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Analysis of the Influence of Laser Parameters on the Microstructure and Surface Properties of Laser Deposited Aluminum Based Coatings

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Abstract: The effects of processing parameters were investigated namely laser intensity and speed of laser scanning of Laser Metal Deposition (LMD) process had on the microstructure, metallurgical evolution, porosity generated in the coating, the geometrical property of the coating and the sizes of the grains in the coating. The processing parameters were applied in combinations in order to find the optimized settings of the process that least affects the metallurgical properties of the Ti-6Al-4V alloy substrate clad with reinforced aluminium based powder. The temperature gradient and the rate of solidification of reinforcing the Ti-6Al-4V substrate with the aluminium based power were also focused on in terms of how they were influenced by the laser intensity and the scanning speed used in the building process. The inherent material properties were dependent on the process input parameters. The characterized performances considered in the investigation was influenced significantly by the laser processing intensity. The results of the investigation showed that the density had increased in proportion to the increase of the processing laser power coupled with the reduction of the speed of the laser scan. Moreover, for a laser power equivalent to and exceeding 950 W, the density became less susceptible to the laser power. The increased temperature field led to changes in geometry of the coatings as a results of more absorbed laser energy. The materials properties were influenced by the Fe-intermetallic compounds. The molten pool had columnar grains which were fully developed, along its volume as determined in the examination of the microstructure. In the direction of processing, the sample processed at 1.0-1.2 m/min had a reduction in width of the coatings from 1.643 to 1.293 mm and along the height it reduced to 0.375 at 2% Fe and 1% Mn. Increase in the percentage of both Fe and Mn increased the width of the coating to 1.833 mm at 1.0 m/min while the height continued to reduce to minimum of 0.272 mm at 1.2 m/min respectively.

Keywords: Al-Fe-Si-Mn coating; Microstructure; Laser Parameters; Laser Metal Deposition; Surface Properties.



1. Introduction

The superiority of advanced materials due to their high temperature and corrosion resistance performance is noticeable in the various application in energy, aerospace, biomedical, defense and environmental. This has been one of the tasks of engineers all over the world. The wide applications of advanced materials have been due to technological innovations demands which can improve the performance of these materials in the aforementioned industries [1, 2]. Friction coefficient reduction, better hardness and wear performance enhancement have been linked to altering of microstructures which in turn lead to surface enhancement. [3]. Modification of surface is very necessary in order to mitigate against catastrophic surface degradation of wear and corrosion. The only solution against this aforementioned degradation is to design coatings that can fight against this menace in order to retain the surface integrity. These fabricated coatings will bring innovative microstructures with exceptional properties and performance. [4].

The inability of conventional techniques to fabricate complex designs, shapes and enhanced microstructures have led to Additive Manufacturing (A.M) techniques in seeking for solution to this problem. Different surface modifications techniques had been published by researchers worldwide but these techniques still have limitations such as adhesion of reinforcement and base metal, pores, cracks, long processing time and not cost effective [5-9]. Additive Manufacturing processes had been the source that link process parameters, materials and the properties of final product as a results of engineering design and analysis abilities.

Due to good mechanical properties and moderately light weight, conventional aluminium alloys have been used extensively [10]. Brittle intermetallic phases are formed when aluminium, iron and silicon are alloyed together and this is very harmful to the performance of aluminium alloy [11]. Much attention has been drawn to the duty of refining the characteristics of iron-containing aluminium alloy coating [12]. Iron which give rise to beta phase during precipitation has become intricate impurities which is disadvantage to performances of aluminium alloy [13]. Changing the morphology of β -Al₅FeSi phase will minimize its deficiency and this has led to advance researches in this area. Addition of manganese (Mn) element which is the most efficient among neutralizing elements like Cr, V and Be, is one of the ways of changing the morphology of β -Al₅FeSi [14]. This study analyzes the influence of laser controls on the microstructure and surface properties of Al-Si-Fe-Mn Coatings.

