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An effective parameter in the deposition of 17-4PH powder with LMD technique: scanning speed

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Abstract

Laser metal deposition (LMD) is a novel additive manufacturing process. Aerospace and automotive sectors utilize LMD to improve performance and speed up the process by minimizing connecting operations (welding, screwing, etc.) in production. This paper investigates the effect of scan speed on the microstructure and microhardness of 17-4 PH stainless steel fabricated via LMD. Differences in microhardness and microstructure are observed by varying the scan speed. The results showed that scan speed is a critical parameter for the LMD process and, it significantly affects the mechanical and microstructural properties.

Keywords: Laser metal deposition (LMD), 17-4 PH stainless steel, Scanning speed, Microstructure, Microhardness

1. Introduction

The Laser Metal Deposition (LMD) process is an Additive Manufacturing (AM) technology that uses powder as feedstock material and laser as a heat source. The laser beam creates a melt pool on the substrate and, the powder is fed directly into the melt pool. The metal powder melts due to the influence of the laser, forming a fission-related residue on the substrate. As the laser moves away, the residue solidifies and creates a track. Track by track, a layer is formed. Layer by layer, a freeform geometry can be fabricated [1-2].

According to the literature, precipitation hardening (PH) stainless steels have higher strengths than austenitic and ferritic stainless steels. PH steels exceed other martensitic stainless steel in terms of strength, ductility, and corrosion resistance. PH steels are cold moulded to the final shape of the product while retaining ductility. The strength and hardness are improved by heat treatment. Among the PH stainless steel family, Precipitation hardened Cr-Ni-Cu stainless steel 17-4 PH is used in applications requiring high strength and corrosion resistance. Precipitation hardening (PH) martensitic stainless steels are widely used in the aviation, marine, and power generation sectors because of their characteristics [3-4].

High scan speed reduces the length of time the laser beam interacts with the substrate and the deposited material. It reduces the heat input per unit area, resulting in incomplete melting of the material. Low scanning rates cause excessive heat build-up in the material due to increased interaction time between the laser and the material. This results in higher dilution and evaporation of certain constituent elements. As the scan speed increases, the dendritic microstructure of the deposition layers changes from coarse to fine and get reduced in size. The main dendritic arm spacing reduces from large to small and, the secondary dendrites degenerate. The melt pool shrinks in size and, the solidification rate is relatively high [5].

One of the effects that occur during production with the LMD method is the formation of heat-affected zones (HAZ). There is limited information in the literature about these heat-affected zones. Heat affected zone is the name of a specific region formed in the substrate to enable microstructural transformations such as grain growth, phase transformation etc. In this region, diffusion is bilateral and occurs both from the substrate to the deposition region and vice versa. A larger HAZ binding area is usually produced during production due to the higher heat input [6].

This study aims to examine the microstructural and microhardness changes of 17-4 PH stainless steel caused by the scan speed variation for the laser metal deposition process. Prior experimentation showed that lower scan speeds increased dilution and deposition time, which are not desirable. Therefore, higher scan speeds of (10mm/s - 15mm/s) are used in this study to understand the effect on the microstructure and microhardness.

2. Material and methods

The powder used was gas atomized 17-4PH stainless steel with a particle size of 45-106 μm and the powder was purchased from Oerlikon Gmbh. The chemical composition of the 17-4PH SS powder is presented in Table 1. Single-track multilayer samples were deposited for each sample. The scan speed was altered between (10mm/s - 15mm/s). The parameters that were fixed are laser power (2000 W), powder flow rate (4.5 revolutions/min), and gas flow rate (8 liters/min). The samples were coded 10, 13 and 16. After the deposition process, the samples were cut and prepared for characterization by cutting, polishing and etching. After etching, the samples were examined by an optical imaging technique. The microstructure was studied to understand how the scan speed affects the microstructure of each of the samples. The change in microhardness of the samples due to the effects of variation in scan speed was also investigated. The experimental matrix is presented in Table 2.

Table 1. Composition of the 17-4 PH stainless steel.

Element	Composition (WT %)
C	0,02
Cr	16,63
Cu	4,00
Fe	73,52
Mn	0,46
Mo	0,01
Nb	0,30
Ni	4,46
P	< 0,010
S	< 0,010
Si	0,49
O	0,03
N	0,01

Table 2. Experimental matrix.

