ADVANCED COATING: LASER METAL DEPOSITION OF ALUMINIUM POWDER ON TITANIUM SUBSTRATE

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Abstract**—Laser Metal Deposition (LMD) is an additive manufacturing technique, which can be used to produce solid components from a Computer Aided Design (CAD) model. The LMD process makes use of feeding powder, which is supported by the shielding gas, into the melt pool that is produced by sharply focused collimated laser beam on the substrate. This study employs aluminium powder in its molten state on titanium substrate through the LMD process. The aluminium powder was deposited at varying laser scanning speeds while the laser power and gas flow rate were kept constant. The presence of alpha phase grains were observed in the microstructures of samples at a lower scanning speed and the beta phase grains at a higher laser scanning speed. It was found that the geometrical properties of the deposits, that is; the width, height and the Heat Affected Zone (HAZ) of each sample decreased as the scan speed increases resulting from the laser-material interaction. The microhardness and the corrosion rates of each sample increased as the laser scanning speed increases.**

Keywords **— Heat affected zone, Laser metal deposition, Powder metallurgy.**

I. INTRODUCTION

Additive Manufacturing (AM) is made up of various categories and processes. Each of these categories and processes is appropriate for different materials and requirements. AM are typically broken into seven categories according to ASTM Standard F2792 [1]. These are, the Binder jetting, direct energy deposition, Material extrusion, Material jetting, Powder bed fusion, Sheet lamination and Vat photopolymerisation. The operation of different AM systems and the relative advantages and limitations of the different technologies are described and reviewed in the literature [2-5]. Among these seven categories, three are laser based AM processes. In the past century, the concept of additive manufcaturing has originated and evolved significantly. In contrast to traditional, 'subtractive' manufacturing methods, AM allows for the genration of a part or prototype from the 'ground-up' as opposed to removing material from an initial (larger) volume or relying on prefabricated dies (e.g. forging, stamping, casting).

Additive manufacturing (AM) has received considerable attention in the past few decades from both the commercial and academic sectors [6], with over 3500 patents related to AM emerging from 1975 to 2011 [6]. The idea of 'printing' a three-dimensional prototype or part on-demand, as opposed to purchasing or sending dimensioned drawings out-of-house for machining, is alluring to both the industry and individuals alike. Time has demonstrated that AM is not just restricted to rapid 'printing' of prototypes, but is also a means for generating fully-functional parts for service in a variety of applications. This offers the potential to reduce production time/costs for low-volume/high-value/complex-shaped components and the opportunity to manufacture in a typical and remote environments.

To accomplish effective material joining, the successful combination of material, or feedstock, and energy delivery is required and these combinations differ with process material and various AM machines. Typically, each AM method is tailored for building a specific type of material (e.g. plastics, polymers, composites or metals) as the effective material deposition and joining can be unique. A more detailed description of the various AM methods can be found in [2-4].

The development of AM systems into user-friendly, commercial units, plus the need for safety, means the laser within them is not always obvious. Further, during AM of metals it is usually necessary to shield the build point from harmful oxidation, either by performing the whole operation in an inert chamber or using blown inert gas, requiring further removal of the user from the 'sharp end' of the manufacturing [7-8].

Existing commercial AM systems utilise a wide range of laser technologies. The power ranges from around 1 W to 6 kW, and wavelengths from the ultraviolet (354.7 nm) to the infrared (10.6 mm). Requirements vary from process to process, but the need to match SLA lasers with the polymer absorption spectrum, the use of different lasers for different materials in the powder bed fusion bed category and the use of the shorter wavelength diode laser, despite poorer beam quality than the fibre laser for directed energy deposition (DMD), indicates absorption is a major factor for laser selection throughout. Use of systems with powers greater than 6 kW have also been demonstrated [9] and some industrial 'home-made' systems also exist, particularly in the DMD category.

One of the reasons why the use of AM is forecast to increase at such a rapid rate is that it expands the boundaries for a design engineer by offering a profoundly different approach to traditional subtractive methods. This can also allow a greater range of components to be made as a single

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part, reducing the material required and the need for joining, by whatever means. However, these benefits can be negated by high costs. Laser Additive Manufacturing with injected powder melting implies layer by layer shaping of materials in the form of powder to arbitrary configurations and geometries, using a comprehensive integration of materials science, mechanical and control engineering, and laser technology. The technology is currently being used in rapid prototyping, coating, tooling and parts repair, cladding and design of novel alloys or functionally graded materials [10].

