Corrosion Performance and Surface Analyses of Laser Cladded Zn-Ni-Fe Coatings on ASTM A29 Steel.

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Abstract:
The corrosion behaviour of the laser coatings was investigated in 3.65 % sodium chloride solutions at 30°C via potentiodynamic polarization technique. The composition of Zn-50Ni-5Fe at parameters 900 W and 1.2 m/min exhibited enhanced electrochemical performance in 3.65wt.% NaCl solution. Microstructures with unique characteristics and refinement of grain size were observed. The fast solidification of the coating is accounted for this unique features. In terms of corrosion performance, results revealed that increasing the laser scanning speed was beneficial to the property, showing that the corrosion performance became better at higher scanning speeds. At the set laser intensity of 900 W and increased laser velocity, Zn-50Ni-5Fe coatings showed enhanced microstructure. The multiple tracks applied in the direct laser metal deposition (DLMD) process had resulting fields of residual stresses which attributed to the solid-state phase transformation that was a repeated process. The study validated the reliability of optimizing DMLD set parameters for metallurgical and mechanical considerations. These bring improvements in coatings which were laser cladded in terms of their corrosion performance and the dimensional accuracy, by optimizing the processing parameters. The only processing parameters which were varied was the laser intensity and the scanning speed, which were employed to numerically design the DLMD experiment. An empirical method was also developed and was used to validate the results achieved experimentally. The Grey relational model (GRM) used in this research described vividly the influence of optimized factors on the improved corrosion resistance and compared reasonably with the experimental results. In addition, the proposed model has the potential to provide induced corrosion rate predictions of coatings fabrication that are additively manufactured.

Keywords: ASTM A29 steel; Corrosion resistance; microstructure; Zn-Ni-Fe coatings; Grey Relational Model;

1. Introduction

Additive manufacturing rate of progressive from global perspective has become a source of joy in the design world. Investment into A.M technologies is mind blowing and has eliminated the drawbacks of complex shape design, fabrication of coatings with exceptional properties and near net shape designs. AM techniques of metals and polymer had been reported by many researchers in the literature. The focus had been on metals and polymers over the years. But literature on the
additive manufacturing of advanced and complex-shape materials are scarce in the literature. In the capabilities of engineering design and analysis, establishing the relationships between process parameters, material and final product properties are largely dispersed in reference to 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. [1-4].

There are cogent factors responsible for DLMD technique. Change in this factor can alter the microstructure positively or negatively. Therefore, optimization of factors is very important in getting better results from our experiments and these factors can also be used to model any property exhibit by the DLMD coating. Physical-mechanical characteristics, deposition time, solidification time, and integrity of the DLMD coatings are depended on optimization factors [5-8].

The rate of spending in aerospace industry cannot be over-emphasised as a result of aircrafts engine components which needs to be repaired and maintained for optimal performance. Most of these engines are fabricated with super alloys materials like chromium based, nickel based and titanium alloys. These materials can give optimal performance at extreme conditions [9-12]. Component parts design and material design determine the effectiveness and lifecycle of that component. To enhance the effective of components parts, several techniques had been highlighted in the literature for this purpose [13-16]. Engineers and scientists all over the world are in the race of developing new materials and techniques with exceptional qualities that can address the issue strength at high temperature, ability to withstand heat and improved mechanical performance. The drive behind new material development and peak performance of components parts are realised through surface modification. Material surface is at the mercy of its environment when in contact, therefore, surface modification can retain and enhance the components integrity against corrosion and wear. This study analyses the surface and corrosion performance of DLMD Zn-Ni-Fe on ASTM A29 steel.

