Effect of Scanning Speed on Laser Deposited 17-4PH Stainless Steel

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***Abstract*— Laser metal deposition (LMD) is one of the additive manufacturing technologies that is used in the production of fully dense parts layer by layer. This innovative manufacturing process has the potential to reduce the weight, time and cost of manufacturing components. It is able to process different metallic powders and also produce custom alloy or functionally graded material by consolidating different metallic powders. The purpose of this study was to investigate and discuss the structural integrity, mechanical property and microstructure of 17-4 precipitation hardened stainless steel processed by laser metal deposition. In this study, the laser scanning speed was varied while other process parameters where kept constant. Material characterization was done using optical microscopy and Vickers indentation testing. The results show that, the processed material was structurally sound and defect free. The microstructure was predominantly martensitic and the laser scanning speed was observed to have an influence on the micro-hardness of the structure.**

Keywords- Functionaly graded material; Laser metal deposition; Mechanical property; Microstructure

I. Introduction

Additive Manufacturing (AM) is a process where a component is fabricated from the bottom up in layers from a 3D computer model. There are three main AM application categories namely Rapid Prototyping (RP), Rapid Tooling (RT) and Direct Manufacturing (DM) [1], Amongst these categories, DM is the most recent addition and also the fastest growing area of AM application [1]. This category only became possible due to advancement in AM technology which resulted in improved quality of manufactured parts and processing of more durable materials like metals.

Laser Metal Deposition (LMD) is one of several AM technologies available today and this innovative manufacturing process was first patented in the late 1980's but only recently emerged as viable manufacturing method. LMD can be used to produce complex structures, manufacture components with multi-material properties or functional graded materials (FGM) as they are commonly referred to and also to repair components [2, 3]. However, solidification cracking and porosity are some of the common problems associated with this process [4].

Stainless steels are referred to as "stainless" because of their good resistant to rust compared to other steel grades. Chromium (Cr) is one of the principal alloying elements in stainless steels, the amount of Cr found in this group of iron alloy is usually greater than 12% and it is responsible their enhanced corrosion properties. Cr improves the corrosion and oxidation resistance by forming a thin, passive layer of chromium oxide on the surface of the alloy [5, 6]. There are five classes of stainless steel and each class consist of a number of stainless steel alloys with different compositions but having similar properties. The main classes of stainless steel are martensitic, ferritic, duplex, austenitic and precipitation hardenable (PH) stainless steel.

Precipitation hardened (PH) stainless steel are high strength alloys that have good weldability, formability and corrosion resistance comparable to the 300 series austenitic grade. They achieve their exceptional strength through the formation of fine precipitates when heat treated. The precipitation hardening process consist of three distinct steps namely solution treatment, quenching and age hardening or precipitation hardening [7]. PH stainless steels are further categorized into three based on their microstructure namely martensitic, austenitic, and semi-austenitic. The martensitic PH grade has superior strength due to strengthening from both the age hardening process as well as through martensitic transformation. 17-4 PH is the most widely used alloy of the martensitic PH grade [8]. Generally, they contain Cu precipitate and delta ferrite in the martensitic matrix [9], and a variety of mechanical properties can be obtained through heat treatment of this alloy to different conditions [10]. The highest strength is obtainable when aged at about 482°C (900 °F) for 1 hour. However, it has been reported that this alloy is more susceptible to stress corrosion cracking (SCC) at high strength levels [11]. Another major drawback is that 17-4PH stainless steel is unsuitable for applications in extreme temperature ranges, that is cryogenic temperature, as well as temperatures exceeding 315°C. 17-4PH stainless steel are mainly used in applications where good corrosion resistance and adequate strength is required, particularly in aerospace, petrochemical, energy and nuclear industry.

Solidification and microstructure evolution of laser processed materials differ from conventional manufactured materials. Non-equilibrium microstructures are more kinetically favoured in rapidly solidification processes like LMD as opposed to equilibrium phases observed in conventional solidification processes [12-14]. Several studies have been conducted on the evolving properties of laser processed stainless steel alloys [15-21]. These studies have shown that the resultant properties and microstructure of LMD manufactured component is largely dependent on the process parameters and the final part shows enhanced mechanical properties, hence extensive research on the right process parameters combination is necessary to ensure reproducibility of parts, stability, dimensional accuracy and integrity of the end product. In other words, it is paramount to have a good knowledge of the underlying physic of the LMD process and how it relates to the microstructural development and properties of the final part.

This study investigates the effects of scanning speed on the microstructure and microhardness of laser deposited 17-4PH stainless steel.

