Optimizing Laser Parameters of Functional Graded Grade 5 Titanium Alloy (Ti6Al4V) and Titanium Carbide (TiC)

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Abstract. Functionally graded materials (FGMs) are materials in which the spatial chemical composition and microstructure gradually change resulting in a corresponding spatial change in the material properties. For this study, grade 5 titanium alloy (Ti6Al4V) and titanium carbide (TiC) powders were co-sintered using laser metal deposition (LMD) on Ti6Al4V substrate. The challenge of this process was determining the processing parameters that minimize or prevent macro cracking due to high thermal gradients and hence the residual stresses. The aim was to determine the optimum parameters. The laser energy density (LED) was used to characterize the processing parameters applied. It was found that when the energy density is in the range of 15 – 25 MJ/m², the FGM cracked. When the energy density is in the range of 12 – 16 MJ/m², the FGM did not crack.

Key words: Laser metal deposition, FGMs, Laser energy density, Ti6Al4V, TiC

1. Introduction

Functionally graded materials (FGMs) are materials in which the spatial composition and structure gradually change resulting in a corresponding spatial change in the material properties. FGMs are not only characterized by the appearance of compositional or other gradients but also by their sophisticated behaviour in comparison with conventional materials [1]. FGMs find use in applications such as aerospace components, medical implants, automobile components, sports equipment, sensors, optoelectronic etc. FGMs applied to titanium and titanium alloys have the potential to reduce the need of thermal protection in extreme environments like those experienced in aerospace vehicles. Functionally graded titanium alloys are also used to reduce wear in hip prosthesis implants which are exposed to three body abrasive wear (titanium, bone cement and poly ethylene cup) [2, 3]. The need to bring in FGM’s is due to the low usage of titanium and its alloys. Although titanium and its alloy have beneficial properties (high strength to weight ratio, corrosion resistance, etc.), their use and application is considered low when compared to other commercial materials such as steel. This is due to titanium and its alloys having a high production cost and being difficult to machine. The high cost of titanium alloy production is due to its high reactivity even with tool materials, high strength that is maintained at elevated temperatures thus leading to high tool wear and hence high cost of titanium components. Most titanium alloys are poor thermal conductors, thus heat generated during cutting does not dissipate through the part and machine structure but is concentrated in the cutting area [7]. Therefore, the high temperatures generated during the cutting process may cause a work hardening phenomenon that affects the surface integrity of component. This could lead to inaccuracies in the part and severe reduction in its fatigue strength. FGM’s can solve this problem by eliminating the issue of titanium being difficult to machine. Also the processes used to form FGM’s will produce more accurate parts with lower material wastage. FGMs can be produced using different fabrication processes. The process used depends on whether the FGM is thin or thick. Thin sections are classified as surface coatings whereas thick sections are those that require a build-up. For thin sections or surface coatings, Physical or Chemical Vapour Deposition (PVD/CVD), Plasma Spraying, Self-propagating High Temperature Synthesis (SHS) and others are used [4, 5]. Thick sections are commonly produced using such processes as Powder Metallurgy, Centrifugal Casting and Solid Freeform Technology [4, 5]. For the purpose of this investigation solid freeform technology, meaning laser metal deposition (LMD), was used to form the FGM. Various investigations have been conducted using LMD for FGMs [6, 7]. One of the major issues related to forming FGMs with LMD is cracking of the deposit. The main reason...
for cracking is the differential thermal straining induced during the high temperature process. In this work the cracking of functionally graded Ti6Al4V and TiC was studied to determine processing parameters that optimize the FGMs and hence reduce or remove crackTo form functionally graded grade 5 titanium alloy (Ti6Al4V) and titanium carbide (TiC), appropriate. Laser parameters have to be selected. Laser parameters for FGMs are not standard as most FGMs are still being developed and processing parameters depend on the material being produced. LMD processing parameters are grouped into three categories: laser, process and material related parameters [8]. It is important to know and understand the processing parameters as they influence the resulting properties (hardness, microstructure, density, strength, etc.) and surface integrity of the LMD manufactured part.