2. Methodology

2.1. Materials Specifications and Sample Preparation Method

Dimensions 70 x 70 x 5 mm$^3$ was used for the rectangular substrate in this research. The composition of the ASTM A29 substrate in wt.% was (wt%) 0.39 Mn, 0.022 S, 0.011 P, 0.160 C and Bal. Fe. Preceding the contact of the base metal to laser treatment, 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 2. The reinforcement metallic powders were used as alloying powders mixed in Zn-50Ni-3Fe (A₁); Zn-50Ni-3Fe (A₂); Zn-50Ni-5Fe (B₁); Zn-50Ni-5Fe (B₂) fractions correspondingly. The thorough mixing of the reinforcements was achieved in 16 hrs at a constant spinning velocity of 72 rpm in a Tube-shaped 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   | Zn | Ni | Fe |
| Particle size (μm) | 50-105 | 50-105 | 50-105 |
| Purity %         | 99.8 | 99.8 | 99.8 |
| Density (g/cm³)  | 7.14 | 8.90 | 7.86 |

Characterizations were done on the coated samples using scanning electron microscopy and energy dispersive spectroscopy (EDS) analysis (SEM/EDS: VEGAS TESCAN) and X-ray diffraction (XRD). 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 800 and 900 W and 1.0-1.2 m/min scan speeds.

3. Result and discussions

3.1. Zn-Ni-Fe ternary alloy coating microstructure

The prepared coating is mainly composed of Zn, Ni and Fe phases; subsequent to laser cladding, reactions occurred between the molten substrate and the reinforcement material which led to formation of advantageous fine-grained microstructure and phases. From Figure 1, it can be
deduced that the following phases: FeNi$_3$, FeNi, ZnNi, Fe$_2$Zn$_{10}$, Zn$_{11}$Ni$_2$, FeNiZn$_{13}$ and Fe$_5$C$_2$ were formed. Furthermore, this could be attributed to the high energy of the laser beam. In addition, it should be noted that FeNi has FCC structures. Jian, Chun and Song [17] affirmed that during cladding intermetallic compounds are formed. The existence of Fe is minimized, probably due to the number of tracks that caused an increase in the diffusion path of Fe, restraining it to diffuse into the surface [18]. The reduction of Fe on the surface could indicate good properties of the alloyed coating, since Fe cannot diffuse towards the surface.

Figure 1: XRD Spectrum of Zn-50Ni-5Fe Ternary Coatings at Laser Power of 900 W and scanning speed of 1.2 m/min

Figure 2 shows SEM image cross-sectional view of Zn-50Ni-5Fe-1.2 coating. It also highlights an area of heat affected zone and interfacial bonding between the Zn-Ni-Fe coatings. In terms of their atomic weights Zn and Ni are much denser than Fe, having weights of 65.38, 58.70 and 55.85 respectively. Therefore, the lighter area indicates the substrate and the darker area indicates the coating. Figures 6 exhibits smoother compact coating, indicating that it contains finer grains and it can be observed that the layers are pore-free, moreover there are minimal grooves which resulted from metallographic grinding.

The dimensions of the molten pool varied in accordance to an invariant energy density and, although a combination of processing parameters might have resulted at the same energy density value, the characteristics of the molten pool varied. This is the reason why process parameters are
optimized. Any tempt in slight changes to process parameters without optimization can affect the microstructure negatively. Design of experiment (DOE) is one of the techniques used in optimizing process parameters. The influence of the parameters is also tied to the thermal history and input energy density. The process creates a molten pool from a small layer on the surface of the material by re-melting it with a laser and the effects of the surface tension in the pool are exploited which results in a less rough surface. Superficial modifications were done to the surface of the fabricated coatings due to the layer of molten pool on the surface that re-solidified instantaneously and the thermal effects on the substrate.