Sample No	Laser Power (W)	Gas Flow Rate (L/min)	Scan Speed (mm/s)	Powder Flow Rate (rev/min)
10	2000	8	15	4.5
13	2000	8	12	4.5
16	2000	8	10	4.5

2.1 Materials and preparation techniques

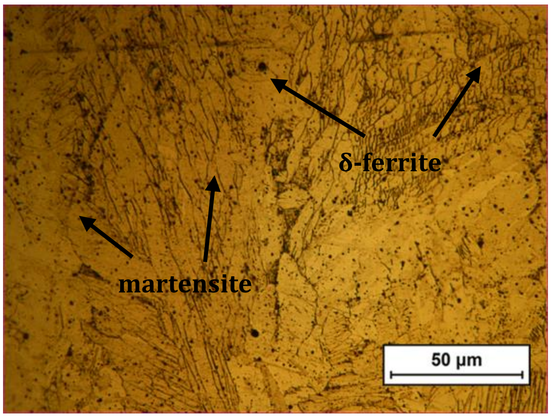
The substrate used in this research was 1050 stainless high carbon steel. The samples were prepared by coarse grinding, fine grinding, polishing and etching. The samples were etched using appropriate solutions (Marble's etching for 17-4 PH stainless steel and Nital etching to the substrate for different times). Microstructural characterization of etched samples was performed under an optical microscope.

2.1.1 Characterization of materials

The Microhardness test was done by applying a 100 gf (100-gram force ≈ 0.98 N) load for 10 seconds using the Future Tech FM-700 Microhardness Tester. It was difficult to differentiate one layer from one another because the layers were almost completely merged. The hardness measurements were made by taking the average of seven indents in the deposition zone.

3. Results and discussion

Fig. 1-3 show the structural phase changes observed under an optical microscope. In Sample #10, the δ-ferrite phase is more common and forms bigger grains in the top layer as shown in Fig. 1(a). The martensite phase is less prevalent in the lower layers. The cooling rate of the top layers is slower than that of the bottom layers depending on the direction, causing the grains to expand and the δ-ferrite phase gets eliminated before reaching room temperature and converting to the martensite phase. It is also noteworthy that the existing structures in the sample show elongation behavior. Fig. 1(b) shows that the size and the amount of δ-ferrite phase increases due to decreasing of ΔT.



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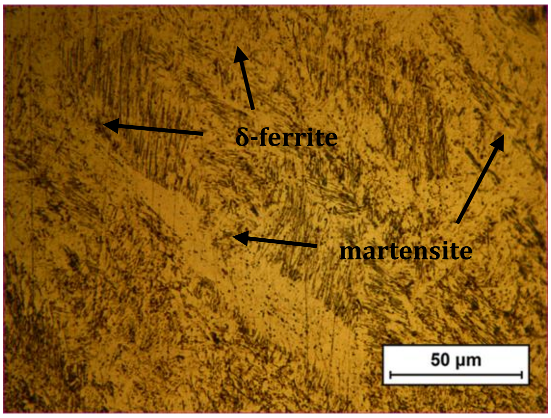
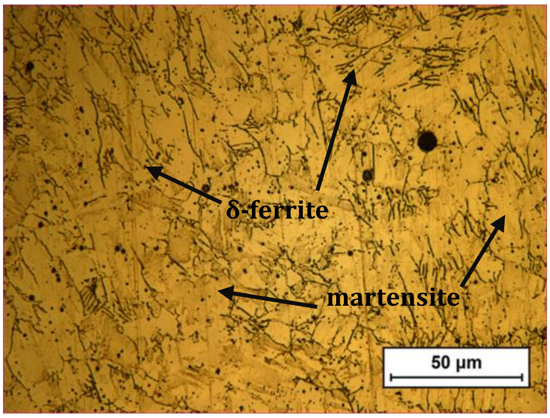


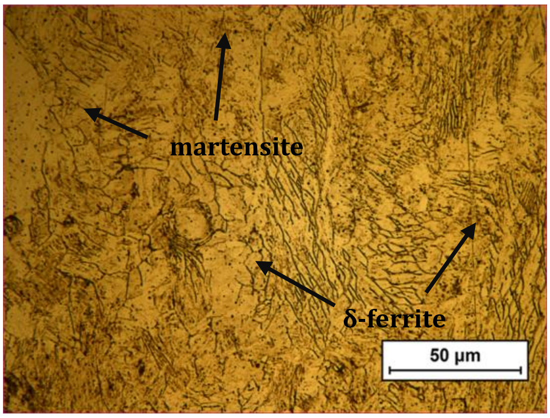
(b)

Fig 1. Sample #10 **a.** deposition zone top layer **b.** the lowest layer of the deposition zone.

