Characterization of Laser Metal deposited 316L Stainless Steel

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***Abstract*—Laser metal deposition (LMD) is an innovative manufacturing technique that uses laser to melt powders to fabricate fully dense components layer by layer. It is capable of processing different metallic powders and can also be used for consolidating different powder to produce custom alloys or functionally graded materials (FGM). The properties of laser processed materials is dependent on the final microstructure of the parts which in turn is dependent on the LMD processing parameters. This study investigates the effects of laser power on the structural integrity, microstructure and microhardness of laser deposited 316L stainless steel. The result showed that the laser power has much influence on the evolving microstructure and microhardness of the components. The average microhardness of the samples were observed to decrease as the laser power increased due to grain coarsening.**

***Index Terms*— Laser Metal Deposition, Microhardness, Microstructure, Stainless steel**

I. INTRODUCTION

Austenitic stainless steels are the most commonly used grade of stainless steel and also the grade containing the highest number of alloys. Austenitic stainless are corrosion resistant in normal environments and also has excellent mechanical properties like ductility, toughness, creep resistance, weldability and show significant plastic deformation during tensile loading [1], [2]. They are non-magnetic and are only hardenable by cold working.

Laser Metal Deposition (LMD) is one of the important Additive Manufacturing (AM) technology that is used for fabricating components. These are more cost effective in fabricating complex and bespoke parts compared to conventional manufacturing methods. LMD has shown great potential for different fields of application such as rapid prototyping, component repair, and direct manufacturing of parts [3], [4].

LMD manufactures parts layer by layer from metallic powder using a high power laser that follows a tool path derived from the CAD model. The resultant mechanical properties of LMD processed materials are usually similar or better than equivalent wrought products [5]. Properties of LMD processed materials depends largely on the solidification microstructure. The rapid melting and quenching during LMD results in grain refinement because there is very little time for grain development and also non-equilibrium microstructures are more kinetically favored. Another important characteristic of LMD processed structures is the change in microstructure with depth, that is, from the bottom to the top of the component [6], [7]. The varying microstructure is mainly as a result of high conductive cooling at the bottom of the component and accumulation of heat at the top. Thermal cycling also affects properties like residual stress and the mechanical strength of laser processed components.

The final microstructure of LMD processed part are dependent on the process parameters. LMD is a very sensitive and complex process because of the high interaction and influence the different process parameters have on one another. Having a good knowledge of the process parameters and its effect on the final properties is vital as it aids in selecting the optimal LMD system processing setting for a particular metal powder that will produce a successful deposition and the required resultant property.

The effect of the process parameters on the properties in LMD has been investigated. Imran et al. [8] in their study found that the optimum powder feed rate for the successful deposition of H13 tool steel powder on cooper substrate was in the region of 1.58 gm/min, above which there were more un-melted powder in the microstructure, irrespective of the laser power, they also observed that a high energy intensity was required for deposition, however laser power above 2kW was unsuitable because of the high reflectivity of copper.

Hofmeister et al. [7] in their study found a relationship between solidification microstructure and melt pool size. They concluded that the smaller the melt pool size, the finer the microstructure.

Pinkerton et al. [9] researched the relationship between process parameters and final material properties of laser deposited Waspaloy powder on mild steel substrate. They found that the microstructure morphology varied when the laser power and the powder flow rate were altered.

Mahamood et al. [10] studied the effect of laser power on microstructure and microhardness of laser deposited Ti6Al4V. The laser power was varied between 0.8 and 3.0kW. Laser power was observed to influence the microhardness, grain structure and dilution of the fabricated component.

Laser scanning velocity also significantly affect the properties and microstructure of laser processed materials.

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Studies have also confirmed that increasing the scanning velocity produces a finer the microstructure [11], [12].

The influence of scanning velocity on microstructure, microhardness and wear resistance performance of laser deposited Ti6Al4V/TiC composite was investigated [13]. Scanning velocity was revealed to have a linear relationship with microhardness and wear resistance of the deposit.

Zhang et al. [14] also observed a similar relationship between scanning speed and microhardness in their study.

On that note, the aim of this study is to investigate the influence of LMD processing parameter on the microstructure, microhardness and the appearance of the deposition.

II. Materials

The materials used in this study was 316L stainless steel powder supplied by TLS Technik GmbH & Co. (Germany). The powder is gas atomized, spherical in shape and were supplied with a particle size of 44 µm. The chemical composition of the SS powders is presented in Table I.

TABLE I
MATERIAL COMPOSITION OF 316L POWDER

Powder	Chemical composition (wt, %)	Size (µm)
316L	≤67.5 Fe, ≤13.0 Ni, ≤17.0 Cr, ≤0.03 C, Others (Balance)	44

The substrate used for this experiment is 316L stainless steel with dimensions of 10 × 10 × 10 mm. It was sand blasting and degreased with the acetone before the deposition process.

