Characterization of Functionally Graded Commercially Pure Titanium (CPTI) and Titanium Carbide (TiC) Powders

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***Abstract*— Functionally Graded Materials (FGM) are advanced materials fabricated using additive manufacturing techniques. It belongs to a class of advanced material characterization in which the properties of the material composition is varied. The resulting property of the composite is always different from the properties of the individual material employed in the formation of the composite. They are known to also exhibit good mechanical and chemical properties and as such, are used for different industrial applications. One of the techniques employed in the fabrication of FGMs is called Laser Metal Deposition (LMD) technique. It uses laser beam to melt powder material on a substrate forming a melt pool that solidifies upon cooling. This paper reports on the material characterization of functionally graded Titanium and Titanium Carbide (TiC) powders deposited on Titanium substrate by laser metal deposition approach. The formed deposits were fabricated by varying the processing parameters such as laser power, scanning speed and the powder flow rate. From the result obtained, the microstructures showed that the laser power has much influence on the grain growth of the material. In addition, with the SEM analysis of the microstructure since the percentages of the titanium and titanium carbide were varied, it was observed that the sharp boundaries of the Titanium Carbide were reduced greatly and this resulting effect can be attributed to the thermal effect of the laser. The microstructures further revealed that as the percentage of TiC decreases, it becomes more difficult to see the TiC as a different material in the composite, emphasizing this as one of the best characteristics of functionally graded materials, which is the elimination of sharp interfaces and layers. Furthermore, it was observed that the laser power has great influence on the evolving hardness of the material compared to the TiC content.**

***Index Terms*— Functional Graded Materials, Laser Metal Deposition, Microstructure, Micro-hardness, Titanium and Titanium Carbide**

I. INTRODUCTION

Titanium and its alloys are widely used in the aerospace industry [1]. Titanium and its alloys generally possess excellent properties, such as high-strength-to-weight ratio, high temperature strength, and excellent corrosion resistance. Despite these excellent properties, Titanium generally have poor wear resistance property [2-4]. Hence, the serious challenges in processing this material using traditional fabrication methods [5], some of these challenges include galling of the cutting tool and the generation of high temperatures at the cutting tool edge [5], hence, the need for alternative manufacturing technique. In addition, it was found that there is great need for surface modification of parts made from titanium to overcome this shortcoming, especially in applications requiring the surface of the part making contact with other surfaces. A mixture of Titanium and Titanium Carbide (TiC) composite in Metal Matrix Composite (MMC) form has been reported in the literature to provide better surface enhancements for Titanium and its alloys [6-10].

Laser Metal Deposition (LMD), an Additive Manufacturing (AM) technique is the recommended technique for processing Titanium and its alloy because it addresses most of the problems of the traditional manufacturing methods [11], since AM is a tool-less process. In addition, AM technology is a promising aerospace manufacturing technique [12] as it has the potential of reducing the buy-to-fly ratio [13] and it is useful for the repair of high valued parts [14-15]. There are various methods for coating surfaces of materials, some of them includes chemical vapour deposition, physical vapour deposition, spraying, etc. but the Laser Metal Deposition (LMD) process, is an additive manufacturing process and it is believed to have a greater advantage when compared to other deposition processes. Some of the advantages of using the LMD process include the ability to produce parts directly from the 3-Dimensional (3D) CAD model of the part with the required surface coating in one single step, as against only coating achievable with other surface coating techniques. Another important advantage of the LMD process is in its ability to be used to repair existing worn out parts that were not repairable in the past [16]. Also, complex parts can be produced with the LMD without requiring later assembly, since the part can be made as one single component, this will greatly reduce the buy-to-fly ratio of aerospace parts [17-18].

The major LMD processing parameters that influences manufactured components properties includes the laser power, scanning velocity, powder flow rate and the gas flow rate. These process parameters are highly interactive in nature and this makes the LMD process a very sensitive system. In view of the sensitive nature of the system, understanding the processing parameters and its effect on the resulting properties will help in effectively controlling the resulting properties. The effect of the processing

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parameters on the properties of laser deposited materials has been reported in the literature [19-22].

Mahamood et al., [4] in their study found that as the scanning velocity was increased, the wear resistance performance also increased, until the scanning velocity of 0.065 m/s, after which the wear resistance performance began to experience a decrease. At low scanning velocity, there were less unmelted Carbide particles in the microstructure due to more melting of the TiC powder taking place, hence the low wear resistance behaviour obtained. A similar work conducted by Akinlabi et al., [7] also revealed that the optimum scanning speed exists for this study at 0.01m/sec, above and below which the powder efficiency will drop. Benjamin et al., [23] conducted a feasibility of laser metal deposition for re-filling milled grooves for repair applications. Stainless steel and titanium-alloy were employed. Different U- or V-groove shapes were rebuilt without defects and good side-wall fusion, as long as the groove is wide enough for good powder jet accessibility. A deposition strategy was developed and this consequently leads to the deposition of defect-free layers without manual adjustment. Hence, the Laser metal deposition technique shows that there is a high potential for an automated repair process.