Observations of the process on the preheated substrate revealed that the preheating allowed for lower processing laser power to be used and reduced the rate of cooling between the peaked temperatures which were generated consecutively, in effect it improved the resistance of micro-cracks. During the cladding process, the heat had built up as the successive layers were deposited and due to this phenomenon, it was observed that the subsequent coats applied had a much lower rate of cooling than the first deposited layer. The application of the first coated layer had a peak stress gradient that exceeded the maximum strength but only for a short while during the process. However, application of the second coating of reinforcement powders had a peak stress gradient that was lower than the maximum strength. This observation served as evidence that with successive coatings applied the micro-cracks susceptibility of the cladded Zn-Ni-Fe materials reduced. In the case of the substrate that was not preheated and had a subsequent coatings and tracks was highly susceptible to cracks that propagated transverse to the tracks in proximity to the substrate. In some cases, the superficial surface of the clad has cracks that propagate across it. Usually what causes the promotion of cracks during the coating of the tracks is the thermal effect that the processing laser has on the tracks alongside the newly formed tracks. The limitation of not preheating the substrate prior to the cladding process made the coating susceptible to experiencing cracks on its surface which originated internally.
Small quantities of blow holes are also visible which would indicate that air could be trapped during rapid cooling as reported by Yuan et al. [19]. The finer grains highlight that the mechanical properties have been enhanced. The structures of coatings are quite homogeneous; due to the rapid cooling rate that solidified faster restricting the formation of large grain sizes [20]. The results had revealed that between the low to moderate energy densities, the Heat Affected Zone (HAZ) had such minimal variation, whereas the volume of the molten pool was linearly proportional to the energy density. Laser cladding process was employed and created in-situ coatings of desirable strength and low coefficient of friction and subjected the ASTM-A29 steel components to corrosion degradation. The industry desires coatings with such characteristics as it renders the components a much longer service life in environments where the material is susceptible to corrosion degradation.

The DLMD process is known to provide a high molten pool solidification rate, and this facilitates in the improvement of corrosion property in coatings which are produced by the process. From the results, it was observed that obtaining desirable material properties is possible through the optimization of the influencing factors thereby enabling more control of the process. Figure 3 shows the EDS spectrum; it shows the elements that are present in the sample. From the EDS the elements that are present are; Zn, Ni and Fe. However, there is presence of carbon as well which could be attributed to the presence of carbon in the substrate during the dilution of reinforcement powders and the substrate.
Figure 3: EDS of Zn-50Ni-5Fe Ternary Coatings at Laser Power of 900 W and scanning speed of 1.2 m/min

3.2 Corrosion test results

The polarisation test results which include the corrosion potential (Ecorr), corrosion current density (Icorr), corrosion rate (Cr) and polarisation resistance (Rp) obtained from the polarization curves in Figure 4 are listed in Table 1.

Table 1: Linear polarization test data of Zn-Ni-Fe Ternary Coating in 3.65wt % NaCl Medium

| Sample           | Ecorr (V) | Icorr (A/cm²) | Rp (Ω.cm²) | CR (mm/yr) |
|------------------|-----------|---------------|------------|------------|
| Control          | -0.7916   | 0.0008384     | 42.499     | 9.74450    |
| Zn-50Ni-3Fe-1.0  | -0.7578   | 0.000473      | 55.953     | 5.50160    |
| Zn-50Ni-3Fe-1.2  | -0.7697   | 0.000498      | 56.455     | 5.78770    |
| Zn-50Ni-5Fe-1.0  | -0.74364  | 0.000188      | 169.21     | 2.17910    |
| Zn-50Ni-5Fe-1.2  | -0.2349   | 0.00002513    | 1820.61    | 0.29208    |
According to Fatoba et al. [21-27], the mechanism behind the attack of chloride ion is due to its properties. Many metals will easily dissolve in solution of chloride as cations due to the fact that strong acid exhibit chloride as anions. The diffusivity of chloride is very high despite it’s fairly size as anion. This makes chloride to tamper with passivation. Attack on steel surface by chloride ion as reported in the literature is shown in the below equations 1-5 [28].

