Evaluation of Bond Strength on Deposition of Aluminium 6063 Alloy over EN24 Medium Carbon Steel by Friction Surfacing Using Different Mechtrode Diameter

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In the present work, an experimental exploration was made to study the bond strength on solid-state coating of aluminum 6063 over EN24 carbon steel by friction surfacing process using different mechtrode diameter. Friction surfacing was carried out by different combinations of elemental process parameters with different mechtrode rods of 12 mm, 18 mm, and 24 mm in diameters. The result showed that the applied axial force and rotational speed has a strong correlation on diameter of mechtrode for obtaining a successful coating during the process. A non-contact infrared (NC-IR) thermometer provided the temperature profile, and the highest temperatures recorded were 358°C, 389°C, and 422°C for the 12 mm, 18 mm, and 24 mm rod diameters, respectively. The mechanical strength of the successful coating was analyzed using the Vickers microhardness and bending tests. The result exhibited that the coating sample obtained by the 18 mm rod diameter gave higher hardness value (142 HV at the interface) and bending strength (481 MPa at 120° bend angle) compared to coating samples obtained from the 12 mm and 24 mm rod diameters. The coating was analyzed using field emission scanning electron microscopy (FE-SEM) and energy dispersive X-ray analysis (EDAX) techniques to know the feature of microstructure and intermetallic bonding. The result revealed the formation of better martensite attributes and more oxide compounds at the interface of sample made by the 18 mm rod diameter, indicating adequate molecular interlocking between aluminium and iron particles.

Keywords Friction surfacing; Rod diameter; Microhardness; Bending; FE-SEM; EDAX

I. INTRODUCTION

Friction surfacing (FS) is a material bonding technology that enhances specific material properties which would be distinct from a substrate material like corrosion and wear resistance. It utilizes the frictional energy dispelled during operation and induces a plasticized metal without the involvement of any extrinsic heat source and creates high strength and high-quality joints with low deformation. In the process of FS, the substrate material is placed in between two clamped plates. The rotating consumable rod is moved along with the substrate with a certain transverse speed with the generation of heat that was the result of frictional effect at the interface of two materials. The duration signifies the adequacy of frictional heat to plasticize the consumable rod is called dwell period. After dwell period, transverse speed was applied between the consumable rod and the substrate which encouraged the deposition of plasticized consumable
materials on the substrate. The application of heat and pressure between two materials triggered diffusion at the interface which nurtured the bonding. As a consequence, the emergence of a solid phase metallurgical bond occurred. This is shown in Figure 1. During the processing, the mechtrode material did not melt and a minimum dilution occurred at the substrate interface which indicated a slight change in chemical composition increasing the hardness of the coating at the interface. The constitution of the deposited coating was approximately the same as that of the consumable materials. The physical, mechanical and metallurgical properties mainly relied on several process parameters, namely downward axial force, rotational speed of the consumable rod and transverse speed. FS is considered to be suitable mainly for producing homogeneous fine-grained coatings, enhancing corrosion resistance, renovation and repair of worn engineering components, i.e., dies and related tools, which could develop surface cracks due to thermal fatigue.

