EVALUATION OF HATCH DISTANCE AND POWDER FEED RATE EFFECTS IN TI-6AL-4V ALLOY DEVELOPED BY LMD TECHNIQUE

P.N. Sibisi[1*], A.P.I. Popoola[2], N.K.K. Arthur[3], S.M. Kubjane[2], A.S.Ngoveni[2] and L.R. Kanyane[2]

ABSTRACT

Laser metal deposition provides various benefits over traditional manufacturing and has since become a research hotspot, as demand for advanced manufacturing persists. The effects of process parameter variation on structural integrity and dimensional accuracy of Ti-6Al-4V alloy fabricated through laser metal deposition was investigated. The laser power, scan speed and gas feed rate were kept constant while overlap distance was varied between 0,3375 and 1,0125mm, and the powder feed rate was varied between 1,6 and 3,8g/min. The microstructure and morphology of the powder and metallography prepared samples were examined by Scanning Electron Microscope incorporated with Energy Dispersive Spectrometry (SEM/EDS) and an optical microscope (OM). The density of samples was studied by Archimedes method using ethanol as a wetting liquid, and dimensions were evaluated using a digital Vernier calliper. The microhardness of specimen was measured using Vickers diamond base microhardness tester. The results revealed a decrease in density with an increase in overlap spacing, and the opposite effect was observed for increasing powder flowrate, whereby an increase in powder flowrate was found to decrease density. The evolution of large pores was favoured by higher powder feed rate at constant overlap spaces. In addition, the microhardness of all samples was found to exceed the conventionally fabricated Ti-6Al-4V alloy.

[1*] Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa (Corresponding author)
[2] Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, South Africa
[3] Laser Enabled Manufacturing Group, Council for Scientific and Industrial Research, South Africa

1. INTRODUCTION

Laser metal deposition (LMD) is one of the laser-based directed energy deposition (DED) methods, which incorporates powders directly fed into the melt pool formed by laser irradiation to fabricate 3 dimensional components. The deposition occurs in a layer-by-layer fashion following the tracks directly from computer-aided design (CAD) data (Arthur, Malabi, Baloyi, Moller, & Pityana, 2016; Thompson, Bian, Shamsaei, & Yadollahi, 2015). In recent years, there has been a growing interest in the process as the technology provides the ability to fabricate complex material geometries, which are normally unattainable through traditional manufacturing techniques (Popoola, Farotade, Fatoba, & Popoola, 2016). Addition to this are countless other benefits, including permitting powder recycling, optimal raw material usage, reduced raw material stock size, fewer machine operations, reduced hard tooling requirements and reduced lead times (Portolés, Jordá, Jordá, Uriondo, & Esperon-miguez, 2016). Despite these significant advantages over conventional manufacturing, further advantages are hindered by the limited understanding of the correlation between process parameters, interaction mechanisms and resultant material properties (Emmelmann, Sander, Kranz, & Wycisk, 2011). The processing parameters such as laser power, scan speed, powder feed rate, feedstock quality, overlap distance and shielding gas flow rate greatly influence the properties of the deposited components. The above-mentioned properties comprise of deposition's dimensional accuracy, microstructure and mechanical characteristics (Guo, Zou, Huang, & Gao, 2017; Sames, List, Pannala, Dehoff, & Babu, 2016; Shukla, Mahamood, Akinlabi, & Pityana, 2012). Therefore, the success of building a component of good quality, structural integrity and relatively precise geometry lies within the proper parameter selection and heat transfer dependant solidification mechanism, as well as microstructural evolutions (Bayode, Akinlabi, Pityana, & Shongwe, 2017; Shamsaei, Yadollahi, Bian, & Thompson, 2015; Thompson et al., 2015).