Sample #13 demonstrates that reducing the scan speed from 15 to 12 mm/s greatly influences the microstructure as shown in Fig. 2(a) and 2(b). This sample exhibits similar results to Sample #10. The only exception is that the grain morphology in the topmost layer of the deposition zone is coarser as seen in Fig. 2(a). It is observed that the higher scan speed improved the cooling rate of the sample, however, it slowed grain development. The high-temperature difference between the substrate and deposition layer increased the cooling rate however it reduced the rate of martensitic structure formation. All three samples (10, 13, and 16) exhibit coarser grain morphology in the top layer and relatively finer grain morphology in the bottom layer. This is because of the temperature difference between the bottom and top layer, which impacts the cooling and solidification rate during the LMD process. Fig. 3(a) shows a reduction in temperature in the top layer causes an increase in grain growth and the martensite phase ratio. Fig. 3(b) shows how fast the cooling rate in the bottom layers results in the formation of extremely thin and high δ-ferrite.



(a)

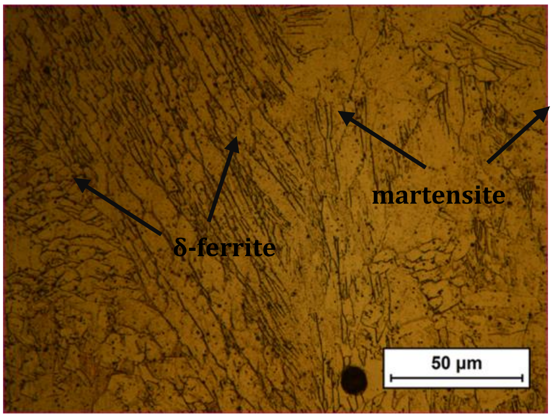


(b)

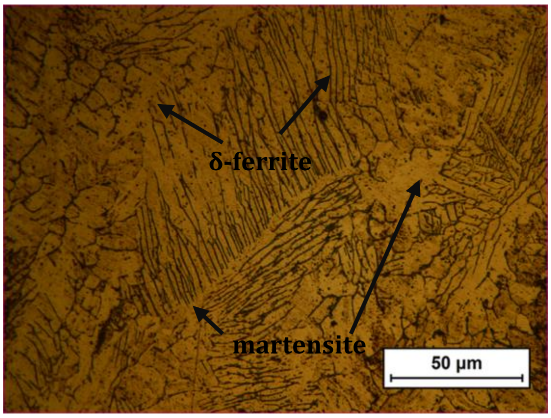
Fig 2. Sample #13 **a.** deposition zone top layer **b.** the lowest layer of the deposition zone.

Table 3. Process parameters of the samples and average microhardness values from deposition zone.

No	Laser Power (W)	Gas Flow Rate (Liter /min)	Scan Speed (mm/s)	Powder Flow Rate (rev/min)	Average Microhardness (Hv)
10	2000	8	15	4.5	402.3 ± 60.5
13	2000	8	12	4.5	385.4 ± 40.9
16	2000	8	10	4.5	346.6 ± 50.9



(a)



(b)

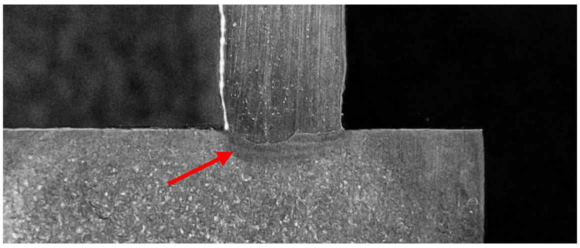
Fig 3. Sample #16 **a.** deposition zone top layer **b.** the lowest layer of the deposition zone.

The average microhardness is presented in table 3. The only variable that changes is scan speed. According to the literature research, by increasing the scan speed, the microhardness in the deposition zone of the sample also increases. It is observed that microhardness also increases with scan speed as seen in table 3. Due to the high scanning speed, hard and frequent grains are developed and it is effective in increasing the microhardness [7].