The FS process was developed by Klopstock in 1941 by his experimental study on frictional heat requirement by hard material joining. Since then many investigations have been made by researchers and scientists in different combinations of dissimilar and similar materials using the FS process for a study of the tribological, mechanical properties of select coating materials. In their study, Gandra et al. [1] showed the performance analysis of friction surfaced coating between mild steel and mild steel and claim the loss of flash mass as around 40% to 60% of the total consumable rod and the energy required during the process as around 2.5–5 kJ g⁻¹. Madhusudan Reddy et al. [2] investigated the surfacing of titanium alloy over aluminium metal matrix composites and found significant improvement in wear resistance of titanium alloy due to interdiffusion of elements and the development of nanocrystalline layer at the interface. In their experimental study, Khalid Rafi et al. [3] measured temperature profiles of the coating, the rotating rod, and the substrate during friction surfacing using infrared thermography and found the development of a higher temperature in the retreating side of the coating than in the advancing side which indicated the flow of the plasticized materials from advancing side to the retreating side. In their work relating to D2 tool steel and low carbon steel, Sekharabaru et al. [4] found a thin coating at a low rotational speed of the consumable rod and a high transverse speed of the substrate. Also, D2 steel coating showed good martensitic microstructure at the interface compared to a consumable rod. In their feasibility study on friction surfaced coating of nonferrous substrate, Prasad Rao et al. [5] showed that interfacial coefficient and mechanical properties like thermal conductivity, thermal stability at high temperature are highly influenced by the formation of coatings. Pereira et al. [6] conducted wear analysis between stainless steel over mild steel and revealed that presence of bainitic and martensitic microstructures at the interface as highly influenced for the hardness of the coatings. Jujare et al. [7] studied the feasibility of copper deposition on mild steel and obtained good deposition under certain parametric combinations. Govardhan et al. [8] made an evaluation study of friction surfaced stainless steel and low carbon steel and concluded that the process parameters on the responses like width, height, surface roughness, tensile strength shear strength and ratio of tensile strength and shear strength were strongly influenced for good bonding. Karthik et al. [9] did research work on friction surfaced titanium over aluminium metal matrix composites and found multilayer deposition of titanium as well bonded and very fine grain size with uniformly distributed over aluminium. Brittle intermetallic bonds were strongly affected by the ductility of the composite materials. Kumar Singh et al. [10] studied the friction surfaced coating of austenitic stainless steel over low carbon steel and developed a mathematical relationship for prediction of pitting corrosion resistance and bonding strength by implementing friction surfacing parameters. Fitseva et al. [11] analyzed the deposition behavior and process characteristics of titanium alloys with various rotational speeds and found increasing the rotational speed causing an increase in the coating width and thickness and also increasing the deposition efficiency up to 39%. Krohn et al. [12] investigated the influence of external cooling on friction surfaced between aluminium alloys and found the intensity and location of cooling affecting process characteristics and modifying the coating geometry. In their experimental work, Stegmueller et al. [13] made a study of the inductive heating effect between stainless steel and aluminium substrate and found an increase in the rotational speed causing a decrease in the coating mass and thickness but an increase in flash masses of the consumable rod. Vijaya Kumar et al. [14] attempted at a relationship among process parameters and physical dimensions of the coating between aluminium and mild steel and observed that parameters like a spindle speed, an axial force, and a traverse speed were the most significant factors for preparing the physical dimensions of the coating. Fitseva et al. [15] investigated the influence of the rotational speed on
the process parameters and material flow on friction surfaced titanium alloys and found that metallurgical processes which influenced the microstructure and a material flow played an important role during FS. George Sahaya Nixon et al. [16] analyzed the effect of process parameters on the friction surfaced coating between stainless steel and a medium carbon steel substrate and observed the thickness of the coating was thinner when the coating width was larger in dimension at a higher combination of the axial force and the rotational speed. Shariq et al. [17] did an optimization and characterization study of friction surfaced coatings of various ferrous alloys and found a decrease in the thickness and the width of the coatings caused by an increase in the rotational speed and the transverse speed. A study of the present literature shows the different explorations made in different combinations of dissimilar and similar materials by the FS process. This was also shown by researchers in a number of different combinations of dissimilar and similar materials in the FS process. Several scientists and researchers conducted different experiments approaches for the analysis of the tribological, metallurgical, and mechanical behavior of selected materials. However, the research till date suggests only limited attempt made towards different approaches of friction surface coating between aluminium and the EN24 carbon steel substrate material which exhibits a poor rate of corrosion resistance.

This work deals with the analysis of the influence of a rotating rod diameter on the coating geometry of the sample obtained from FS. A successful and high strength aluminium 6063 coating over EN24 steel has offered a new potentiality for a large number of industrial applications like automobile, agriculture, etc.

II. MATERIALS AND EXPERIMENTAL METHODS

A. Materials

EN24 carbon steel was used as the substrate material and was machined to dimensions of 150 mm × 100 mm × 6 mm. AA6063 aluminium alloy was used as consumable rods with three different diameters of 12 mm, 18 mm, and 24 mm and a constant rod with a length of 100 mm. Details of the chemical composition of EN24 carbon steel and AA6063 aluminium alloy are presented in Tables 1 and 2.

Before commencement of the FS process, the substrate material was machined by a milling machine to extract a thin layer of thickness 0.5 mm to ensure flat and even surface to make a smooth and close contact of consumable rod and also avoid oxidation on the surface of the substrate. Prior to the FS process, both the substrate and the consumable rod were polished to obtain a smooth surface.