2. Methodology

2.1. Materials Specifications and Sample Preparation Method

Dimensions 90 x 90 x 5 mm³ was used for the rectangular substrate in this research. The composition of the titanium substrate in wt.% was 6.12 Al, 0.0039 N, 0.19 Fe, 0.0002 H, 3.76 V, 0.13 O, and 89.80. Ti. Preceding the exposure of the substrate to laser irradiation, the substrates were blasted with sand, washed in H₂O, eviscerated with acetone and desiccated at 25 degrees. The process was necessary in order to avoid radiation reflection at the time of laser processing thereby allowing the substrate to absorb more laser irradiation. The reinforcement materials properties used in this research study is stated in Table 1. The reinforcement metallic powders were used as alloying powders mixed in in Al-10Si-2Fe-1Mn-1.0, Al-10Si-2Fe-1Mn-1.2, Al-10Si-4Fe-2Mn-1.0, Al-10Si-4Fe-2Mn-1.2, Al-10Si-6Fe-3Mn -1.0, Al-10Si-6Fe-3Mn-1.2 fractions correspondingly. The powders were brought into homogenization by mixing for 16 h at a stable turning speed of 72 rpm in a Tubular shaker mixer (T2F). The mixer has a 3-dimensional design that allows reinforcements of different particle sizes, weights and contents to be mixed unvaryingly. The mixture occurred in a bolted bottle that is air-tight.

Table 1: Reinforcement powders information

Reinforcement	Al	Si	Fe	Mn
Particle size (µm)	50-105	50-105	50-105	50-105
Purity %	99.8	99.8	99.8	99.8
Density (g/cm³)	2.70	2.32	7.86	7.43

Characterizations were done on the coated samples using scanning electron microscopy and energy dispersive spectroscopy (EDS) analysis (SEM/EDS: VEGAS TESCAN). A 3-kW continuous wave (CW) Ytterbium Laser System (YLS) was used for the fabrication of the coatings. The distance between the substrate and the three co-axial nozzle was 2 mm. The mixed homogeneous reinforcements were delivered through powder feeders at 3.0 g/min and the argon inert gas protecting the powder was set at 3.0 L/min. Intersecting tracks were attained at 75% overlap. Design of experiment (DOE) was applied to obtain optimal process constraints. The best process parameters were used to fabricate the composite coatings at 950 and 1000 W and 1.0-1.2 m/min scan speed.

3. Result and discussions

3.1. Microstructural Analysis

Table 2 shows the dimensions of the Al-Si-Fe-Mn coating geometry. While Figures 1-2 show the physical appearance of the deposits on the substrate after LMD of the reinforcement powders. The height and width of the layers varies with scanning speeds. The width appears to be wider at lower scanning speed but decreases with increasing scanning speeds as also reported by Sobiyi et al. [15].

Table 2: Dimensions of deposited Al-Si-Fe-Mn Coating

Sample	Scanning speed (m/min)	Width of Deposit (mm)	Height of Deposit (mm)
Al-10Si-2Fe-1Mn	1.0	1.643	0.540
	1.2	1.293	0.375
Al-10Si-4Fe-2Mn	1.0	1.570	0.306
	1.2	1.208	0.288
Al-10Si-6Fe-3Mn	1.0	1.833	0.484
	1.2	1.582	0.272

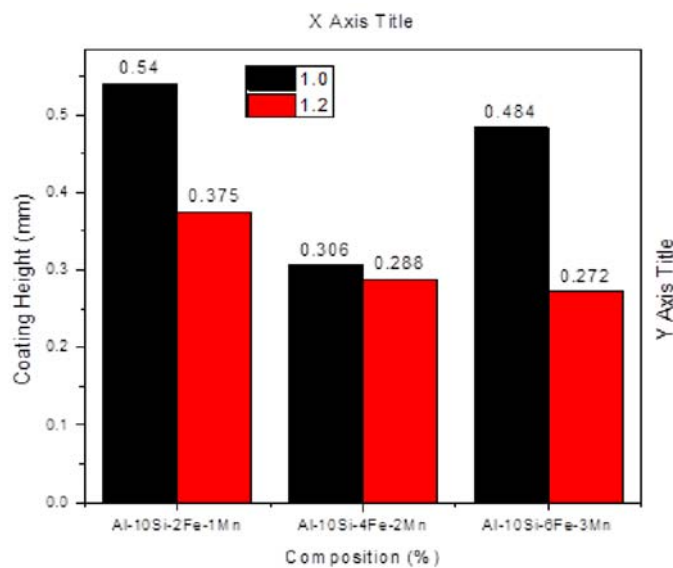


Figure 1: Variation of Coating Height with Scanning Speed and Al-Fe-Si-Mn Compositions.

