88 and 5.76 g/min while the laser power was kept constant between 1.8 KW and the scanning was at 0.005 m/s. The results revealed that the results indicated that the track width, track height and deposit weight decreases as the gas flow rate increases because of the higher disturbance in powder flow path which is caused by high gas flow rate. Furthermore, Kong et al., [8] conducted a study on the effect of average powder particle size on deposit quality, surface finish and powder deposition efficiency using direct laser metal deposition. Five samples of Inconel 625 powder with a range of particle sizes were used. The results obtained revealed that for the Inconel 625, the average particle size has a direct and indirect effect on the deposit height and efficiency. In addition, smaller particle sizes can be focused more easily, hence, consequently yield better efficiencies and larger deposits. However, very small particle sizes causes powder delivery and flow problems as a result decreasing the deposit height and efficiency. Furthermore, it is important to note that the powder size is a critical variable in optimizing laser metal deposition.

The effect of process parameters on laser deposited Ti-6Al-4V was conducted by Davis [9]. Due to detrimental effect of oxygen on titanium, oxygen content is one of the main important deposition properties that were monitored. Likewise, the powder efficiency build rate and build height of each layer are properties with strong influence on the laser deposited titanium. The process parameters varied includes the laser power, CNC velocity, gas flow rate, powder flow rate and deposition geometry. The results obtained showed that increasing the laser power enhances the powder efficiency and the build rate. However, an increase in laser power affects the oxygen pickup. Furthermore, the results also proved that increasing the powder flow rate and decreasing the gas flow rate consequently improved the deposition properties. In addition to the studies of the effect of the processing parameters on the deposited material, Mahamood *et al.*, [10] investigated the effect of laser power and powder flow rate on the properties of laser metal deposited Ti-6Al-4V. In this study, four sets of experiments were conducted to establish repeatability using laser power of 1.8 KW, powder flow rate of 2.88 g/min and 5.67 g/min keeping gas flow rate constant at 2 l/min and scanning speed constant at 0.005 m/s. The results on the physical properties revealed that the width and the height of the deposit increased with increasing laser power and increased in powder flow rate. In addition, the material utilization was favored by high power whilst high powder flow rate decreases material utilization. In this paper, the influence of the rate of powder flow rate on titanium carbide deposited on titanium grade 5 was investigated and reported.

II. EXPERIMENTAL SETUP

The Experimental work was conducted at the laser facility of CSIR in Pretoria. Prior to the laser metal deposition (LMD) process, the substrate was sand blasted in order to remove dirt on the surface of the plate. The LMD process was achieved by using ytterbium laser system (YLS-2000-TR) with coaxial powder injection nozzles. A KUKA robot was utilized to carry the laser and also responsible for controlling the deposition process through the computer system. The laser created a melt pool and then the coaxial powder nozzle injected the titanium carbide powder into the melt pool in an Argon controlled environment as shielding gas to protect the deposit from oxidation. Seven layers were deposited onto the substrate all at different powder flow rates from 0.5 to 3.5 g/min at a step of 0.5, while the laser power was set to 1400 W. The gas flow rate was kept constant at 2 l/min and a scanning speed of 0.6 m/min. Figure 2 shows a photograph of the layers deposited on the substrate. Ti-6Al-4V substrate with dimensions of 102 x 102 mm^2 was used. The thickness of the substrate was 7.45 mm.

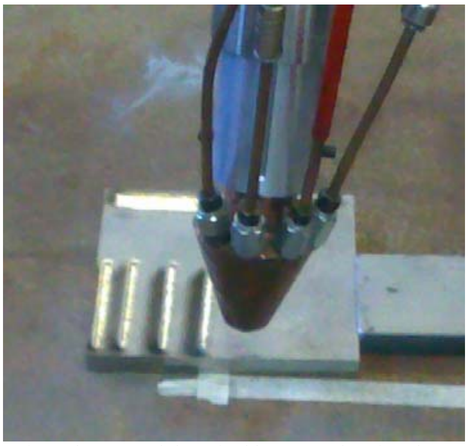

Fig. 2: laser metal deposited layers on the Ti-6Al-4V

After the deposition process, the deposited 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 (Olympus BX51M) was used to study the microstructures of the prepared samples to confirm the soundness of the deposited tracks. The macrostructural examination was conducted to study the size of the deposited track and possible porosity.

III. RESULTS AND DISCUSSION

The results obtained through material characterization are presented in this section. These include the microhardness, microstructure of the deposited samples, the height and width of the deposited TiC and porosity characterization.

A. Physical appearance of the clads

The physical appearance of the substrate with seven laser metal deposited layers is shown in Figure 3. Seven layers were deposited on the substrate at different powder flow rates.

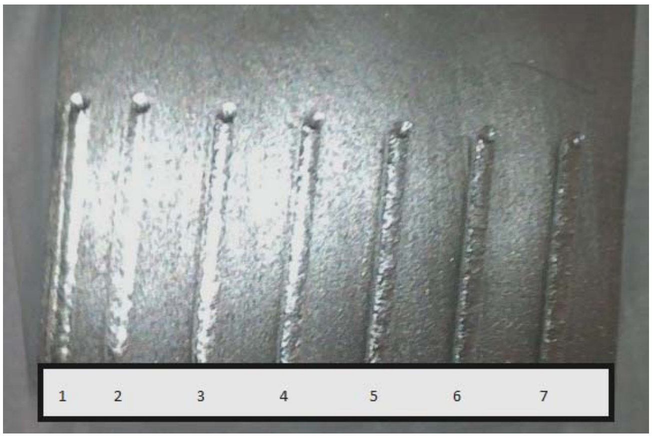

Fig. 3: Physical appearance after laser metal deposition

All the deposited layers appeared sound without any visible defect. A closer look at deposits one and two appeared smoother than deposit three to seven. It was further observed that deposit five to seven had a rough surface finish. Also, comparing the height, the first deposit through to the seventh deposit, a fairly increased in the height was observed and the highest being the seventh deposit, this was anticipated due to the increase in the powder flow rate. Further measurement of the heigh and width of the deposited layers was conducted with Olympus BX51 optical microscope and is presented in Table 1.