Titanium and its alloys are advanced materials with an excellent combination of desirable properties such as a high specific strength, superior corrosion resistance and good biocompatibility (Hu, Wang, Ning, & Cong, 2016). Ti-6Al-4V, the most popular aerospace material, is known to be difficult to machine and expensive (Boyer, 1996). As a result, this material is a good candidate for near net shape processes such as LMD fabrication technologies as these technologies require minimal post processing thus the achievable cost saving fabrication operations can enable a wider appliocation spectrum for the above mentioned material (Shukla et al., 2012). The materials compatible with laser-assisted additive manufacturing are still limited, fortunately titanium and its alloys are prominent to the process, thus enabling them to reap the benefits offered by Laser Additive Manufacturing (LAM) fabrication (Kumar & Pityana, 2011). However, attempting to improve the extent of these benefits requires a more advanced knowledge of the process' underlying physics, which is yet to be established (Shukla et al., 2012).

In considering the importance of process parameters regarding structural integrity and geometrical accuracy for achieving a high-quality component, Qiu et al. (Qiu et al., 2015) focused on a parametric study to investigate the influence of processing and design conditions on structural integrity, geometrical integrity, microstructure and mechanical properties of large Ti-6Al-4V structures fabricated through Laser Engineered Net Shaping (LENS). Results revealed that a lower powder feed rate coupled with a high laser power produce minimal porosity, decreasing power resulted in the formation of lack-of-fusion pores, due to the incomplete melting of powders. In addition, authors pointed out that the specified vertical distance between the laser head and the build plate or previously built layers greatly affects the design-to-build error i.e. overbuild or underbuild ratio. In another study, Kummailil et al. (Kummailil, Sammarco, Skinner, Brown, & Rong, 2005) observed that an increase in mass flow rate or laser power resulted in an increase in the deposition height while increasing hatch-spacing or scan speed resulted in a reversed consequence. In addition, the authors pointed out that the effects of the mass flow rate and scan speed on dimensional accuracy were significantly greater than that of hatch distance and laser power. According to Shukla et al. (Shukla et al., 2012), the complexity of interactions occurring during laser deposition requires studying fewer (one or two) process parameters to ensure a proper grasp of knowledge.

The primary aim of the present work is to study and optimize LENS process parameters (particularly powder feed rate and overlap distance) to improve the relative density and design-to-part dimensional accuracy of the laser metal deposited Ti-6Al-4V alloy components. The former will help improve mechanical performance by reducing porosity while the later decreases the number of discarded components in production.

2. METHODOLOGY

The LENS technique was used to fabricate a total of four samples from gas atomised Ti-6Al-4V ELI spherical powder with particle size in the range of 40-90 µm. The test samples were built on 75 mm*75 mm*40 mm Ti-6Al-4V plate using a LENS system, which is mounted with a 1 KW IPG fibre laser. Laser deposition manufacturing was performed at the Council for Scientific and Industrial Research (CSIR) National Laser Centre (NLC) in Pretoria. The deposition process parameters are shown in Table 1. The powder feed rate was altered between 1.6 and 3.8 g/min and two hatch distances were used which were 0.3375mm and 1.0125mm. The substrates were sandblasted and cleaned with acetone prior to deposition in order to improve laser absorption and remove excess dirt. Once deposition was complete, a flat surface was achieved by grinding with P320 SiC grit paper using water as a lubricant and aka-allegran disk using the 3micron diamond suspension. Subsequently, polishing was undertaken in order to achieve a fine surface finish using aka-chemal cloth with 0.2µ fumed silica suspension. The Olympus BX51M optical microscope was used to capture the micrographs for evaluation of the effect of selected process parameters on microstructure. Density measurements were done by Archimedes method by means of Density test rig using distilled water as the wetting liquid. The microhardness of the test samples was conducted using a Vickers diamond base indenter along the cross section with the inter-indent spacing of 200µm. The dimensional accuracy of square samples was studied by comparing the design heights of 5,06mm with the build dimension achieved through Vernier Caliper measurements. The design dimensions of square samples were 10mm*10mm*5mm, and this was compared to the actual heights to measure the percentage over-build of LAM deposition, under-build was reported as negative over-build.

Table 1: LENS Processing Parameters used for deposition of samples.

Sample	Laser power (W)	Scan speed (mm/s)	Powder feed rate (g/min)	Hatch Spacing (mm)
A-1	300	16,93	1,6	0,3375
A-2	300	16,93	3.8	0,3375
B-1	300	16,93	1.6	1,0125
B-2	300	16,93	3.8	1,0125

3. RESULTS AND DISCUSSIONS

The results revealed that both the overlap distance and powder feed rate have an influence on porosity of the samples as seen by the difference in pore density observed on micrographs in Figure 1.