Laser spot size is the diameter of the laser beam. This has an effect on surface finish, accuracy of the completed part and delivered heat input. The smaller the beam diameter, the higher the laser energy density available to melt the powder or wire material. The available laser energy is then concentrated on a smaller area. This has been reported to produce better surface finish. Laser scanning speed is the rate at which the laser interacts with the material. The scanning speed can be achieved in two ways: by moving the laser relative to the material or (2) the laser remains stationary while the material moves meaning the base plate on which the components is placed moves [8] the laser scanning speed is inversely proportional to LED. This implies that the slower the scanning speed the larger the LED and vice versa. The scanning speed can have significant effect on the material usage efficiency, microstructure and properties of the fabricated part. Laser power is a function of the laser source machine. LED is directly proportional to laser power, meaning the greater the power the higher the LED. LED is the most important factor among laser parameters as it determines the amount of energy that is available per unit area to fabricate the material. The interaction time, which is the rate at which the heat is delivered, also determines the amount of energy delivered per unit area. From equation (1), LED is dependent on laser power, scanning speed and laser spot diameter. The energy calculate determines whether the powder will be fully or partially melted or not melted at all. Process parameters are related to powder and shield gas flow rate. Shield gases are used to protect the powder from environmental attack (molten titanium is highly reactive and if the melt pool is not shielded by an inert gas severe oxidation will take place). The powder flow rate also has a major influence on the properties of the part being fabricated. If the powder flow is too high, material is delivered which cannot be fully melted as the energy might not be sufficient to melt all the material. This then leads to poor coagulation and hence poor mechanical properties and surface finish. And if the powder flow rate is too low, excessive melting of the substrate may occur which may cause dilution of the deposited material. This results in higher dissolution and hence unintended properties [8]. These factors need to be carefully determined prior to deposition to achieve desired mechanical performance and hence reduce scrap. The shape and size of powder particles affects the rate at which the laser energy will be absorbed or reflected. The smaller the powder particles, the better the density of the final part produced [8]. The substrate surface condition also has a considerable influence on the properties of the resulting part. Too smooth surface increases the reflectivity of the material surface causing significant energy loses [8]. Therefore, smooth substrate surfaces should be avoided during laser additive manufacturing process. With regards to titanium, the substrate condition is of relatively little importance as titanium has a relatively high absorption. Moreover, after the laser additive manufacturing processes, some parts may require secondary or finishing operations depending on the service requirement of the part. The finishing can either be completed by traditional or non-traditional manufacturing processes.

The aim of this work was to determine the optimum parameters for the LMD of Ti6Al4V with TiC. The parameters which must be controlled include the laser power, laser scanning speed, beam diameter and the powder flow rate. Grade 5 titanium alloy (Ti6Al4V) plate was used as substrate for this investigation. The plate dimensions were 102 × 102 × 7 mm. Ti6Al4V and titanium carbide (TiC) powder were then used to produce the FGM. Ti6Al4V powder was supplied by TLS Technik Gmbh & Co. and the particle sizes ranged between 45 – 100 µm. The shape of these particles appears to be spherical as it is gas atomized. TiC powder was supplied by Weartech (Pty) Ltd and had a particle size of -100/+40 microns. TiC appears to be irregular as it is ball milled powder.
2. Material and method

LMD process was conducted at the National Laser Centre (NLC) at Council for Scientific & Industrial Research (CSIR) using a Kuka robot with a Nd: YAG laser. The laser had maximum power of 3 kW. The angle of incidence of the laser used was 12°. The type of nozzle used was co-axial nozzle. The carrier gas and shield gas employed was Argon. Fig. 1 illustrates the equipment used and Figure 2 illustrates the laser deposition process setup.

![LMD setup](image)

(a) Kuka Robot (KR 30) with laser head
(b) Kuka SmartPad (controller)
(c) GTV powder feeder (Hopper)

Fig. 1 Kuka Robot (KR 30) with laser head, Kuka SmartPad (controller) and GTV powder feeder (Hopper)

2.1 Experimental procedure

Table 1 presents the initial laser parameters that were used for the specimen preparation. These parameters were selected on the basis of the percentage volume of TiC that was deposited. The TiC composition was varied from 5% to 20% in increments of 5 percentage points. Four tracks were prepared with the laser power remaining fixed at 1.2 kW, the gas flow rate at 2 l/min and the beam diameter at 4 mm. An overlap of 50% was applied and minor variations allowed in scanning speed and powder flow rate.
Table 1: Initial laser parameters

| Vol. % TiC | Laser Power (kW) | Scanning Speed (m/min) | Powder Flow Rate (X) (g/min) | Gas Flow Rate (l/min) | Beam diameter (mm) | Overlap percentage (%) | Number of tracks |
|------------|------------------|------------------------|-------------------------------|-----------------------|-------------------|------------------------|------------------|
| 5          | 1.2              | 0.552                  | 4.6                           | 2.00                  | 4                 | 50                     | 4                |
| 10         | 1.2              | 0.45                   | 3.34                          | 2.00                  | 4                 | 50                     | 4                |
| 15         | 1.2              | 0.45                   | 3.34                          | 2.00                  | 4                 | 50                     | 4                |
| 20         | 1.2              | 0.432                  | 3.34                          | 2.00                  | 4                 | 50                     | 4                |

Parameters from Table 1 were used to determine powder flow rate for both Ti6Al4V and TiC. To determine the powder flow for Ti6Al4V the following equation was used:

\[
\text{Powder flow rate Ti6Al4V (Y) = X \times \text{vol.\% of Ti6Al4V}} \quad (1)
\]

To determine the powder flow rate of TiC the following equation was used:

\[
\text{Powder flow rate TiC} = X - Y \quad (2)
\]

at machine independent values.

