Investigating the Microstructural Evolution and Characterization of Additive Manufactured Zn-Sn-Ti/Ti-6Al-4V Composite.

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Abstract:
The investigation focused on studying how the reinforcement powders and titanium alloy substrate were influenced by the volumetric energy which was absorbed. The only processing parameters which were varied was the laser intensity and the scanning speed, which were employed to design the direct laser metal deposition (DLMD) single- and multi-tracks. Laser surface modification techniques have unique benefits and properties compared to other conventional techniques. These techniques have process factors that affect directly the microstructure of materials which in turn influence the materials properties. The results revealed dense microstructure in the fabricated coatings in terms of the microstructural evolution, the sizes of the different grains, the structure of the phases formed and the orientation. The modified surface layer of the additively manufactured coating had improved and had a fine microstructure. Optimizing the DLMD processing conditions resulted in a crack-free surface layer but still promoted a few population of gas defects. The micro-hardness measured in the 5Zn-10Sn-Ti coating at 900 W and scan speed of 1.0 m/min was approximated to be 637 HV at all processing conditions employed, and with respect to the hardness of the substrate, there was a 51.33% increase from 310 HV. But increase of 57.2% was noted at 900 W, 1.0 m/min for 5Zn-10Sn-Ti coating. There was enhancement in the results of the micro-hardness tests conducted and this was due to the resulting microstructural evolution. Homogeneous and dense microstructures was accountable for the micro-hardness performance measured.

Keywords: Ti-6Al-4V alloy; micro-hardness; microstructure; Zn-Ti-Sn coatings; characterization.

1. Introduction

Applications of Titanium alloy in aerospace due to its active strength-to-weight competency, immunity against corrosion and thermal steadiness could make titanium alloy an extremely alluring metal. Application of this metal can occur at higher temperature with an important temperature of roughly 600°C. Initially, aerospace application was the center of utilization of titanium alloy, however, ist applications has surpassed aerospace and can also be found in sports, automotive, energy and medical where the exeptional characteristics of titanium alloy are being used. [1-3]. Varied components of aircraft in the aerospace industry has a touch of titanium where
titanium alloy is chiefly and immensely employed such as the mechanical device blades, turbine and jet engines, and frame parts components. The extension of titanium applications in other sectors had been due to continual process and passion for new engineering components and industrial growth. For example, energy, medical and marine industries have thought-about its application thanks to its wide read of most popular properties that symbolize outstanding corrosion resistance, unique mix of durability and high strength [4].

Weight reduction in a specific material is one of the ways of advancing the performance of that particular materials and builds its capacity to perform optimally [5]. This means development of materials can improve the general efficacy of airplane performance [6]. Discoveries and inventions of new techniques, materials and advanced technologies have made aerospace sector the most vibrant industry over the years. Various factors such as cost, reduction in weight and enhanced thermal capacity have been responsible for materials advancement in the aerospace industry. This in turn has positive effects both economically and environmentally [7].

The enhancing of the wear and mechanical properties can be done by laser surface modification technique. This technique has two-folds ability by increasing the resistance to wear and corrosion and also alleviates metal ions from escaping thereby hardening the surface of the alloy [8]. Surface engineering through laser technique has shown tremendous growth over the years and has the capability to refining and widening the applications of engineering components. Several surface modifications through laser techniques had been reported [9-11]. This study investigates the microstructural evolution and characterization of Zn-Sn-Ti/Ti-6Al-4V composite.