Against this background, this investigation focuses on the influence of the processing parameters on the structural integrity, microstructure, microhardness, as well as the wear resistance behaviour of CPTi/TiC composite using the LMD process.

II. EXPERIMENTAL SETUP

The experimental investigation was conducted using a 4.4 kW Nd: YAG laser with a Kuka robot attached to it. Attached to the robot's end effector is the coaxial powder delivery nozzle system. The two powders (CPTi and TiC powder) were placed in a separate hopper of a dual hopper powder feeder. The laser beam diameter was maintained at approximately 2 mm at a focal distance of 195 mm to the substrate. Argon gas was used as a shield to the powder as well as the deposit using glove box to keep the oxygen level below 10 ppm. The deposition process was achieved by feeding the powders into the melt pool created on the substrate by the laser. The experimental setup employed is shown in Figure 1.

Fig. 1: Experimental Setup

The substrate employed in this investigation is a hot rolled 5 mm Titanium alloy grade 5 (Ti6Al4V) block with a dimension of 72 X 72 mm^2. The two types of powders used are 99.5% TiC of particle size range below 60 µm and the CPTi powder is 99.6% pure with particle size range between 150 and 200 µm. Each of the two powders was placed in each hopper at the same setting given 50 wt% TiC and 50 wt% CPTi for the composite. The substrate was prepared before the deposition processes by sand blasting and cleaning with the acetone to remove oil and grease on the surface. After the preparation, multiple tracks were deposited at a 50% overlap. The processing parameters employed for the samples are presented in Table 1.

TABLE 1
EXPERIMENTAL PROCESS PARAMETERS MATRIX

SAMPLE 1				SAMPLE 2			
Laser Power (W)	Scanning Speed (m/min)	Powder flow rate Ti (l/m)	Powder flow rate TiC (l/m)	Laser Power (W)	Scanning Speed (m/min)	Powder flow rate Ti (l/m)	Powder flow rate TiC (l/m)
1600	0.46	1.9	0.1	1200	0.55	2	1
1620	0.5	1.8	0.2	1220	0.55	1.9	1.1
1650	0.54	1.7	0.3	1240	0.6	1.8	1.2
1680	0.58	1.6	0.4	1260	0.65	1.7	1.3
1700	0.62	1.5	0.5	1280	0.7	1.6	1.4

After the deposition process, the samples for the microstructural examination were cut laterally and hot mounted in a resin to study the cross section of the samples. The samples were prepared metallurgically, according to the standard metallurgical preparation of Titanium and its alloys according to ASTM E3 – 11, standard [24]. The polished samples were etched with Kroll's reagent. Optical Microscopy (OP) (Olympus BX51M) and Scanning Electron Microscopy (SEM) equipped with Oxford Energy Dispersion Spectrometry (EDS) (Tescan) were used to characterize the samples.

III. RESULTS AND DISCUSSION

The results obtained through material characterization are presented. These include the microhardness, microstructure of the deposited samples and the physical properties that is, the height and width of the deposited composites. It is striking to note that the melting temperature of TiC is 3160 °C which is much higher than that of the Titanium (1604–1660 °C) but the absorptivity of the TiC is higher than that of the Titanium alloy [25] hence, the power requirement to melt the two powders is expected to be very close.

A. Physical appearance of the deposits

The physical appearances of the substrate with the laser metal deposited layers is shown in Figure 2. Five layers were deposited on the substrate at different processing parameters as indicated in Table 1.

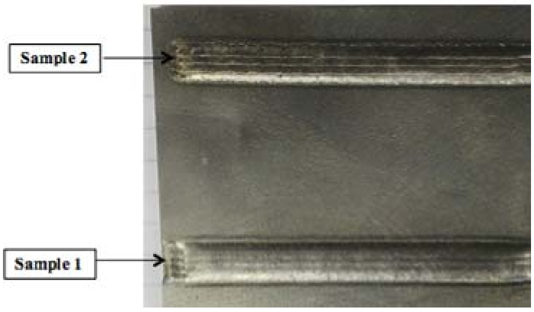
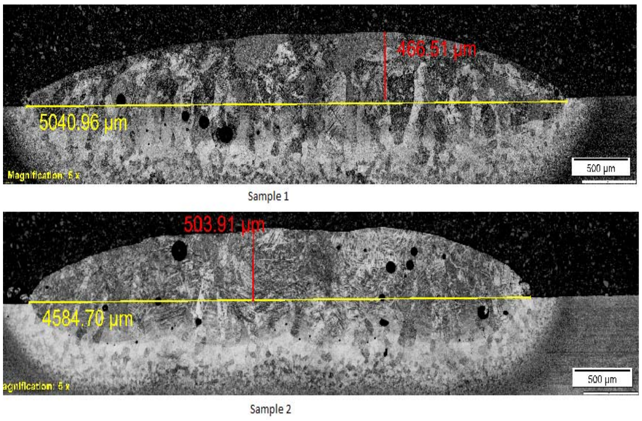