III. Experimental Setup

The laser deposition was conducted at the National Laser Centre of Council for Scientific and Industrial Research (CSIR) using a Roffin Sinar continuous wave 4.4 kW Nd: YAG laser. The deposition head was attached to a Kuka robotic arm. Argon gas was used to shield and delivered the powder into the melt pool created on the substrate by the laser. A picture of the experimental setup is presented in Fig. 1.

Fig. 1. Experimental setup of the LMD system

Five consecutive tracks were deposited at 50% overlap and with laser beam diameter of was set at 2 mm. Detailed experimental parameters are presented in Table II.

TABLE II
LMD PROCESS PARAMETERS

	Power (kW)	Scanning speed (m/s)	Beam diameter (mm)	Powder flowrate l/min
Sample 1	1.8	0.6	2	2.0
Sample 2	2.0	0.6	2	2.0
Sample 3	2.2	0.6	2	2.0
Sample 4	2.4	0.6	2	2.0

Transverse sections of the cladded layer were cut and metallographic samples were prepared according to ASTM E3 – 11 standard for metallurgical preparation of stainless steel [15]. The surface of the polished samples was etched with Kalling's No. 2 reagent (5g $CuCl_2$, 100 ml HCl, 100 ml ethanol). Microstructural analysis was carried with an optical microscope. Vickers microhardness profile were obtained along the cross section with a load of 100g at intervals of approximately 0.1mm between indentations and a dwell time of 10s.

IV. Results and Discussion

A. Macroscopic View of LMD Samples

Multiple tracks of the deposited stainless steel powder on the substrate based on the process parameters given in the previous section is shown in Fig. 2. The samples were fully dense with no pores and cracks. It has a rough surface which is typical of most Laser deposited materials.

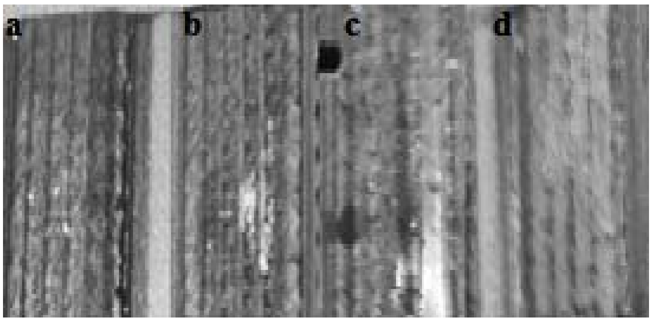

Fig. 2. Deposited tracks at different laser power: (a) 1.8kW, (b) 2.0kW, (c) 2.2 and (d) 2.kW.

LMD produces different zones in the processed material [16]. A macro-view of sample 1 with laser power of 1.8kW is presented in Fig. 3. showing the deposit zone, the melting zone and the heat affected zone.

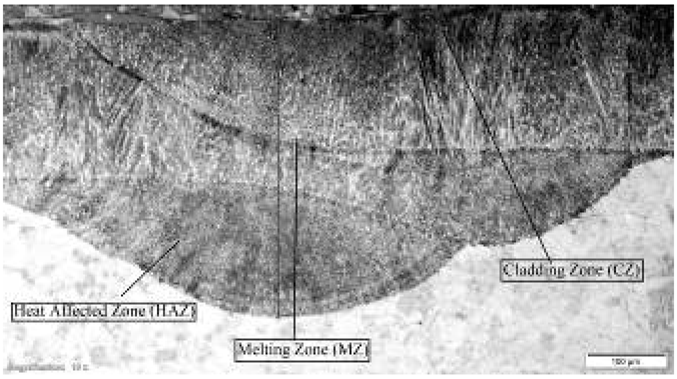

Fig. 3. Microstructure of sample 1 showing the different zones

B. Optical Microscopy

The morphology of the substrate is shown in Fig. 4. It consists of austenitic-grain structure, which is the typical microstructure of 316L stainless steel.

Fig. 4. Microstructure of the substrate

Fig. 5. shows the optical micrograph of the top and bottom of sample 1 with a corresponding laser power of 1.8kW laser power, scanning speed of 0.6m/s and powder feed rate of 2l/min.