\[
Fe + Cl^- = Fe(Cl^-)_{\text{surface}} \tag{1}
\]
\[
(FeOH)_{\text{surface}} + Fe(Cl^-)_{\text{surface}} = Fe + FeOH^+ + Cl^- + 2e^- \tag{2}
\]
\[
Fe(OH)^+ + H^+ = Fe^{2+}_{\text{solution}} + H_2O \tag{3}
\]
\[
Fe_{\text{surface}} + 2Cl^{-}_{\text{solution}} = FeCl_2_{\text{surface}} + 2e^- \tag{4}
\]
\[
FeCl_2_{\text{surface}} = FeCl_2_{\text{interfac}} = FeCl_2_{\text{solution}} \tag{5}
\]

The resistance to polarization measured was approximated to Rp (55.953 $\Omega$.cm$^2$), at low scan speed. The current density was also shown in four magnitudes $I_{\text{corr}}$ (4.73x10$^{-4}$ A/cm$^2$), as the rate of corrosion reduce a bit compared to the substrate. As predicted, the substrate couldn’t withstand the chloride ion and this is shown in the corrosion rate and resistance to polarization. As shown in equations 1-5, the results gotten from the substrate is as explained in the equations. Sample B2 showed greater resistance to the chloride ion by displaying higher corrosion potential and lowest corrosion rate. The corrosion density was also at the lowest value while the resistance to polarization picked the highest value in chloride solution as shown in Table 1. The SEM image of

Figure 4: Linear polarization curves of Zn-Ni-Fe Ternary Coatings on AISI 1010 steel in 3.65wt. % NaCl medium
B2 in Figure 5 also gave passivation that could withstand the chloride ions in the solution due to the reactions of ZnNi in DLMD which formed passivation films on the coatings.

![SEM Image of Zn-50Ni-5Fe Ternary Coatings at Laser Power of 900 W and scanning speed of 1.2 m/min after Corrosion.](Image)

3.3. Mathematical models

3.3.1. Grey relational model.

lower-the-better condition in equation 6:

\[ G_j(m) = \frac{highH_j(m) - H_j(m)}{highH_j(m) - lowH_j(m)} \]  \hspace{1cm} (6)

bigger-the-better condition in equation 7:

\[ G_j(m) = \frac{H_j(m) - lowH_j(m)}{highH_j(m) - lowH_j(m)} \]  \hspace{1cm} (7)

The above equations are normalized [22].

3.3.2. Grey coefficient and grade.

The Grey relational coefficient \( \zeta_i(j) \) can be calculated in equation 8 as:
\[ \zeta_j(j) = \frac{\Lambda_{\text{low}} - \psi\Lambda_{\text{high}}}{\Lambda_{\text{oi}}(j) + \psi\Lambda_{\text{high}}} \]  

(8)

Where \( \Lambda_{\text{oi}} = \|x_o(j) - x_i(j)\| \) is the absolute value of the difference of \( x_o(j) \) and \( x_i(j) \); \( \psi \) is the distinguishing coefficient \( 0 \leq \psi \leq 1 \). \( \psi = 0.5 \) is generally used.

\[ \Lambda_{\text{low}} = \forall m^{\text{low}} \in i \forall j^{\text{low}} \|x_o(j) - x_m(j)\| \] is the smallest value of \( \Lambda_{\text{oi}} \); and

\[ \Lambda_{\text{high}} = \forall m^{\text{high}} \in i \forall j^{\text{high}} \|x_o(j) - x_m(j)\| \] is the largest value of \( \Lambda_{\text{oi}} \).

Table 2 shows the orthogonal experimental design for corrosion rate. After averaging the Grey relational coefficients (As seen in Table 3), the Grey relational grade \( \rho_i \) (Table 4) can be computed as seen in equation 9 [29]:

\[ \rho_i = \frac{1}{n} \sum_{j=1}^{n} \zeta_j(j) \]  

(9)