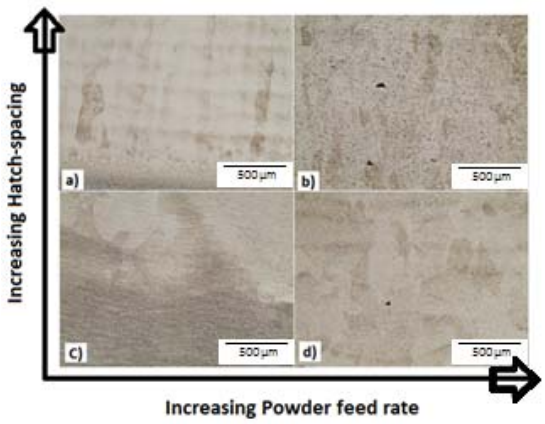

Figure 1: OM micrographs of Ti-6Al-4V by LENS at different process conditions a) B-1, b) B-2 c) A-1 and d) A-2.

The powder feed rate had a relatively less influence on the porosity of samples, especially at low hatch spacing, in contrast to the hatch-spacing which shown significantly greater effect on porosity regardless of powder feed rate. Figure 1a) and c) reveals a defect/pore free morphology while Figure 1b) shows a relatively more pores distributed across the whole surface of the sample. The presence of these pores is attributed to a large hatch spacing resulting in gaps between laser tracks. In addition, high powder feed rate results in incomplete melting of powder, thus leading to the formation of lack-of-fusion pores. Figure 1d) shows a micrograph with pores to some degree though relatively less porous than b). The higher degree of porosity found in Figure 1b) as compared to d) though processed at similar powder feed rate serves as evidence of the influence of hatch spacing on the porosity of the builds.

The microstructural make up of additive manufactured components is influenced by the melt pool's cooling rate of which is predetermined by process parameters. Figure 2 depicts the SEM micrograph and EDS spectra of the Ti-6Al-4V samples fabricated by.

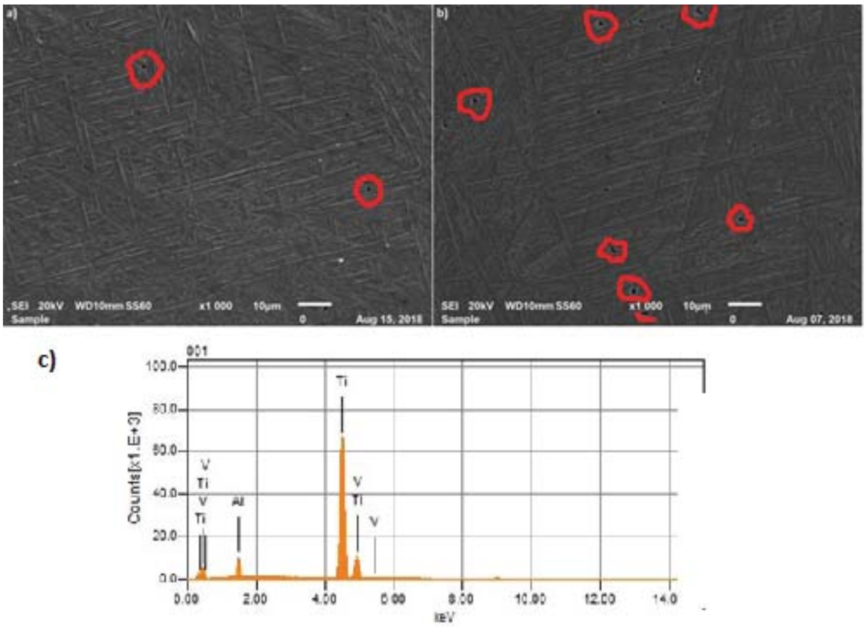

Figure 2: SEM micrographs of sample a) A2, b) B2 and c) EDS spectra for sample A2.