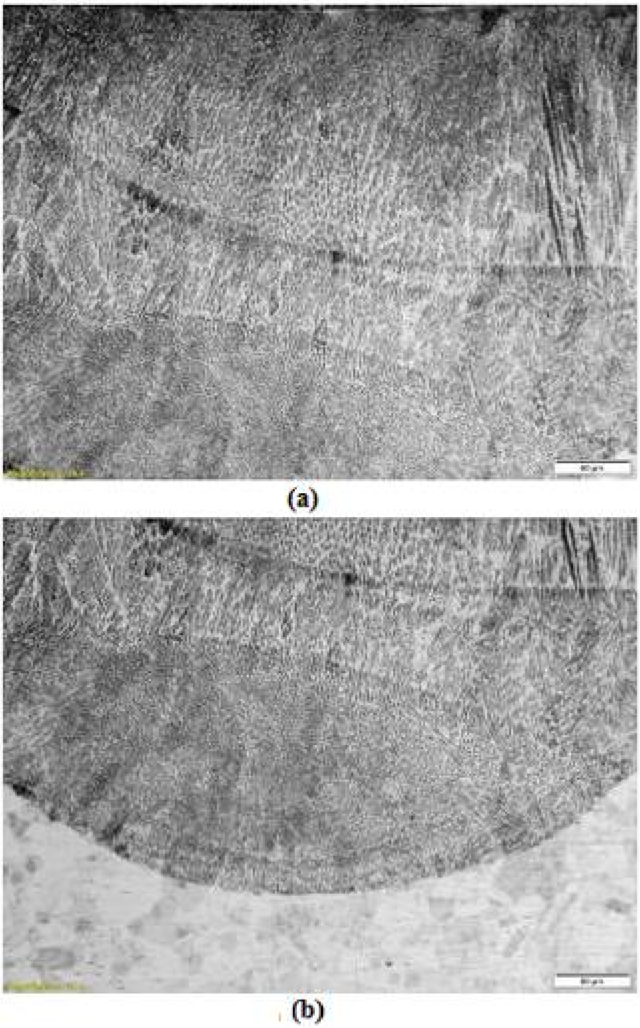

Fig. 5. Microstructure at 1.8kW of the laser deposition: (a) top layers and (b) bottom layers.

The microstructure comprises of fine cellular cells with directional solidification pattern synonymous with microstructure observed in rapid solidification process. However, Increasing the laser power, increases the melt pool depth [17] and also produces a coarser grain structure due to high energy input and reduced cooling rate as can be seen in the microstructure of the specimens. The microstructural zones of samples 2 - 4 and are shown in Fig. 6. Sample 2 is represented by (a) and (d) while sample 3 and 4 are represented by (b) – (e) and (c) –(f) respectively.

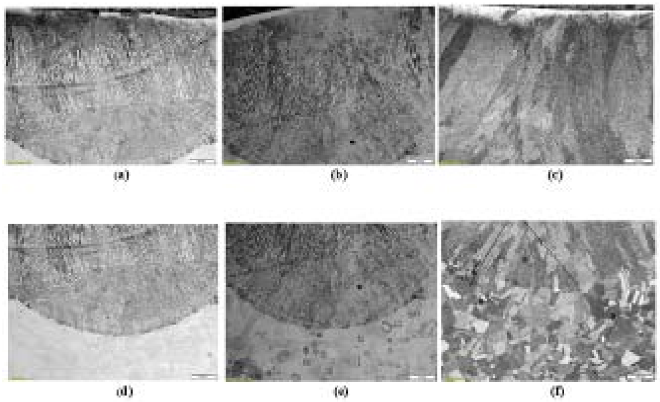

Fig. 6 Microstructures of the top and bottom zones of laser deposited 316L stainless steel powder at: (a) and (d) sample 2, (b) – (e) sample 3, and (c) – (f) sample 4.

Grain growth in the CZ in all samples is controlled by heterogeneous nucleation which may be as a result of the similarity between the powder and substrate material.

C. Microhardness

Fig. 7. presents the effect of various laser power on the hardness of samples.

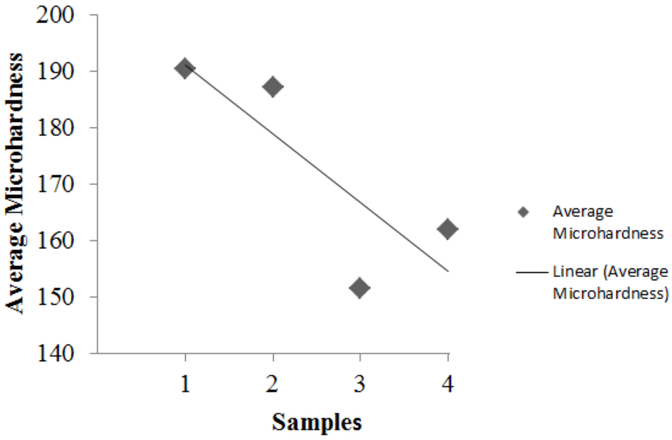

Fig. 7 Average microhardness of the samples

According to the results, the average Vickers hardness of sample 1 is 190Hv and sample 4 is 162Hv. These hardness values are higher than that of the traditionally processed annealed 316L alloy (155Hv). The decrease in microhardness value with increasing laser power can be attributed to the change in microstructure from fine to coarse.

V. Conclusion

The effects of laser power on the evolving microstructure and microhardness of LMD AISI 316L stainless steel using Nd:Yag laser were studied. The laser power was varied between 1.8 - 2.4 kW while the scanning speed and powder feed rate were kept constant at 0.6 m/s and 2l/min respectively. Three dissimilar zones observed on the samples were HAZ, MZ and CD. Increasing the laser power increased the coarseness of the grain structure of the deposit. The average microhardness of the sample was observed reduced as the laser power increased.

Acronyms

AISI – American Iron and Steel Institute
AM – Additive Manufacturing
CZ: cladding zone
Laser Additive Manufacturing
HAZ - Heat affected zone
LMD – Laser Metal Deposition
MZ - Melting zone

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