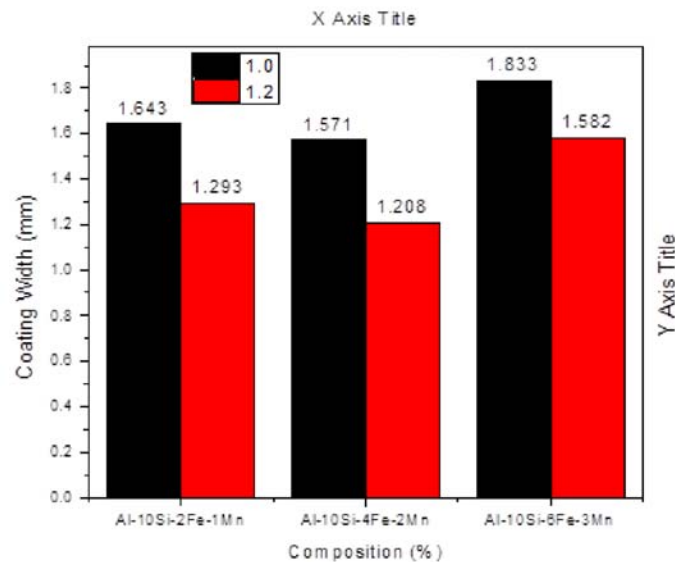


Figure 2: Variation of Coating Width with Scanning Speed and Al-Fe-Si-Mn Compositions.

The higher the scanning speed, the lower the dilution percentage. This is due to the increased cladding rate that has small heat input with respect to the clad height. Moreover, the melt penetration is high when the scanning speed is low because the thickness of clad layer is bigger and thus minimum in the substrate will occur. It was also observed that melting in the substrate surface happens only if the clad height is small and therefore dilution is high. It was found that laser power and scanning speed have greater impact on dilution. It was observed that laser cladding production time must be reduced to per unit distance in order to have a low dilution. It was discovered that distinct powder composition during laser cladding process caused the fluctuation of dilution [15-18].

The utilization of independent processing parameters produced characteristics specific to the molten pool, but energy densities are in general proportional to the resulting characteristics of the molten pool as shown in Figures 3 and 4. Observations showed that the size of the molten pool enlarged as successive tracks were scanned and this was consequent to the heat which was accumulated during the deposition of the multiple tracks. It was observed that the unsymmetrical

shape of the molten pool after completion of the first deposited track had moved in the direction of the adjacent subsequent tracks deposited. As the adjacent tracks were deposited, the material was undergoing great cyclic heating and cooling [19]. The increased temperature field led to changes in geometry of the coatings as a results of more absorbed laser energy. It was ascertained that the mechanical properties are mainly dominated by the final modified microstructure, which is affected by the molten pool size [20-26].