TABLE 1
HEIGHT AND WIDTH OF EACH DEPOSIT

Samples	Height (µm)	Width (µm)
1	61.88	1510.33
2	65.34	1594.04
3	74.80	1613.21
4	84.54	1680.32
5	86.36	1717.05
6	114.92	1729.93
7	155.76	2116.38

Table 1 shows that the height and the width of all the samples increases as the powder flow rate was increased. This is attributed to laser-material interaction owing to the fact that as the powder flow rate increased, more powder were deposited during the cladding, yet the laser power was still able to cope with the deposition to achieve an increasing geometry. However, this does not necessarily correspond to the inherent properties of the clads.

B. Microstructures of the deposited zone

The microstructure of sample seven was evaluated and Figure 4 shows the microstructure of deposited area of sample seven produced at a powder flow rate of 3.5 g/min.

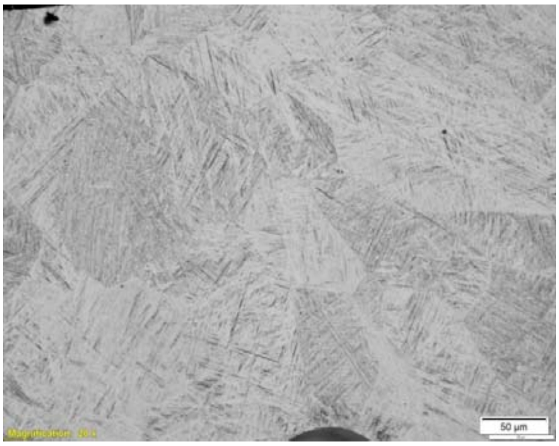

Fig. 4: Microstructure of the deposited zone of sample seven

The microstructure indicates two phases, the beta phase and the alpha phase. The beta phase is characterised by the dark grains and the alpha phase is characterised by white grains. The beta phase was observed scattered in the matrix of the alpha phase. The microstructures of all the seven samples were compared using the optical microscopy and found to be similar. However, a constant laser power and scanning speed during the deposition resulted in constant amount of energy in the heat affected zone.

C. Porosity characterization

Although the physical appearances of the clads appear sound, the inherent evolving properties were investigated to ascertain the optimum setting within the range of process parameters considered. The porosity characterization result is presented in Table 2.

TABLE 2
POROSITY CHARACTERIZATION RESULT

Sample	Porosity (%)	Pore Count	Pore Density (mm^{-2})	Maximum Pore size (μm)
1	0.04	4	0.80	34.86
2	0.41	5	0.96	74.20
3	0.34	6	1.46	76.22
4	2.31	14	3.60	97.35
5	0.93	37	9.10	161.16
6	0.52	84	19.46	187.02
7	0.62	119	27.57	215.45

According to Table 2, it was observed that the pore count increases as the powder flow rate increases, this is attributed to the fact that the amount of powder delivered increases as the powder flow rate increases and it takes longer to solidify the melt pool. In addition, the pore density also increases with an increase in the powder flow rate. The maximum pore sizes measured were as a resulted of the unmelted powder entrapped in the clad zone during solidification. From the results obtained, lower powder flow rates need to be considered to optimize the system for fully dense defect free clads for structural engineering applications.

D. Microhardness profiling

The result of the average of the microhardness profile of the clads and the substrate is presented in Table 3.

TABLE 3
AVERAGE MICROHARDNESS RESULTS FOR EACH SAMPLE

Samples	Average Microhardness
1	387,3
2	385,9
3	375,7
4	356,8
5	369.8
6	369,2
7	349,8
Parent Material	332,9

A fairly uniform pattern was observed across the measured average microhardness of the cladded zone from sample one to sample seven indicating homogenous distribution of the profiles. However, sample one produced at the lowest powder flow rate is the hardest which can be attributed to the fact that all the powder delivered were adequately melted resulting in the martensitic structure, hence the hard structure.

IV. CONCLUSION

The effect of varied power flow rate of TiC powder deposited on Ti6Al4V substrate during laser metal deposition was successfully studied. The results obtained from material characterization were consequently presented and discussed. The physical appearance of the samples appeared sound without defect. However, the surface of the samples was rough. The microstructural evaluation revealed that the alpha-beta phases with martensitic structure due to the effect of the heat from the laser during deposition. The hardness of the clad zone had homogenous distribution. In addition the porosity characterization revealed that the number of pores increases as the powder flow rate increases. A further study with lower powder flow rate is required to fully optimize the system for defect free clads.

A. Abbreviation and Acronyms

AM – Additive Manufacturing
LAM – Laser Additive Manufacturing
LMD – Laser Metal Deposition
PM – Parent Material
Ti6Al4V – Titanium Alloy Grade 5
TiC – Titanium Carbide

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