### Table 2: Orthogonal Experimental Results for Corrosion Rate.

| Run Order | Samples     | Laser Power(W) | Scan Speed (m/min) | Corrosion Rate (mm/yr) |
|-----------|-------------|----------------|--------------------|------------------------|
| 1         | Zn-50Ni-3Fe | 800            | 1.0                | 5.5016                 |
| 2         | Zn-50Ni-3Fe | 800            | 1.2                | 5.7877                 |
| 3         | Zn-50Ni-5Fe | 900            | 1.0                | 2.1791                 |
| 4         | Zn-50Ni-5Fe | 900            | 1.2                | 0.2921                 |

### Table 3: Grey normalized values, analysis and coefficient.

| Run Order | Normalized Values | Grey relational analysis (\( \Lambda_{\text{oi}} \)) | Grey relational coefficient (\( \zeta_j(j) \)) |
|-----------|-------------------|---------------------------------------------|---------------------------------------------|
| 1         | 0.0521            | 0.9479                                      | 0.3453                                      |
| 2         | 0.0000            | 1.0000                                      | 0.3333                                      |
| 3         | 0.6566            | 0.3434                                      | 0.5928                                      |
| 4         | 1.0000            | 0.0000                                      | 1.0000                                      |

### Table 4: Grey Relational Grade for Factors and Levels of the Experiment.

| Run Order | Sample     | Laser Power | Scan Speed | Grey relational grade (\( \rho_i \)) |
|-----------|------------|-------------|------------|-------------------------------------|
| 1         | Zn-50Ni-3Fe| 800         | 1.0        | 0.3393                              |
| 2         | Zn-50Ni-3Fe| 800         | 1.2        | 0.5322                              |
| 3         | Zn-50Ni-5Fe| 900         | 1.0        | 0.7117                              |
The grey approach devised by Taguchi and used in the study revealed that the most desirable material performance in terms of corrosion was found optimised at a 900 W laser intensity and 1.2 m/min laser scanning speed. The Grey Relational Analysis (GRA) methodology applied and the results of the Grey Relational Grades (GRG) confirmed that there was great improvement in the values, as the enhanced GRG value was found to be 1.0000 (Table 4). The multi-objective approach of optimisation based on Taguchi’s Grey Relational Analysis was a suitable empirical design approach based on the significant enhancement on the multiple characteristic corrosion performance evaluated. The study proved that the Laser Metal Deposition process is a feasible process in improving the life of parts made from ASTM A29 steel. This also correlates with Figure 6 (Grey relational grade) which has highest at 900 W and 1.2 m/min.

4. Conclusion

- Observations of the process on the preheated substrate revealed that the preheating allowed for lower processing laser power to be used and reduced the rate of cooling between the peaked temperatures which were generated consecutively, in effect it improved the resistance of micro-cracks.
In terms of the corrosion performance, the results revealed that increasing the laser scanning speed was beneficial to the property, showing that the corrosion performance became better at higher scanning speeds. At the set laser intensity of 900 W and a 1.2 m/min laser scanning speed, the fabricated coatings showed enhanced microstructure, measured.

Stable and metastable intermetallic phases like FeNi$_3$ and FeNi were formed which have substantial influence on the microstructural evolution performance of the clad.

Grey relational model showed excellent correlation with the experimental results. The Grey Relational Analysis (GRA) methodology applied and the results of the Grey Relational Grades (GRG) confirmed that there was great improvement in the values, as the enhanced GRG value was found to be 1.0000.

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References

[1] Popoola, A.P.I., Fatoba, O.S., Aigbodion, V.S. And Popoola, O.M. (2017). Tribological Evaluation of Mild Steel with Ternary Alloy of Zn-Al-Sn by Laser Deposition, International Journal of Advanced Manufacturing Technology, 89(5-8), 1443-1449. DOI 10.1007/s00170-016-9170-7.

[2] Fatoba, O.S., Akinlabi, E.T. Akinlabi, S.A. (2018). Effects of Fe addition and Process Parameters on the Wear and Corrosion Properties of Laser Deposited Al-Cu-Fe Coatings Ti-6Al-4V Alloy. 2018 IEEE 9th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT 2018), Cape town, South Africa, pp. 74-79. doi: 10.1109/ICMIMT.2018.8340424.