### Table 1: Chemical composition of EN24 carbon steel.

| Material         | C  | Mn  | P   | S   | Si  | Cr  | Ni  | Mo  | N   | Fe   |
|------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| % of composition | 0.42 | 0.65 | 0.035 | 0.03 | 0.3 | 1.4 | 12  | 0.3 | 1.6 | remainder |

### Table 2: Chemical composition of AA6063 aluminium alloy.

| Material         | Mg  | Si  | Cr  | Mn  | Ti  | Zn  | Fe  | Al  |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| % of composition | 0.55 | 0.4 | 0.1 | 0.1 | 0.1 | 0.1 | 0.35 | remainder |

### Table 3: Mechanical properties of EN24 carbon steel and aluminium 6063.

| Material          | Yield stress (MPa) | Ultimate strength (MPa) | Hardness |
|-------------------|--------------------|-------------------------|----------|
| EN24 carbon steel | 680                | 900                     | 270 HV   |
| Aluminium (6063)  | 170                | 214                     | 75 HV    |

### Table 4: Parameters of the FS process.

| Group | Diam. \(^a\) (mm) | Exp. No. | Trans. \(^b\) (mm min \(^{-1}\)) | Ax. force \(^c\) (kN) | Rot. spd. \(^d\) (rpm) |
|-------|-------------------|----------|---------------------------------|----------------------|-----------------------|
| 1     | 12                | A1       | 150                             | 4                    | 1500                  |
|       |                   | A2       | 150                             | 4                    | 2500                  |
|       |                   | A3       | 150                             | 6                    | 1500                  |
|       |                   | A4       | 150                             | 6                    | 2500                  |
| 2     | 18                | B1       | 150                             | 4                    | 1500                  |
|       |                   | B2       | 150                             | 4                    | 2500                  |
|       |                   | B3       | 150                             | 6                    | 1500                  |
|       |                   | B4       | 150                             | 6                    | 2500                  |
| 3     | 24                | C1       | 150                             | 4                    | 1500                  |
|       |                   | C2       | 150                             | 4                    | 2500                  |
|       |                   | C3       | 150                             | 6                    | 1500                  |
|       |                   | C4       | 150                             | 6                    | 2500                  |

\(^a\) Rod diameter. 
\(^b\) Transverse speed. 
\(^c\) Axial force. 
\(^d\) Rotational speed.
able rod were cleaned properly by acetone to avoid contamination during processing. Important mechanical properties of both substrate and mechtrode materials are summarized in Table 3.

B. Experimental process and parameters

A conventional FS machine was used to carrying out the experimental work with a single line deposition in a length of about 100 mm. The machine had a maximum power of 20 kW and a transverse speed of 1000 mm min\(^{-1}\). The selection of materials for the FS experiments was done for developing a thick crack free coating of high corrosion resistance and improved mechanical properties. By considering these properties the coating can enhance the life of the substrate. This type of coating can be used on products where the rate of corrosion is more important.

On the basis of earlier experiment evaluation and literature analysis, parameter selection was made for the present experimental study, as shown in Table 4. During the process, the substrate plates were placed over a planar rigid anvil and were fastened at the side corresponding to the transverse speed of the consumable rod. Figure 2 is the schematic diagram of the experimental arrangement and the coating samples obtained from the experiments.

III. RESULTS AND DISCUSSION

A. Quality of deposition

Initially the bond quality of the aluminium deposition was decided on the basis of a visual inspection. The aluminium deposits were categorized into continuous, discontinuous, uniform, non-uniform, narrow, greater width, variable width, deposit due to shear, are they attained by several combinations of the process parameters. The dependency of the coating condition was based on process parametric combination as shown in Table 5. The observation showed that, in 12 mm rod diameter, the sample (A1) was obtained at a lower axial force and rotational speed combination was good and continuous However at a higher combination, the sample (A4) obtained was non-uniform and discontinuous due to uneven pressure distribution at the interface during processing. Similarly, samples (B2, B3) obtained from the 18 mm rod diameter showed continuous and uniform coating throughout the bed at both lower and higher levels of the rotational speed. This was due to the adequate surface contact between the rotating rod face and the substrate metal resulting in uniform pressure distribution between them. The value of axial force had a significant effect on the formation of coating width and thickness. Uneven and poor deposition of aluminium was noticed from the sample (C1) obtained from the 24 mm rod diameter. It was due to excess heat transfer towards rotating rod resulting in improper heat