Fig. 2: Physical appearance after laser metal deposition

The appearance of the two deposited samples is characterized by a rough surface. From the top view of the deposited samples. The rough surface of the samples is one of the disadvantages of the LMD process and is a result of the layer build up method and also the powder particles which are released and sticking onto the surface of the deposit and substrate during the deposition process. Processing parameters and surface inclination angle also contribute to the rough surface of the deposits.

Presented in Figure 3 is the dimensional appearance showing the thickness and width of the deposits for both samples. The thickness is represented in the vertical direction indicated by the red measurement line and the widths in the horizontal direction indicated by the yellow measurement line both in the Figure 3.



Sample 1

Sample 2

Fig. 3: Dimensional appreance of the deposits for sample 1 and 2

As observed in Figure 3, sample two has a higher thickness (503.91 µm) compared to sample one (466.91 µm). The difference is caused by the changing scanning speed during the deposition process. On an average, the scanning speed used to form sample two is higher compared to the scanning speed used to form sample one. It was observed that the width of sample one is greater than the width of sample two. At low scanning speed, the melted pool stays longer on the substrate before another layer of material is added and this causes more laser-material interaction which enhances the powder to settle and forming a wide but relatively thin deposit. This phenomenon is anticipated and is valuable in the modelling of the process and the physical properties of the deposits.

B. Microstructural characterization

The microstructure of the substrate is characterized by the beta and the alpha phases as shown in Figure 4.The beta phases are the dark grains while the alpha phase are the light grains.

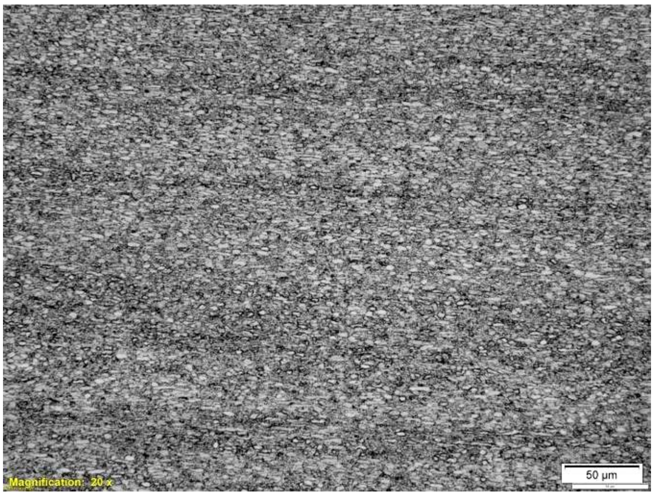


Fig. 4: Microstructure of the substrate

The microstructural zones of samples 1 and 2 are shown in Figure 5, sample 1 is represented by (a) and (c) whereas sample 2 is represented by (b) and (d). As it was observed from the micrograph, grain growths were observed on the heat affected area, this was attributed to the increase in the laser power. The heat-affected zone is further characterized by acicular alpha grain structure. While the microstructure of the sample two is characterized by martensitic structure resulting from the heat input during the process.

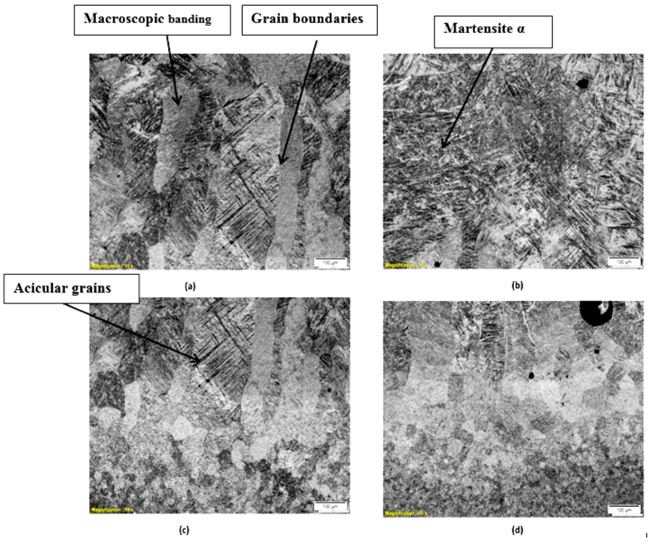


Fig. 5: Microstructural appearances of sample 1 and 2

A more detailed characterization of the martensitic structure shown in Fig. 5 (b) is presented in Fig. 6 (a) and (b) while Figure 5 (d) is presented in more detail in Figure 6 (c) and (d).