[3] Fatoba O.S., Akinlabi S.A., Gharehbaghi R., Akinlabi E.T (2018). Microstructural Analysis, Microhardness and Wear Resistance Properties of Quasicrystalline Al-Cu-Fe Coatings on Ti-6Al-4V Alloy. Materials Express Research. 5(6), 1-14. https://doi.org/10.1088/2053-1591/aaca70.

[4] Gharehbaghi, R., Fatoba, O.S., Akinlabi, E.T. (2018). Influence of Scanning Speed on the Microstructure of Deposited Al-Cu-Fe Coatings on a Titanium Alloy Substrate by Laser Metal Deposition Process. 2018 IEEE 9th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT 2018), Cape town, South Africa, pp. 44-49. doi: 10.1109/ICMIMT.2018.8340418.
[5] Fatoba O.S., Adesina O.S. Popoola A.P.I. (2018). Evaluation of microstructure, microhardness, and electrochemical properties of laser-deposited Ti-Co coatings on Ti-6Al-4V Alloy. The International Journal of Advanced Manufacturing Technology. 97(5), 2341-2350. http://dx.doi.org/10.1007/s00170-018-2106-7.

[6] Gharehbaghi, R., Fatoba, O.S., Akinlabi, E.T. (2018). Experimental Investigation of Laser Metal Deposited Icosahedral Al-Cu-Fe Coatings on Grade Five Titanium Alloy. 2018 IEEE 9th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT 2018), Cape town, South Africa, pp. 31-36. doi: 10.1109/ICMIMT.2018.8340416.

[7] Fatoba, O.S., Akinlabi, E.T., Akinlabi, S.A. (2018). Numerical Investigation of Laser Deposited Al-Based Coatings on Ti-6Al-4V Alloy. 2018 IEEE 9th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT 2018), Cape town, South Africa, pp. 85-90. doi: 10.1109/ICMIMT.2018.8340426.

[8] Fatoba O.S., Popoola A.P.I., Aigbodion V.S., Rambau T.G. (2017). The Influence of Laser Parameters on the Hardness Studies and Surface Analyses of Laser Alloyed Stellite-6 Coatings on AA 1200 Alloy: A response Surface Model Approach. International Journal of Microstructure and Materials Properties, 12(5-6), 319-331.

[9] Schaff, P. (2010). Laser processing of materials: fundamentals, applications and developments. Springer Science & Business Media.

[10] Schafrik, R., Walston, S. & Reed, R. (2008). Superalloys 2008. TMS Publications, Warrendale, PA.

[11] Schwartz, W., Harrison, J. & Moulton, P. (1996). A diode-pumped, solid state Nd: YLF laser for micro-machining. ICALEO’96. Laser Materials Processing.

[12] Sefer, B. (2014). Oxidation and Alpha–Case Phenomena in Titanium Alloys used in Aerospace Industry: Ti–6Al–2Sn–4Zr–2Mo and Ti–6Al–4V. Luleå tekniska universitet.

[13] Qin, L., Liu, C., Yang, K. & Tang, B. (2013). Characteristics and wear performance of borided Ti6Al4V alloy prepared by double glow plasma surface alloying. Surface and Coatings Technology, 225:92-96.

[14] Rajamure, R.S., Vora, H.D., Gupta, N., Karewar, S., Srinivasan, S. & Dahotre, N.B. (2014). Laser surface alloying of molybdenum on aluminum for enhanced wear resistance. Surface and Coatings Technology, 258:337-342.

[15] Rambabu, P., Prasad, N.E., Kutumbarao, V. & Wanhill, R. (2017). Aluminium Alloys for Aerospace Applications. In: Aerospace Materials and Material Technologies. Springer:29-52.