At the advanced scan speed of 1.2 m/min, the surface geometry was observed to be significantly improved. The surface geometry was adversely affected by the cumulative heat generated during the process at high laser power. Therefore, the processed Ti-6Al-4V/Al-Si-Fe-Mn samples at 1.2 m/min produced satisfactory surface geometry in both height and width of the coatings with respect to the base material. As compared to scan speed of 1.0 m/min, delineated by the large variances in values of the surface geometry between these two processing conditions. The heat generated and stirring effects on the surface of the material attributed to the formation of four distinct zonal microstructures, including: the stirred area of the material constituted with a microstructure which was recrystallized, it had fine compact needle-shaped martensitic and alpha grains as shown in Figure 3. The area in which transition took place had a microstructural matrix consisting of alpha and beta and possessed fine alpha lamellae; the zone which was heat affected had very fine lamellae and the untreated substrate area retained its initial microstructure. The advancing scan speeds were varied for the three processing conditions and it was observed that the microstructural zones identified were susceptible to change as the scan speed was varied. However, the compositions of the reinforcements also had influence on the surface geometry of the coatings. Increase in the weight percent of iron and manganese to 6 and 3 % respectively increased the width of the coating while the height decreased. Since iron and manganese melt at 1538 and 1246 degree Celsius respectively, more laser power would be needed to melt the iron and manganese as their contents increased. This in turn affect the geometry of the melt pool leading to change in width and height. This made up the distinct microstructural zones were affected by the varying scan speeds [27-29].

Thin martensitic primary alpha phase was observed in the cladded specimens in attribution of generated heat applied locally, a fast rate of solidification coupled with prompt cooling. In addition, the produced specimens also had the primary alpha microstructure developed on the inside of long original grains of the columnar beta. There was a formation of primary alpha phase elongated in structure, as well an alpha-beta structure which was transformed from the initial martensitic primary alpha after the specimens were heat treated as shown in Figures 5 and 6. The

metallurgical analysis revealed that the morphology of the microstructure constituted of needle-like structures in double phases possessing favourable transitioning and minimal defects.

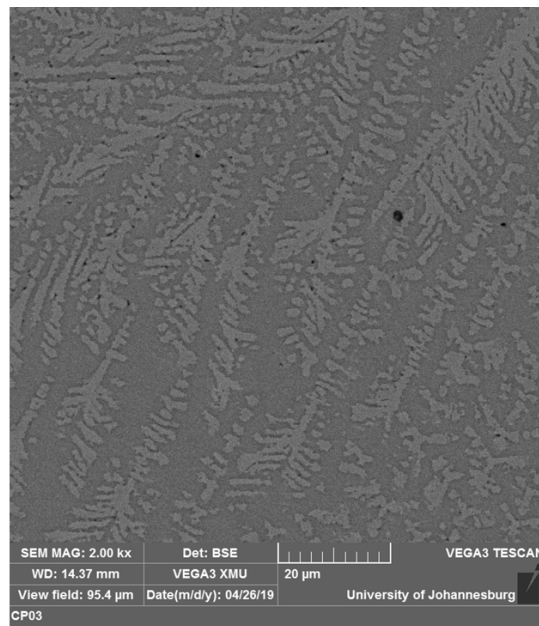


Figure 3: SEM Micrograph of Al-10Si-4Fe-2Mn Coatings at scanning speed of 1.0 m/min

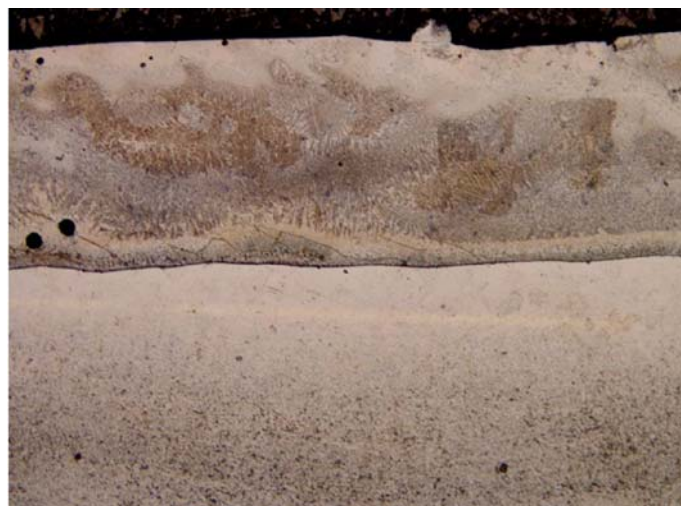


Figure 4: Optical Micrographs of Al-10Si-4Fe-2Mn Coatings at scanning speed of 1.2 m/min at 1000 W