2. Methodology

2.1. Materials Specifications and Sample Preparation Method

Dimensions 90 x 90 x 5 mm$^3$ 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 Bal. Ti. Preceding the exposure of the substrate to laser irradiation, the substrates were blasted with sand, washed in H$_2$O, 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 5Zn-10Sn-Ti-1.0 (A1); 5Zn-10Sn-Ti-1.2 (A2); 10Zn-15Sn-Ti-1.0 (B1); 10Zn-15Sn-Ti-1.2 (B2) 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.

| Reinforcement | Zn | Ti | Sn |
|---------------|----|----|----|
| Particle size (μm) | 50-105 | 50-105 | 50-105 |
| Purity % | 99.8 | 99.8 | 99.8 |
| Density (g/cm³) | 7.14 | 4.51 | 7.31 |

Characterizations were done on the coated samples using scanning electron microscopy and energy dispersive spectroscopy (EDS) analysis (SEM/EDS: VEGAS TESCAN) and optical microscope (OPM). 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 2.0 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 900 and 950 W and 1.0-1.2 m/min scan speeds.

3. Result and discussions

3.1. Morphological and phase analyses of the Zn-Sn-Ti/Ti-6Al-4V Composite coatings

The particle size of the titanium powder was spherical in shape and gas atomized as shown in Figure 1. The spherical shape is what determines the flowability of the powder during direct laser metal deposition (DLMD). This shape factor is very necessary during DLMD technique. Dense and homogeneously SEM of the titanium powder is shown in Figure 1. Based on Table 1, the purity of all the powders were maintained at 99.8 %. The chemical reactions that occurred during DLMD of titanium, zinc, tin produced few compounds like TiZn₁₆, Ti₃Sn, Ti₂Sn and Ti₆Sn₅. These
are the results of partial melting of the substrate with combinations of reactions of the various reinforcements in the melt pool. Rapid cooling and solidification had impacts on the types of compound formed in the coatings. Since all the three reinforcements have different melting points, intermetallics were formed due to rapid solidification of DLMD technique. The DLMD process factors also had significant effects on the microstructures which in turn influence the coating properties. The ability to form more compounds was determined by the content in wt.% of titanium present in the reinforcements. El-Faramawy et al. [16] had reported how refinement of grains was influenced by titanium addition and this enhance the mechanical performance. Forming of TiZn$_{16}$ and Ti$_6$Sn$_5$ at the control-coating interface signifies good bonding between the control-substrate interface [17]. Factors like titanium composition of the control, temperature of the melt pool, cooling speed and laser power can also influence the formation of intermetallic in the reaction of reinforcements and the substrate [18].

Rates of solidification in the DLMD process differ and this is due to the process parameters influence. dense microstructures thus and enhance performance of coatings resulted from these optimized parameters (Figure 2). The solid-state phase transformation caused a change in the volumetric strain, which was ascertained by the thermal histories that measured the evolution of the volumetric fraction in the microstructural phases. It was discovered that the thermal histories and the solid-state phase transformations had induced strains. The investigation also focused on studying how the reinforcement powders and titanium alloy substrate were influenced by the volumetric energy which was absorbed. The only processing parameters which were varied was the laser intensity and the scanning speed, which were employed to design the DLMD single- and multi-tracks. The advancing scan speeds were varied for the two processing conditions and it was observed that the microstructural zones identified were susceptible to change as the scan speed was varied as shown in Figures 2-5. A change in grain size as a result of scan speed changes had been reported in the literature [19-21]. Quick rate of cooling as the materials solidify with enhanced microstructure was also reported by other researchers [22-24] as a result of the scan speed changes.
The metallurgical analysis revealed different transformation in the microstructures to a final alpha/beta structures that had transformed with martensitic primary alpha and a morphology woven like a basket (Figure 3).
Microstructural analysis revealed that the initial primary alpha microstructure transformed into a matrix of alpha-beta as shown in the cross-section of the coatings and microstructures (Figures 2 and 4). The thermal history during the DLMD process led to the evolution of various beta grain types, change in morphology, stability value reached when the grain size increased, the growth of grains, and the stability reached upon reduced grain size (Figure 6). During the successive scanning of the laser beam on the material, structures of alpha-beta were formed which were decomposed in-situ from the transformation of martensitic structures upon solidification in the zone which was identified being fully transformed. It was identified that the observed transitioned layer has coarse grains and increased in volume. The modified surface layer had improved and had a fine microstructure. Optimizing the DLMD processing conditions resulted in a crack-free surface layer but still promoted a few population of gas defects.