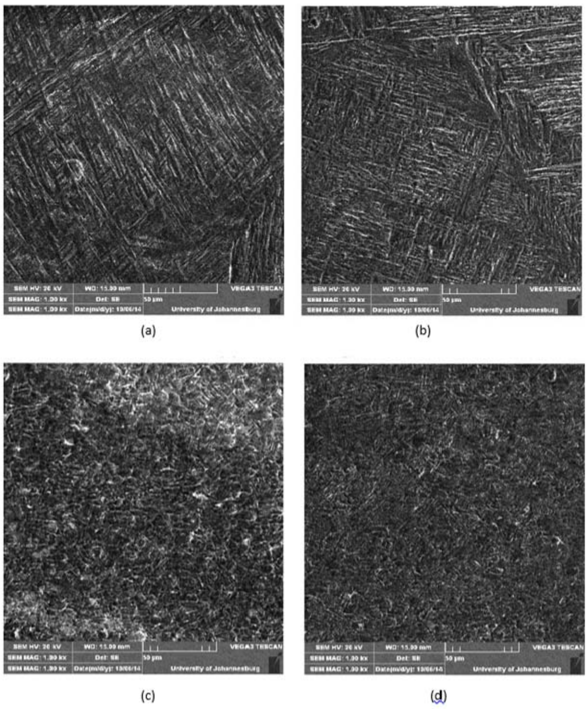


Fig. 6: (a) and (b) martensitic structure; (c) and (d) epitaxial microstructural band

The basket weave martensitic structure is as presented in Fig. 6 (a) and (b) resulting from the thermal process of the LMD process while the microstructure band is shown to grow epitaxially on the globular microstructure of the heat affected zone shown in Fig (c) and (d). The microstructural characteristics of the various zones in an FGM as indicated in this case, makes it possible to prepare a typical sample for tailored applications.

C. Microhardness profiling

The microhardness profile for sample 1 and 2 are Presented in Figure 7 as Dataset A and Dataset B respectively.

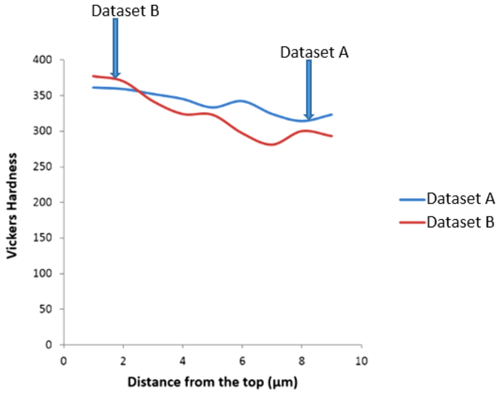


Fig. 7: Vickers microhardness profiles for both samples 1 (Dataset A) and 2 (Dataset B)

The microhardness profiles show a similar progression as indicated in the graph. According to the microhardness plot, it was observed that the hardness decreases as the distance from the top of the deposit decreases. The reason for the decrease is due to the decrease of the TiC content in the deposit. It was further observed that the microhardness of sample one is fairly on an average trend and higher compared to that of sample two although, the content of the TiC in sample two is more than that of sample one which is unusual, but it is observed that laser power also has a great influence on the microhardness of a deposit. The laser power of sample one is 1.650 kW on average and increases throughout the deposition process compared to that of sample two which is 1.240 kW on an average. It is observed that the increase in the laser power influences the microstructure of the deposit and changes it from fine to coarse, hence resulting into an increase in the hardness of the deposits.

IV. CONCLUSION

The functionally graded material of Commercially Pure Titanium and Titanium Carbide powders were successfully fabricated using the Laser Metal Deposition (LMD) technique and characterized with the aim of investigating the structural integrity of the deposited tracks. The investigation revealed that a tailored functionally graded material of both materials can be achieved by varying the parameters of the system. It was observed that laser processing parameters such as the laser power and the scanning speed play a very crucial role on the evolving properties of the deposits. It was found that the hardness was highly influenced by the laser power. Microstructural analyses revealed that customized tailored microstructures can be obtained for specific applications.

Acronyms
AM – Additive Manufacturing
CPTi – Commercially Pure Titanium
CSIR – Council for Scientific and Industrial Research
LAM – Laser Additive Manufacturing
LMD – Laser Metal Deposition
NLC – National Laser Centre
PM – Parent Material
Ti6Al4V – Titanium Alloy Grade 5

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