| Exp. No. | Observations | Acceptance |
|----------|--------------|------------|
| A1 | Continuous, good deposition at the advancing side and good overlaying at the retreating side. | Yes |
| A2 | Discontinuous, uniform width, and uneven deposition of consumable. | No |
| A3 | Non-uniform, poor deposition at the advancing side | No |
| A4 | Discontinuous, uniform width, and uneven deposition of consumable. | No |
| B1 | Uniform, good deposition at the advancing side, good in ripple formation. | Yes |
| B2 | Continuous, uniform width excellent overlaying of the consumable material. | Yes |
| B3 | Continuous, uniform deposition and very good overlaying of the consumable material. | Yes |
| B4 | Nonuniform continuous deposition shearing deposition at the advancing side. | No |
| C1 | Discontinuous, uniform width uneven deposition of consumable. | No |
| C2 | Non-uniform, poor deposition at the advancing side, uneven deposition of consumable. | No |
| C3 | Continuous, good and uniform deposition of consumable. | Yes |
| C4 | Continuous very good deposition varying width thinner overlay. | Yes |

Figure 2: An equipment (a) and a process (b) of FS.
The materialization of the deposits and the image of the tool surfaces are shown in Figures 3 and 4. An investigation has been made to know the supremacy of frictional energy which precipitate between mechtrode and substrate surface during FS. From the data developed by the FS machine, the interfacial coefficient of kinetic friction μk is calculated by using the formula; 

\[
\mu_k = \frac{F_s}{N_m}\]  

where \(F_s\) is frictional force offered by substrate along with traverse speed, and \(N_m\) is normal force offered by the substrate along the mechtrode speed. The input power \(P\) was calculated by using the formula; 

\[
P = \frac{2πNT}{60}\]

From Table 6, it has been observed that the coefficient of friction of 18 mm rod diameter was around 0.38 to 0.43 which was high compared to 12 mm and 24 mm rod diameters. Development of a high interfacial coefficient at the mechtrode and the substrate faces resulted from the high bonding strength which was authenticated by conducting bending test. Similarly, greater heat input could result in the development of brittle intermetallic bond while lesser heat input can be deficient to the generation of good metallurgical bonding between the coating and the substrate, as demonstrated by Janakiraman et al. [18]. Torques for all these combinations are nearly constant (around 7.5 Nm), which indicates that the axial force has a great commanding influence over all physical and mechanical characteristics of the coating.

Figure 3 shows the appearance of the coatings and face of the mechtrode with a low combination of the axial force and the rotational speed (4 kN, 1500 rpm). Figure 3(a) shows the mechtrode face of the 12 mm diameter which experienced a high pressure of 35.37 MPa (shown in Table 7) during the process. Uneven roughness around 4.3 \(\mu m\) to 5.2 \(\mu m\) was found at the center of the tool face which indicates less

### Table 6: Development of coefficient of friction and torque for different parametric combination.

| Group | Diam. a (mm) | Exp. No. | \(\mu_k\) b | \(P\) c (W) | \(T\) d (Nm) |
|-------|--------------|----------|--------------|-------------|--------------|
| 1     | 12           | A1       | 0.2825       | 542.37      | 8.42         |
|       |              | A2       | 0.3117       | 584.24      | 8.21         |
|       |              | A3       | 0.2987       | 648.58      | 7.93         |
|       |              | A4       | 0.3056       | 684.72      | 7.58         |
| 2     | 18           | B1       | 0.4253       | 723.28      | 8.89         |
|       |              | B2       | 0.3884       | 742.36      | 7.64         |
|       |              | B3       | 0.4173       | 782.41      | 6.95         |
|       |              | B4       | 0.4316       | 810.91      | 6.87         |
| 3     | 24           | C1       | 0.3404       | 874.12      | 7.21         |
|       |              | C2       | 0.3218       | 886.28      | 6.42         |
|       |              | C3       | 0.3674       | 926.85      | 7.48         |
|       |              | C4       | 0.3391       | 941.29      | 6.38         |

a Rod diameter.  
b Interfacial coefficient.  
c Input power.  
d Torque.