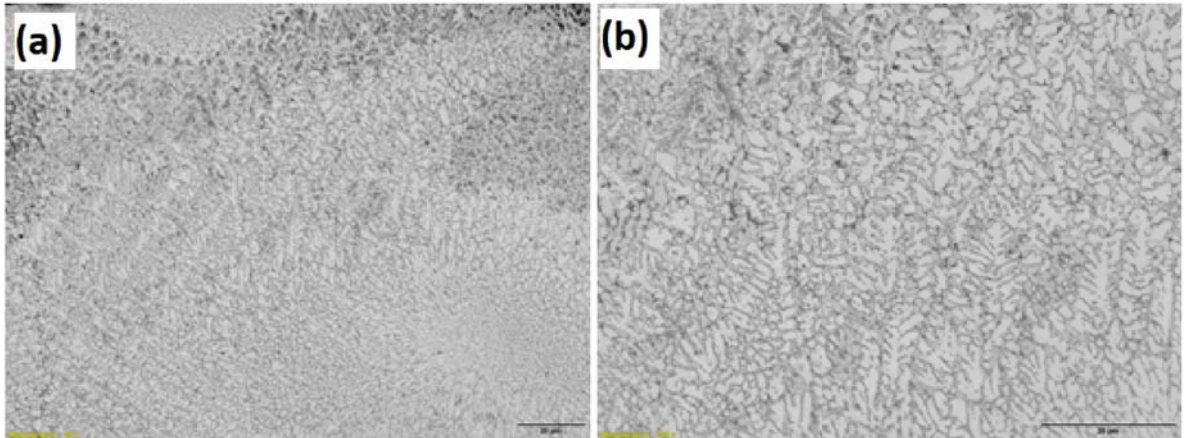


Figure 5: Optical Micrographs of Al-10Si-2Fe-1Mn Coatings at scanning speed of (a) 1.0 and (b) 1.2 m/min at 950 W

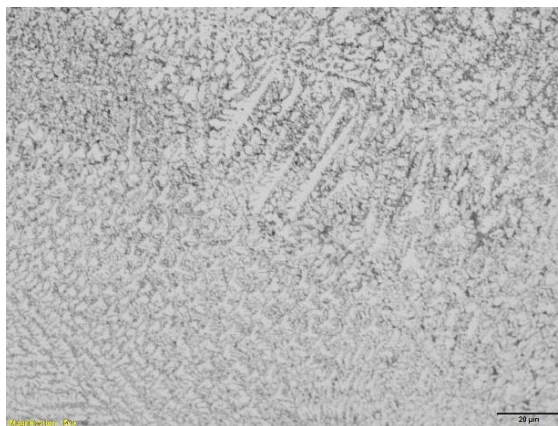


Figure 6: Optical Micrograph of Al-10Si-6Fe-3Mn Coatings at scanning speed of 1.2 m/min

Moreover, three zones were also observed namely; the region where the powder melted, a region that was re-melted and a region which was reheated. The heat flux direction and the spacing of the hatch between the overlapped adjacent tracks deposited induced by the heat cycles in the melt pool influenced the morphology and direction in which the prior beta grains grew (Figure 4).

4. Conclusion

- ✚ At the advanced scan speed of 1.2 m/min, the surface geometry was observed to be significantly improved. The surface geometry was adversely affected by the cumulative heat generated during the process at high laser power.
- ✚ Thin martensitic primary alpha phase was observed in the clad specimens in attribution of generated heat applied locally, a fast rate of solidification coupled with prompt cooling. In addition, the produced specimens also had the primary alpha microstructure developed on the inside of long original grains of the columnar beta.
- ✚ The sample processed at 1.0-1.2 m/min had a reduction in width of the coatings from 1.643 to 1.293 mm and along the height it reduced to 0.375 at 2% Fe and 1% Mn. Increase in the percentage of both Fe and Mn increased the width of the coating to 1.833 mm at 1.0 m/min while the height continued to reduce to minimum of 0.272 mm at 1.2 m/min respectively.

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