II. EXPERIMENTAL SETUP

A. *Material*

The metallic powder used in this study was gas atomized 17-4 precipitation hardening stainless steel powder. The chemical composition of the powder is presented in Table I.

The substrate was hot rolled 316 austenitic stainless steel. The substrate was sectioned into rectangular shaped coupons, with dimensions of 100 mm x 100 mm x 10 mm. Before the deposition process the substrate surface was first roughened by sandblasting to improve laser absorptivity and then cleaned with acetone.

TABLE I. ELEMENTAL COMPOSITION

Powder	Chemical Composition (wt. %)							
	Ni	Cr	Cu	C	Mn	Si	Nb	Fe
17-4PH	4.4	16.4	4.0	0.01	0.9	0.7	0.32	Bal.

B. *LMD Machine*

The LMD experiment was conducted at the Council for Scientific and Industrial Research (CSIR) Pretoria. The LMD system consist of three key components, powder feeder, laser head and computer control system. As the name implies, the computer control system is used to input the processing parameters selected for the deposition process. The powder feeder and laser head will be briefly described.

The powder feeder transports the powder by extracting it in a carrier gas (argon gas). The carrier gas used was argon which also minimizes oxidation of the powder. The powder feeder used for this experiment was a GTV PF 2/2. It is a dual hopper, disk type powder feeder and is calibrated in revolutions per minute (rpm). Each hopper is separately driven and this allows for the two experimental powder to be separately controlled and delivered. Powder feed rate is linearly proportional to angular velocity of the feeder disc and is calibrated in revolutions per minute. A picture of the powder feeder is shown in Fig 1.

Figure 1. Powder Feeder

The laser head comprises of a laser unit attached to a Kuka Robotics six-axis robotic arm positioning system, and also the nozzles from the powder feeder are attached to robotic arm. The laser attached to the kuka robot is a continuous wave 4.0kw Rofin Sinar (DY044) Nd:YAG laser with a wavelength of 1.06 μm. While the nozzles from the powder feeder are coaxially arranged to the end effector of the robot. A picture of the laser head is presented in Fig 2.

Figure 2. Experimental setup of the LMD system

C. *LMD process*

The LMD process was achieved by simultaneously melting the substrate with the laser and delivering powder to the melt pool created on the substrate. As the laser beam moves along the preset path, the deposited powder forms a solid track that is metallurgically bonded to the substrate. The length of the deposited track and overlap percentage is determined by the input parameters entered into the controller.

Three different samples were made, labelled A1-A3. For each sample, five successive tracks were deposited at 50% overlap. The main process variable considered in this study was scanning speed. Consequently, the scanning speed was varied while other process parameters were kept constant. The LMD parameters are provided in Table II.

TABLE II. LMD PROCESS PARAMETERS

Samples	Power (kW)	Scanning speed (m/s)	Beam diameter (mm)	Powder flowrate (rev/min)	Gas flowrate (l/min)
A1	2.4	0.4	2.0	2.0	2.5
A2	2.4	0.6	2.0	2.0	2.5
A3	2.4	0.8	2.0	2.0	2.5

III. RESULTS AND DISCUSSION

C. *Microstructure*

The optical micrograph of sample A1 processed at scanning speed of 0.4m/s is shown in Fig. 3. The sample is fully dense and defect free, which is indicative of good metallurgical bonding. The substrate is austenitic, showing distinct grain boundary. The microstructure of the melt zone comprises of tempered lath martensite. Retained austenite and delta ferrite have been reported in laser deposited 17-4PH stainless steel [17, 18]. The microstructure of the substrate is coarser than the deposited material, this is because of the high cooling rates associated rapid solidification processes. Fig. 4 shows the optical image of the deposit zone of samples A2 and A3 produced with scanning speed of 0.6m/s and 0.8m/s respectively. Similarly, sample A2 and A3 are crack free and fully martensitic.