Laser additive manufacturing has emerged as an interdisciplinary technology, it employs the advantageous features of laser technology, additive manufacturing techniques, and computer-aided design and manufacturing process (CAD-CAM) [11-12]. The metallic materials, which are used for the build-up of layers, are available in fine powders. Additive manufacturing makes it possible to manufacture components with ease instead of having to mill a work piece from a solid block and it also makes it possible to manufacture complex components [12]. This technology can be applied to manufacture prototypes and the additive manufacturing system is being used in Series Production [12-13]. The schematic diagram of the laser additive manufacturing process is shown in Figure 1. This process makes use of a powder feeder and a laser beam in order to produce a melt pool [11].

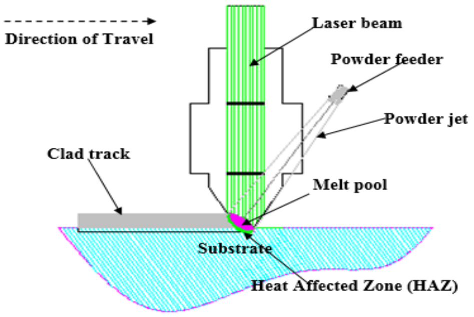

Fig. 1: Schematic of the laser additive manufacturing process

II. LITERATURE REVIEW

Aluminium has been identified as the most common metal on earth. Only silicon and oxygen exists in more quantities than aluminium. The existence of aluminium was discovered in 1808, by a British electrochemist named Humphrey Davy. [14]. The protection conferred by the thin but tenacious film of oxide results in Aluminium having higher corrosion resistance as compared to many other materials. This oxide layer can always be found on the surface of aluminium in oxygen atmospheres. Aluminium is a very reactive chemical element. The successful resistance of aluminium to corrosion depends on the completeness with which the protective film of aluminium oxide stops this underlying activity from coming into play [14]. Aluminium is a durable and lightweight metal. It is a good conductor of electricity and heat, has a silvery appearance when it's freshly cut, is easily shaped through molding and extruding.

Applications of Aluminium and its alloys in the aviation industries as large and critical load-bearing structural components such as bulkheads in modern civilian and military airliners and integrally bladed disks (blisks) in advanced gas turbine engines, are ever increasing because of their excellent combination of low density, high specific strength, excellent elevated-temperature mechanical properties, exceptional corrosion resistance and good compatibility to polymer matrix composites [15-17]. However, Aluminium and its alloys are also well-known for their poor materials-processing and components manufacturing abilities compared to other metallic structural materials such as iron and nickel-base alloys, owing to their inherent physical and chemical properties [16-18].

The laser additive manufacturing technology has attracted increasing and world-wide attentions since middle 1990s and a series of technologies with the same principles but different names have been developed, such as Laser Engineered Net Shaping (LENS) by the Sandia National Laboratories [19-21], Directed Light Fabrication (DLF) by the Los Alamos National Laboratories [22-23], the Direct Metal deposition (DMD) by the University of Michigan [24-25], Laser Powder Deposition (LPD) by the Fraunhofer Laser Technology Institute [26-27], and laser melting deposition (LMD) by the Beihang University (China) [28-31].

Despite being a promising manufacturing technology, it is essential to understand and control the material behavior during the LAM process to be capable of producing functional parts for critical industries such as the aerospace, energy and automotive. The real promise of LAM is the potential to integrate superior material properties with a precise fabrication process. LAM provides attractive characteristics including minimal dilution, concentrated heat source and smaller heat affected zones compared to the more traditional subtractive manufacturing techniques. The formation of the fine equiaxed grains in LAM has two main advantages [32]. First, the fine grains help reduce susceptibility to cracking during deposition in LAM as shown by Mitzner et al. [33]. Secondly, fine grains can improve ductility and fracture toughness of the deposit in the case of steels and stainless steels [32]. These advantages make it possible to produce locally tailored microstructures.