The micrographs predominantly reveal a typical laser processed Ti-6Al-4V martensite microstructure consisting of the α' needles contained in columnar prior β grains with a good metallurgical bond between scan tracks obtained under optimized process conditions, for instance small hatch spacings or high powder feed rates results in less gaps between scan tracks thus resulting in reduction in porosity and enhanced densification. The α' martensitic structure attained therein is characteristic to the rapid cooling from above the martensite start temperature and the β transus achieved by localized instantaneous melting of the moving melt pool (Knowles, 2012). The pore density of B1, the sample with least densification is greatest amongst the other built samples as in seen in the circulated regions in Figure 2. The EDS spectra in Figure 2c) reveal the expected chemical composition with major peaks for Titanium followed by aluminium and vanadium which are present in small contents.

The results revealed a significant height difference between samples fabricated at similar conditions but varied hatch spacing, with larger hatch spacing distances producing samples with relatively shorter heights. **Table 2** and Figure 3 depicts the build height, density and Microhardness of the LENS fabricated samples. Sample A1 was closest to the designed height with a slight over-build of 0,18mm, sample B2 followed with an -0,54mm under-build, followed by sample A2 at 1,16mm over-build and sample B1 at -2.43 under-build. Illustrated in Figure 1 are the optical micrographs of the specimen deposited at varied hatch spaces and powder feed rates. All the observed hardness values of the samples were above that of conventionally fabricated Ti-6Al-4V alloy (344 HV) (Arthur et al., 2016). A comparison of samples at the same powder feed rate revealed that the smaller hatch-spacing produced elevated sample heights in comparison to their counterparts. This is shown in Figure 1.

Table 2: Summary of the Heights, Density and Microhardness results.

Sample	Height (mm)	Overbuild (mm)	Density (g/cm^3)	Average Hardness ($HV_{0.3}$)
A-1	5,18	0,18	4,4102	383,48 +/- 2,38
A-2	6,16	1,16	4,3272	374,63 +/- 2,87
B-1	2,57	-2,43	4,3976	386,19 +/- 2,19
B-1	4,46	-0,54	4,2487	368,37 +/- 3,11

Furthermore, the results reveal that the hardness substantially increases with a decrease in powder feed rate and improves with decreasing hatch spacing which can be attributed to full melting of powder thus leading to sufficient consolidation of powder. This observation is in line with the observation by Tang & Pistorius (2017).

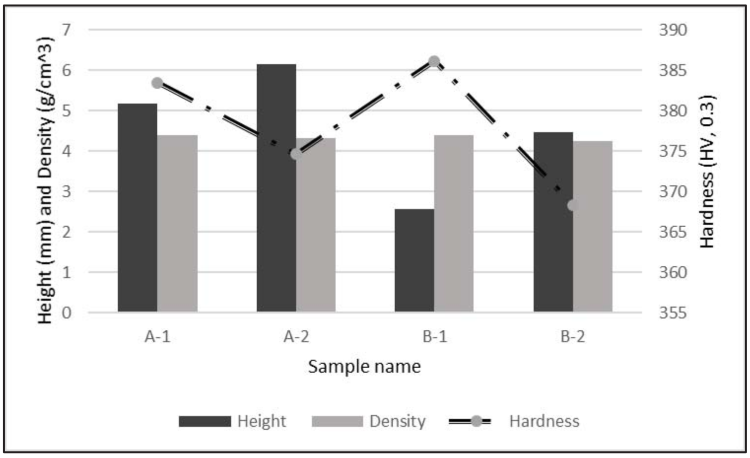

Figure 3: Microhardness variation, Density and Height measurements of the samples fabricated at different processing conditions.

4. CONCLUSION

The LENS additive manufacturing technique can produce depositions with properties similar or better to the commercially available manufacturing processes, as the hardness values obtained through the LENS process were higher than achievable in conventional manufacturing practices. In this study, it was revealed that increasing the hatch-spacing reduces the density. In addition, increasing the powder feed rate has a negative influence on densification due to the lack of fusion. The most accurate build in terms of design-to-build dimensions measured by heights is seen in the sample A1, built at the powder feed rate of 1,6 g/min and 0.3375 mm hatch spacing. This sample also had a hardness greater than that of the commercially available Ti-66Al-4V.

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