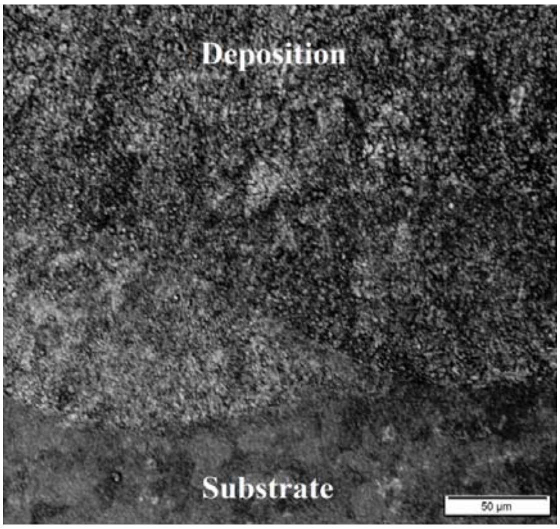

Figure 3. Optical micrograph of sample A1

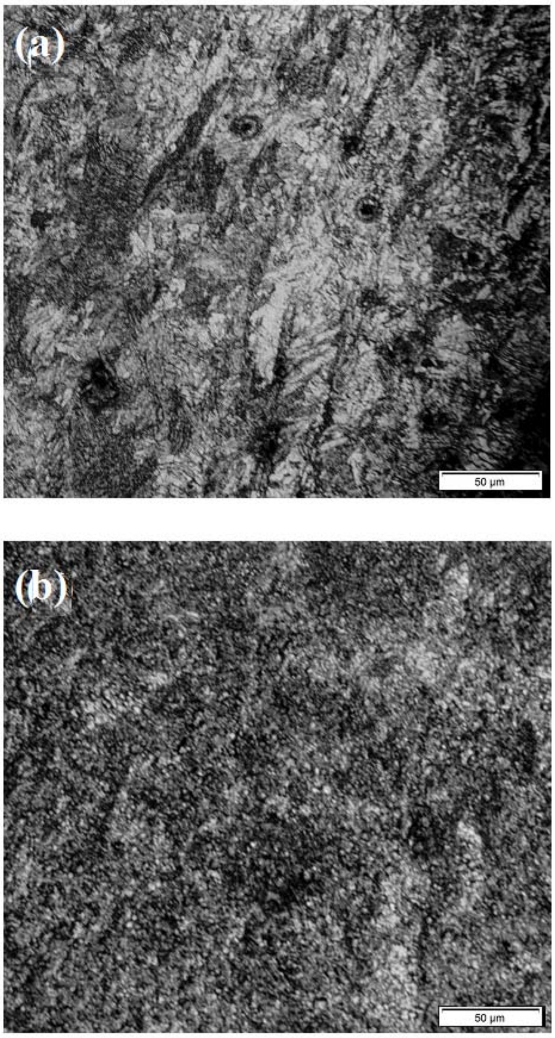

Figure 4. Optical micrograph of (a) sample A2 and (b) sample A3

D. Microhardness Analysis

The Vickers microhardness profile from the top of the deposit to the substrate is presented in Fig. 5.

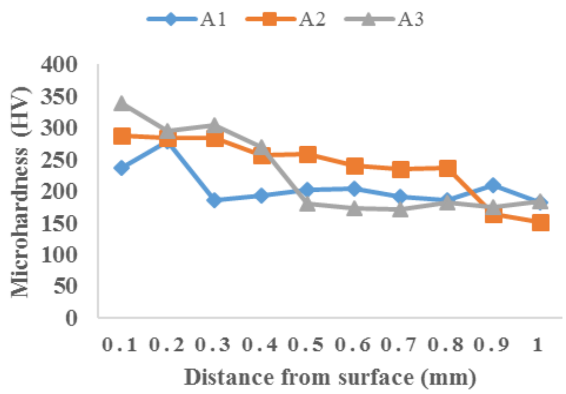

Figure 5. Variation of microhardness with depth

The microhardness value was observed to decreases with depth. This is attributed to the different grain structure in the melt zone and melt zone/substrate interface. The melt zone has a finer grain structure than that of the deposit/substrate interface.

Furthermore, the microhardness was observed to increase as the laser scanning speed increased. Sample A1 fabricated with laser scanning speed of 0.4m/s had the lowest hardness value, while sample A3 produced at 0.8m/s scanning speed had the highest microhardness value (339.5 HV). This increase in microhardness could also be attributed to grain refinement cause by a reduction in the amount of energy supplied by the laser. Since increasing the laser scanning speed results in shorter laser interaction time.

IV. CONCLUSSION

The effect of laser scanning speed on the microstructure and microhardness of LMD processed 17-4PH stainless steel powder has been investigated. The 17-4PH stainless steel powder was deposited on grade 316 austenitic stainless steel substrate at laser scanning speed ranging from 0.4 – 0.8m/s, while all other process parameter where unchanged. The samples showed good metallurgical bonding, the microstructure resemble that of tempered martensite. The microhardness was observed to have a relationship with the laser scanning speed.

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