When it comes to the AM of metallic parts, the DED and PBF processes are the most proven and feasible methods. Both processes involve the deposition of powder metal (or less common preforms such as wire) and their simultaneous or subsequent melting via a focused thermal energy source. Unlike plastic or polymeric-based AM processes, PBF and DED require an electron beam or laser beam (or any thermal energy source) to accomplish layer-to-layer metallurgical bonding to overcome the relatively high enthalpy of fusion and melting temperature of metals. When a laser is used foreither DED or PBF (as the energy delivery type) the processes can be referred to as a form of Laser-Based Additive Manufacturing (LBAM) while DED can be further specified as Direct Laser Deposition (DLD) [34].

Several researchers have attempted the deposition of aluminium with other alloys to improve the property of the deposit. One of such was the work conducted by Vora et al. [35], they laser alloyed Tungsten and Aluminium (W-Al) coatings on aluminium 1100 substrate to improve the corrosion resistance. The formation of Al_4W intermetallic phase occurred as a result of the low enthalpy of formation. Consequently, the intensity of the pitting attack was found to be relatively low for laser treated sample.

Similarly, selective laser melting (SLM) was employed to manufacture ALSi10Mg parts by selectively melting powder particles by the use of a high-energy laser beam [36]. It was found that the unique process conditions during SLM results in the production of a very fine microstructure, which grow towards the centre of the melted pool. The face centred cubic aluminium cells, which are decorated by a diamond-like silicon phase results with a high hardness of the SLM parts. The unique solidification conditions and additive character of the process results in the presence of morphological and crystallographic texture.

Cruz and Dahotre [37] conducted a research work based on the study of the microstructure and wear of an A-365 aluminium alloy, which is superficially modified by laser alloying. The powders used composed of 96wt%, 2wt% Mg and 2wt% Ti was alloyed at various traverse velocities with 2000-W Nd-YAG laser. It was observed that the traverse velocity employed had an effect on the tribological behaviour of the treated samples, microstructure and the amount of phases produced during processing.

Furthermore, in the work of Pelletier [38], elements were added on an aluminium surface, by first placing the elements on the aluminium surface and then laser alloyed. This technique of placing elements on the aluminium surface and laser alloying them, gave outstanding results which improved the material properties such as porosity elimination, microhardness and microstructure homogeneity. The results from the Al-Cu alloy formed were found to be homogeneous, increased microhardness, increased elastic modulus of elasticity in the plastic index and homogeneous wear tracks were formed but with decrease wear rate.

An experimental work performed involve the laser surface alloying (LSA) of mild steel AISI 1050 [39]. This was achieved by firstly placing the alloy powder on the substrate surface using the flame spraying gun and then the re-melting of the preplaced layer was performed by using the 2.5-kW CW Nd: YAG laser beam. The developed microstructures were analysed. The corrosion and cavitation erosion of the produced layer were analysed in 3.5 % NaCl solution at 23°C by making use of the potentiodynamic polarization technique and by also using 20-kHz ultrasonic vibratory facility. The laser-aluminized layer was found to be a ferritic matrix, which was reinforced with the intermetallic phases Fe_3Al, FeAl, and tiny amount of Fe_2Al_5. The presence of the Fe_3Al, FeAl and solid solution hardened α-ferrite resulted in the laser-aluminized samples having cavitation erosion that was about 17 times more than that of the substrate. The laser aluminization performed on the specimens resulted in a much improved corrosion resistance as it was observed from the lower corrosion current density.

In this study, Aluminium powder was melted on Titanium substrate using the laser metal deposition technique. The evolving properties of the samples were analyzed and presented in this paper.

III. METHODOLOGY

The Laser Metal Deposition process employed the deposition of aluminium powder on titanium substrate through the powder feeding hoppers with the laser beam attached to the robot arm of the Kuka robot. Also employed in the experimental setup are both the control unit and the laser cooling system. The experimental setup of the Kuka and the robot is shown in Fig. 2.

Fig. 2: Experimental setup of Kuka robot and laser beam

The deposition of the aluminium powder was made on 6 mm thick rectangular titanium piece of 100 mm x 100 mm. The aluminium powder was fed into the hoppers with the gas flow rate set at 1.5l/mm and the scan speed set at 0.5m/min with an incremental rate of 0.5m/min. A total of six aluminium deposits were produced on each titanium block under the set of process parameters. The experiments were performed by varying the scanning speed from 0.5 to 3 m/mm with an increment of 0.5. The laser power was kept constant at 1 kW while the gas flow rate was also kept constant at 1.5 l/min. The deposited aluminium tracks were characterized through microstructural evaluation, microhardness measurement, and corrosion resistance tests. A set of deposited aluminium tracks on the titanium substrate is shown in Fig. 3.