Visibility of few blow holes in the microstructure (Figure 3) as a result of trapped air that occurred via rapid cooling could be scantily observed. This correlates with the works of Yuan et al. [25].
There is relationship between the enhanced mechanical properties and the refined grains. Homogeneous and dense microstructure can be observed in the microstructures (Figures 4 and 5). This came to be as a result of rapid cooling rate. Formation of larger grains was barred due to fast rapid cooling that quickly solidified [26-28]. The Laser Metal Deposition process is known to provide a high molten pool solidification rate, and this facilitates in the improvement of coating property which are produced by the process.

Figure 4: SEM Image of 10Zn-15Sn-Ti Ternary Coatings at Laser Power of 950 W and scanning speed of 1.2 m/min
Figure 5: SEM Image of 10Zn-15Sn-Ti Ternary Coatings at Laser Power of 950 W and scanning speed of 1.0 m/min

Figure 6: Optical Micrograph of 5Zn-10Sn-Ti Coatings at Laser Power of 900 W and scanning speed of 1.2 m/min
3.2 Micro-Hardness of Zn-Sn-Ti/Ti-6Al-4V Composite Coating

The micro-hardness measured in the 5Zn-10Sn-Ti coating at 900 W and scan speed of 1.0 m/min was approximated to be 637 HV at all processing conditions employed, and with respect to the hardness of the substrate, there was a 51.33% increase from 310 HV. But increase of 57.2% was noted at 900 W, 1.0 m/min for 5Zn-10Sn-Ti coating. A micro-hardness of approximately 929 HV was measured at the 10Zn-15Sn-Ti coating at 900 W and scan speed of 1.2 m/min and there was a 51.33% increase from 310 HV. 10Zn-15Sn-Ti coating showed slight decrease in hardness (913 HV) at 900 W and 1.0 m/min. The HAZ had a micro-hardness under 449 HV and close to the 310 HV measured for the substrate. Due to the similar microstructural composition in each processed zone, there was major discrepancy in the hardness values for all three zones as shown in Figure 2.

The micro-hardness analysis indicated of the uncoated and the coated DLMD specimens showed that the uncoated specimens had their hardness lower compared to the DLMD coated. The highest hardness was found at their centre. The Vickers Micro-hardness measurements obtained were influenced by the formation of the dense alpha case and that there was anisotropy. Micro-hardness analysis showed that the average hardness of the Ti-6Al-4V substrate was approximately 310 HV and the improved hardness was 929 HV which was found within the coating at a laser scan speed of 1.2 m/min.

4. Conclusion

The metallurgical analysis revealed that prior beta grains which were columnar in structure had formed in the microstructure and was described precisely by the alpha grain boundary and the alpha/beta structures that had transformed with martensitic primary alpha and a morphology woven like a basket.

The modified surface layer of the additively manufactured part had improved and had a fine microstructure. Optimizing the DLMD processing conditions resulted in a crack-free surface layer but still promoted a few population of gas defects.

The chemical reactions that occurred during DLMD of titanium, zinc, tin produced few compounds like TiZn_{16}, Ti_{3}Sn, Ti_{2}Sn and Ti_{6}Sn_{5}. These are the results of partial melting of the substrate with combinations of reactions of the various reinforcements in the melt pool. Rapid cooling and solidification had impacts on the types of compound formed in the coatings.

The micro-hardness measured in the 5Zn-10Sn-Ti coating at 900 W and scan speed of 1.0 m/min was approximated to be 637 HV at all processing conditions employed, and with
respect to the hardness of the substrate, there was a 51.33% increase from 310 HV. But increase of 57.2% was noted at 900 W, 1.0 m/min for 5Zn-10Sn-Ti coating.

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