Table 2 and table 3 present the powder flow rate for 4.6 g/min and 3.34 g/min which were calculated using equation 2 and 3 (RPM units are machine specific and proprietary. Calibration work is currently in progress or arrives at machine independent values).

Table 2: Powder flow rate for Ti6Al4V and TiC at 4.6 g/min

| Constant parameters | Ti6Al4V (%) | Powder flow rate for Ti6Al4V (Y = Ti6Al4V /100 * 4.6 g/min) | TiC (%) | Powder flow rate for TiC (4.6 g/min - Y) |
|---------------------|-------------|-------------------------------------------------------------|--------|-----------------------------------------|
| Laser Power: 1.2 kW | 100         | -                                                           | -      | -                                       |
| Scanning Speed: 0.552 m/min | 95 | 4.37 | 5 | 0.23 |
| Powder flow rate: 4.6 g/min | 90 | 4.14 | 10 | 0.46 |
| Spot size: 4 mm | 85 | 3.91 | 15 | 0.69 |
Table 3: Powder flow rate for Ti6Al4V and TiC at 3.34g/min

| Constant parameters | Ti6Al4V (%) | Powder flow rate for Ti6Al4V (Y= Ti6Al4V/100 * 3.34 g/min) | TiC (%) | Powder flow rate for TiC (3.34 g/min - Y) |
|---------------------|-------------|------------------------------------------------------------|---------|------------------------------------------|
| Laser Power: 1.2 kW | 100         | -                                                          | -       | -                                        |
| Scanning Speed: 0.45 m/min | 95         | 3.17                                                       | 5       | 0.17                                      |
| Powder flow rate: 3.34 g/min | 90         | 3.00                                                       | 10      | 0.33                                      |
| Spot size: 4 mm | 85          | 2.83                                                       | 15      | 0.50                                      |
| Percentage overlap: 50% | 80          | 2.68                                                       | 20      | 0.67                                      |
| Number of tracks: 4 | 75          | 2.51                                                       | 25      | 0.84                                      |
| Track length: 90 mm | 70          | 2.34                                                       | 30      | 1.00                                      |
| Gas flow rate: 1.5 RPM | 65          | 2.17                                                       | 35      | 1.17                                      |
| Shielding and carrier gas: Argon | 60          | 2.00                                                       | 40      | 1.34                                      |

When powder was deposited at a scanning speed of 0.552 m/min with a laser power of 1.2 kW, it was found that cracks were forming when the 3rd layer (90% Ti6Al4V and 10% TiC) was deposited. Thereafter, when powder was deposited at a scanning speed of 0.45 m/min at a power of 1.2 kW it was found that cracks were forming when the 4th layer (85% Ti6Al4V and 15% TiC) was deposited. The deposition was repeated three more times by keeping the scanning speed constant at 0.45 m/min and the power was reduced to 1 kW and further to 800 W and 600 W using the same parameters. Table 4 presents the results of all the trial parameters used for the deposition.

Table 4: Parameterization of functionally graded Ti6Al4V with TiC

| Trial | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|----|
| Laser power (kW) | 1.2 | 1.2 | 1.0 | 0.8 | 0.6 | 1.5 | 1.5 | 1.2 | 1.5 | 1.5 | 1.2 | 1.5 | 2.5 |
| Scanning speed (m/min) | 0.55 | 0.45 | 0.45 | 0.45 | 0.45 | 3.0 | 3.0 | 1.5 | 1.5 | 3.0 | 1.5 | 2.5 | 3.0 |
| Laser spot size (mm) | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 2 |
| Overlap percentage (%) | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| Number of tracks | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 8 |
| Gas flow rate (l/min) | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| Powder flow rate (g/min) | 3.34 | 3.34 | 3.34 | 3.34 | 3.34 | 3.34 | 6.68 | 6.68 | 6.68 | 6.68 | 6.68 | 6.68 | 6.68 |
| Cracking | Yes | Yes | Yes | Yes | Yes | No | No | Yes | No | No | Yes | No | No |

From the trials it was found that as the laser power and scanning speed were increased, cracking was minimal. Cracking occurred when the laser power and scanning speed were low due to re-melting of the powder as it is deposited on the substrate.
3. Results and discussion

The energy density was calculated as per equation 1. Table 5 shows the energy densities of the 13 trials conducted.