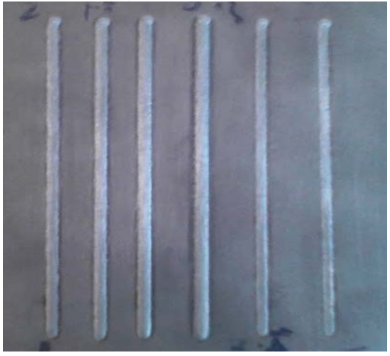

Fig. 3: Deposited aluminium tracks on the titanium substrate

The samples were cut using an abrasive wet cutting machine into smaller mountable pieces and hot mounted using polyfast resin. The mounted samples were then grounded and polished for the microscopic examination. The samples were etched using a combination of 4ml of nitric acid, 100ml of water and 3ml of hydrofluoric acid. The microscopic examination of the etched sample was conducted under Olympus optical microscope. Microhardness measurements were conducted across the cross section of the deposited aluminium tracks, using digital microhardness tester. The corrosion resistance test was conducted using a linear potientiodynamic scan and an open circuit corrosion potential measurements setup shown in Figure 4. All the tests were conducted in accordance to the ASTM standards.

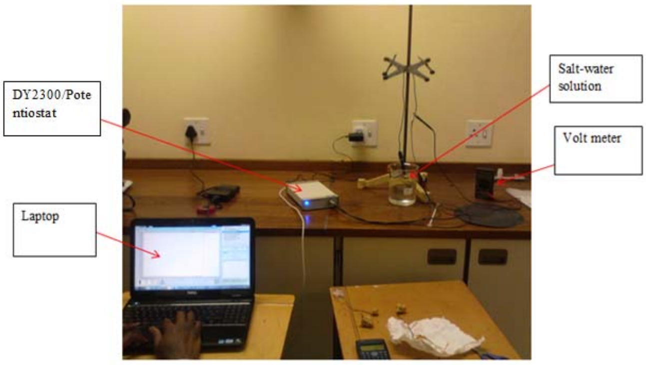

Fig. 4: Corrosion experimental setup

IV. RESULTS AND DISCUSSION

The experimental results from the characterization of all the treated samples are presented in this section.

A. *Microscopic Analysis*

The microstructure of the deposited aluminium powder was observed under the optical microscope. The microstructural evolution was investigated in order to establish the effect of laser scanning speed on the tracks. The bonding and the penetration of aluminium into the titanium substrate were also investigated. This fusion of the aluminium into titanium was expected because of the lower density of aluminium (2.7kg/m^3) compared to that of titanium (4.5kg/m^3). The result revealed that aluminium powder deposited at 0.5m/min, 1m/min and 1.5 m/min were characterized with white particles referred to as alpha phase grains structures. While aluminium powder deposited at 2, 2.5 and 3 m/min respectively were characterized with black coloration known as the beta phase grain structure. Consequently, an increase in the laser scanning speed results in the microstructure of the deposit changing from the alpha phase into the beta phase.

Typical microstructure of the deposited aluminium powder at 0.5m/min is shown in Fig. 5. The Figure shows the various sample regions such as the deposition width, height and the height of the Heat Affected Zone (HAZ).

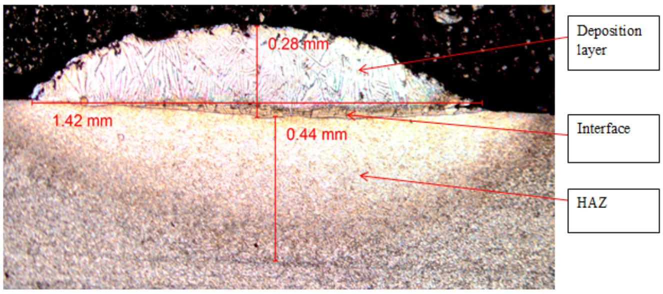

Fig. 5: Microstructure of deposited aluminium at 0.5m/min and dimensions of the regions

The measured dimensions of the deposited height, deposited width and the HAZ of the deposited aluminium track are presented in Table 1. The results show that there was a decrease in the deposited height; width and HAZ as the laser scan speed increases.