[16] Reddy, A.V.K., Kumar, T.S., Kumar, D.T., Dinesh, B. & Saisantosh, Y. (2014). Improving the efficiency of IC engine Using Secondary Fuel. International journal of technology enhancements and emerging engineering research, 2(652):2347-4289.

[17] Jian-Min, C., Chun, G. and Jian-Song, Z. (2012). Microstructure and Tribological Properties of Laser Cladding Fe-Based Coating on Pure Ti Substrate. Transactions of Non-Ferrous Metals Society of China, 22, 2171–2178.

[18] Gaoa, Y., Takahashia, M., Nomuraa, M. and Nozawa. (2016). Characteristics of Nickel and Iron Diffusion in Molten Lead–17lithium Alloy. Fusion Engineering and Design, 109–111:1604–1608.
[19] Yuan, G.C., Li, Z.J., Lou, Y.X. and Zhang, X.M. (2000). Study on Crystallization and Microstructure for New Series of Al-Sn-Si Alloys. *Materials Science and Engineering-A*, 280, 108-115.

[20] Lan, X., Hong, W., Liu, Y., Zhang, W., Li, R., Chen, S., Zai, X. and Hu, T. (2016). Microstructures and Tribological Properties of Laser Cladded Ti-Based Metallic Glass Composite Coatings. Materials Characterization 120: 82–89.

[21] O.S. Fatoba; A.P.I Popoola; V.S. Aigbodion (2018). Electrochemical Studies and Surface Analysis of Laser Deposited Zn-Al-Sn Coatings on AISI 1015 Steel. International Journal of Surface Science and Engineering. 12 (1), 40-59.

[22] Fatoba, O.S; Popoola, A.P.I. Aigbodion, V.S. (2016) Laser Alloying of Al-Sn Binary Alloy onto Mild Steel: InSitu Formation. Hardness and Anti-Corrosion Properties. Lasers in Engineering, 39(3-6), 292-312.

[23] Fatoba, O.S; Popoola, A.P.I; Aigbodion, V.S (2016). Experimental study of Hardness values and Corrosion Behaviour of Laser Alloyed Zn-Sn-Ti Coatings of UNS G10150 Mild Steel, Journal of Alloys and Compounds, 658, 248-254.

[24] Fatoba, O.S., Popoola, A.P.I., Fedotova, T. And Pityana, S.L. (2015). Electrochemical Studies on the Corrosion Behaviour of Laser Alloyed Zn-Sn Coatings on UNS G10150 Steel in 1M HCl Solution. Silicon. 7(4), 357-369.

[25] Fatoba, O.S; Popoola, A.P.I; Fedotova, T. (2015) Characterization and Corrosion behaviour of Zn-Sn Binary Alloy Coatings in 0.5M H2SO4 solution. Journal of Electrochemical Science and Technology. 6(4), 65-74.

[26] Aigbodion, V.S; Popoola, A.P.I; Fatoba, O.S (2016). Evaluation of Hardness values and Corrosion Behaviour of Laser Alloyed 20Al-20Sn-60Ti Coatings of UNS G10150 Mild Steel. International Journal of Advanced Manufacturing Technology, 86(1-4), 291-301.

[27] Makhatha, M.E., Fatoba, O.S. & Akinlabi, E.T. (2018). Effects of rapid solidification on the microstructure and surface analyses of laser-deposited Al-Sn coatings on AISI 1015 steel. Int J Adv Manuf Technol. 94 (1-4), 773-787.

[28] Sherif, E.S.M., Erasmus, R.M. and Comins, J.D. (2010). “In Situ Raman Spectroscopy and Electrochemical Techniques for Studying Corrosion and Corrosion Inhibition of Iron in Sodium Chloride Solutions.” Electrochim. Acta. 55, 3657–3663.

[29] Datta, S. Bandypadhyay, A. and Pal, P.K. (2008). Grey-Based Taguchi Method for Optimization of Bead Geometry in Submerged Arc Bead-on-Plate Welding, International Journal of Advanced Manufacturing Technology, 39, 1136-1143.