| Trial | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Energy density (MJ/m²) | 20.76 | 25.5 | 21.22 | 16.98 | 12.7 | 4.77 | 4.77 | 7.64 | 9.55 | 9.55 | 15.28 | 11.46 | 15.92 |
| Laser power (P) (kW) | 1.2 | 1.2 | 1.0 | 0.8 | 0.6 | 1.5 | 1.5 | 1.2 | 1.5 | 1.5 | 1.2 | 1.5 | 2.5 |
| Scanning speed (V) (m/min) | 0.552 | 0.45 | 0.45 | 0.45 | 0.45 | 3 | 3 | 1.5 | 1.5 | 3 | 1.5 | 2.5 | 3 |
| P/V | 2.18 | 2.67 | 2.22 | 1.78 | 1.33 | 0.5 | 0.5 | 0.8 | 1 | 0.5 | 0.8 | 0.6 | 0.83 |
| Cracking | Yes | Yes | Yes | Yes | Yes | No | No | Yes | No | No | No | No | No |

From Table 5 the ratio of laser power and scanning speed was calculated. It can be seen that when P/V > 1 cracking does occur but when P/V ≤ 1 then cracking does not occur. Fig (a) and (b) show plots of the energy densities for the trials where cracking was visible and where cracking was not visible respectively. From Figure 3a it can be seen that the maximum energy density is 25.46 MJ/m² and minimum is 7.64 MJ/m². A higher energy density is obtained when the power is relatively high (1.2 kW) and when the scanning speed is relatively low (0.45 m/min) as the power is inversely proportional to scanning speed. From Figure 3b it can be seen that the maximum energy density is 15.92 MJ/m² and minimum is 4.77 MJ/m². It can be concluded that if the energy density lies in the range of 9 – 16 MJ/m² cracking will not occur provided that the laser spot size is 2 mm when the energy density is greater than 12 MJ/m².

![Graphs](image-url)

Fig. 3 (a) Energy densities of the cracked samples and (b) Energy densities of the samples that did not crack
In Fig. 4(a) this case, cracking occurs in the edge and bottom centre of the deposit indicated by red circle. In figure 4(b) cracking was visible at the base of the deposit similar to Fig. 4(a) mainly at the top and middle sections.

To visualize the microstructure of the specimen an Olympus DP25 optical microscope was used. Microstructural analysis was conducted on trials 1, 2, 11, 12 and 13. The micrographs of the respective trials are illustrated in Figure 4. The micrographs have been fully described in the figure to get a better understanding on the behaviour of Ti6Al4V and TiC when deposited to form an FGM.

For this deposit, no cracks were visible or no initiation of cracks was seen. This is due to lack of fusion. It can also be seen that when a single layer is deposited the deposit appears to have discontinuities and lumps
No cracks were observed for this trial. Once again, the deposit appears to be discontinuous like trial 11.
No cracks were visible on the base of the deposit or on the entire deposit.

Fig. 4 Micrographs of various trials: a) Trial 1, b) Trial 2, c) Trial 11, d) Trial 12 and e) Trial 13.

The microstructures of all the trials had a similar characterization. The heat affected zone appeared to have a 2 phases structure with large grains. The grains appeared to be needle like structures. These structures were visible throughout the deposit. However, when the TiC was fused with Ti6Al4V, dendritic structures were observed. On the top half of the deposit where a greater vol. % of TiC was deposited, re-solidified TiC was observed as a result of TiC not melting.

4. Conclusion

In this work, FGM was produced by additive deposition of grade 5 titanium alloy power with titanium carbide powder on a grade 5 titanium alloy substrate. Titanium carbide fraction was varied from 5 to 20 vol. % in increments of 5 percentage points. In addition other parameters such as laser power, laser spot size and power flow rate were also varied. The processing parameters were reduced to laser density in characterising the process. Analysis of the resulting materials using microstructural examination led to the following conclusions:

1. If the laser density is in the range 15 – 25 MJ/m² produced specimens cracked for laser spot size of 4 mm
2. If the laser energy density is in the range 9 – 16 MJ/m², no cracking occurs as long as the laser spot size is reduced to 2 mm for LED greater than 12 MJ/m²
3. If the laser power to scanning speed (P/V) ratio is less than or equal to 1 then cracking will not occur
4. Cracking is mainly concentrated in the interface region between the substrate and the FGM which suggests a discontinuity in thermal behavior of the FGM and substrate

However, the process parameters reported as optimum may be influenced by other external factors such as ambient conditions which were not monitored in this work. It is suggested that future work be conducted with full characterisation of environmental conditions together with more detailed analysis of changes in mechanical and thermal properties of the materials.

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