TABLE 1:
DIMENSIONS OF DEPOSITED ALUMINIUM TRACK

Scan speed (m/min)	Deposited height (mm)	Deposited width (mm)	HAZ (mm)
0.5	0.28	1.42	0.44
1	0.15	1.07	0.34
1.5	0.09	1.20	0.29
2	0.07	0.95	0.23
2.5	0.02	0.85	0.16
3	0.05	0.92	0.11

B. *Microhardness Measurements*

The microhardness indentations were conducted on three regions of the deposited aluminium: the deposited layer, interface and HAZ. The microhardness indentation profile is shown in Fig. 6.

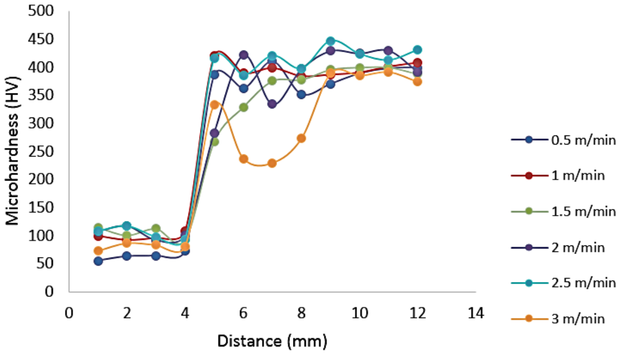

Fig. 6: Microhardness indentation profiles

The microhardness profiles have similar patterns with exception of some points at 3 mm/min. However, this is expected as there is less laser-material interaction which could result in less heating thereby leading to lesser formation of harder phases. The lowest and the highest measured microhardness value on the deposited layer across all the six samples were found to be 55 and 116HV respectively.

C. *Corrosion Resistance Tests*

The corrosion resistant tests were conducted to determine the deterioration resulting from the material loss of cross sectional area. This loss was determined through the use of the Potentiostat to examine how the material reacts to its environments by determining the rate of corrosion. The surface area of each deposited aluminium powder and mass of each sample before and after the corrosion test was recorded and presented in Table 3. The results show that the change in mass was very small. The samples with 1m/min laser scan speed had the largest change in mass and the sample with 1.5m/min had the least change in mass.

TABLE 3:

CHANGE IN MASS DATA

Scan speed (m/min)	Mass before corrosion test (g)	Mass after corrosion (g)	Change in mass (g)
0.5	8.43	8.37	0.06
1	17.34	17.24	0.08
1.5	6.26	6.22	0.04
2	14.02	13.95	0.07
2.5	14.62	14.56	0.06
3	9.04	8.98	0.06

The corrosion rate of the deposited aluminium was measured with the Potentiostat and is presented in Table 4.

TABLE 4
CORROSION RATES OF DEPOSITED ALUMINIUM POWDER

Scan speed (m/min)	Open circuit potential (mV)	Corrosion rate (mm/year)	Open circuit potential time
0.5	-671	0.01695	30
1	-681	0.01728	30
1.5	-671	0.01268	30
2	-644	0.0189	30
2.5	-334	0.6843	30
3	-673	0.1446	30

The Potentiostat was used to measure the corrosion rate of the deposited aluminium powder. The corrosion rates and the open circuit potential were determined and presented in Table 4. The corrosion test was conducted for 30 minutes per sample. The open circuit potential was also measured. The effect of the laser scanning speed on the corrosion resistance behaviour of the deposits was studied by making use of the corrosion rates in Table 4. It was observed that the corrosion rate increases when the laser scanning speed was increased.

V. CONCLUSION

Laser deposited aluminium on titanium substrate was successfully conducted to determine the effect of scan speed on the property of the deposited tracks. The treated samples were characterized and the result of the microscopy evaluation revealed three unique region as a result of the effect of the treatment; that is the deposit region, interfacial region and the Heat Affected Zone (HAZ). The presence of alpha phase grains were observed in the microstructures of samples produced at a lower scanning speed while beta phase grains were observed at a higher laser scanning speed. The dimensions of these three identified regions were measured – the deposited height and width and the HAZ. It was observed that the height, width and HAZ of the deposited aluminium tracks were found to decrease as the laser scanning speed increases due to the degree of the laser-material interaction. The microhardness profiles have similar profiles with the hardest being the deposit zone. The corrosion tests conducted show that the corrosion rates of all the treated samples increased as the laser scan speed increases.

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