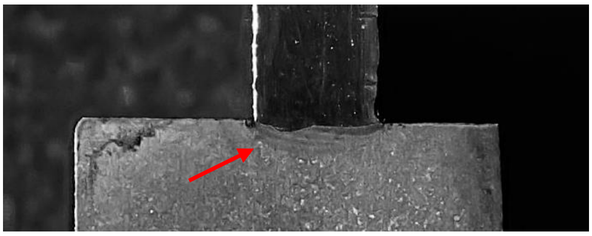
Process parameters directly impact the penitration and dilution in the substrate. Different amount of penitration in the substrate is observed for different parameter combinations as shown in Fig. 4. It is observed that by decreasing the scan speed, the penetration values generally increase.

Fig. 5 shows the effect of varying scan speed on the substrate microstructure. Fig. 5(a) shows a less dense HAZ region. This is because, at a higher scan speed, the interaction time between the laser beam and the substrate reduces, leading to a less dense HAZ region. At the same time, at lower scan speed, the substrate is exposed to the laser beam for a higher time interval which increases the temperature and melt pool size.

This increased melt pool increases the diffusion between the deposition zone and the substrate, resulting in an appearance as in Fig. 4(c) and Fig. 5(c).



(a)



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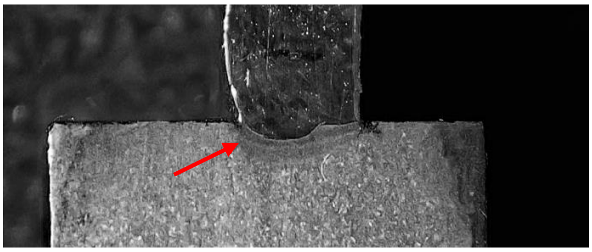
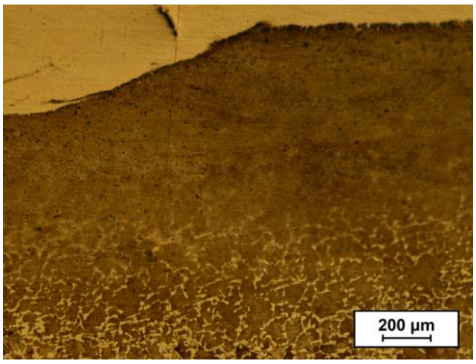
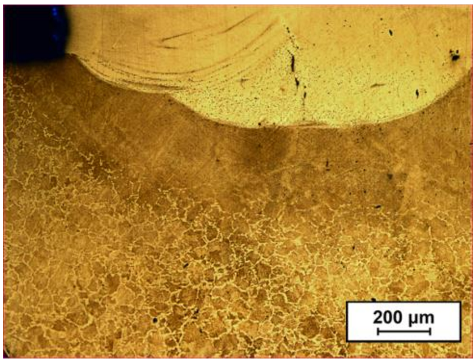


(c)

Fig 4. Macrographs of **a.** sample number 10 **b.** sample number 13 and **c.** sample number 16.



(a)



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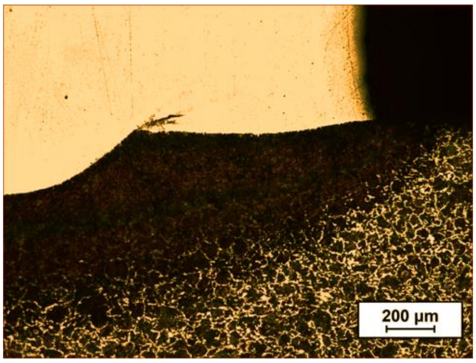

(c)

Fig 5. Micrographs of a. sample number 10 b. sample number 13 and c. sample number 16.

4. Conclusions

The microstructure and microhardness of laser metal-deposited 17-4PH stainless steel were studied. Increasing scan speed is beneficial in grain refining and, it modifies the δ-ferrite and martensite ratios based on the cooling rate difference in the sample's bottom and upper layers. The grain shape gets coarser with decreasing scan speed and, the martensite phase is dominant in the top layers, where the cooling rate is minimal. The microstructural changes are affirmed by micro-hardness tests. A decrease in micro-hardness with decreasing scanning speed is observed due to grain coarsening. On examination of the HAZ regions, it is observed that scan speed directly impacts the penetration and dilution in the substrate. High scan speed reduces the laser-substrate interaction time hence reducing the dilution. On the contrary, low scan speed increases the laser-substrate interaction time hence increasing dilution.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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