The axial force and the rotational speed were 4 kN and 1300 rpm, respectively. Figure 3 shows the appearance of the coatings and face of the mechtrode with a low combination of the axial force and the rotational speed (4 kN, 1500 rpm). Figure 3(a) shows the mechtrode face of the 12 mm diameter which experienced a high pressure of 35.37 MPa (shown in Table 7) during the process. Uneven roughness around 4.3 \(\mu m\) to 5.2 \(\mu m\) was found at the center of the tool face which indicates less

### Table 7: Pressure development with different diameters of the mechtrode.

| Mechtrode diam. | Axial force (kN) | Pressure (MPa) |
|----------------|------------------|----------------|
| 12 mm          | 4                | 35.37          |
|                | 6                | 53.05          |
| 18 mm          | 4                | 15.71          |
|                | 6                | 23.57          |
| 24 mm          | 4                | 8.84           |
|                | 6                | 13.21          |

Uneven Roughness at centre  
Uniform Roughness throughout the face  
Concave tip formation at centre

**Figure 3**: Appearance of the coating and the tool face of the rotating rods with different diameters; (a) 12 mm, (b) 18 mm, and (c) 24 mm. The axial force and the rotational speed were 4 kN and 1300 rpm, respectively.
material deposition towards the end of the process but obtained a successful coating. Figure 3(b) clearly shows the mechtrode face of the 18 mm diameter which was developed a pressure of 15.71 MPa during deposition. The face has flattened and uniform roughness (5.6–6.8 μm) throughout the bed reflecting a continuous and uniform coating. Figure 3(c) exhibits the appearance of the mechtrode face of the 24 mm rod diameter which was developed a pressure of 8.84 MPa during the process. It shows a shallow tip formation at the mechtrode center, indicating a lack of pressure distribution during the process. Figure 4 shows the appearance of the coating and the mechtrode face with a high combination of the axial force and the rotational speed (6 kN, 2500 rpm). Figure 4(a) shows a flat and smooth face of the mechtrode (12 mm diameter) due to development of the excessive pressure (53.05 MPa) at the interface, which indicates non-uniform material deposition during process, caused an unsuccessful coating. Figure 4(b) exhibits flat and uniform roughness at the mechtrode face of 18 mm diameter (pressure 23.57 MPa), resulting in continuous and uniform deposition on substrate material during the process. Figure 4(c) shows a tip formation at the middle of the mechtrode rod (24 mm diameter) due to insufficient pressure development (13.26 MPa), indicating narrow deposition of the mechtrode materials towards the end of the process and resulting in a non-uniform coating.

The development of optimum pressure for uniform material transfer at the mechtrode can be analyzed by considering the dimensions and the shape of the mechtrode after processing. For the uniform material transfer, the flash mass deposition at the mechtrode should be minimum and have a flat face with considerable amount of roughness throughout the surface area of the tool.

Various mechtrode faces obtained after the FS process are shown in Figure 5. It has been seen that the thickness of flash mass deposition was minimum (2.4 mm) at the 18mm mechtrode diameter compared to other mechtrode diameters (8.33 mm and 6.8 mm for the 12-mm and 24-mm rods, respectively). Uniform roughness throughout the tool face at both combination of axial load (4 kN and 6 kN) has been observed. So, it can be considered that, at the interface, the pressure development of 15.71 MPa (for 4 kN) and 23.57 MPa (for 6 kN) for the 18 mm mechtrode diameter was optimum for the uniform material transfer during the FS process.

The supremacy of the FS process parameters and the physical dimensions of the coating are explained in Figure 6. Decrease in the thickness of the coating (Ct) with an increase in the axial force and the rotational speed is seen. The width of the coating (Cw) became wider when the consumable rod was having a high rotational speed. At a high level of a constant axial force and a rotational speed, the width of the coating decreased while the thickness of the coating remained nearly constant with increase in the transverse speed, whereas with a lower level of an axial force and a rotating speed, both coating width and thickness were nearly constant. Normally, the coating width depends on the diameter of the mechtrode rod and usually at the
range of 0.9 to 1.2 times of the diameter of the mechtrode rod, as shown by Vitanov et al. [19]. The coating thickness was in the range from 2.56 mm to 1.44 mm at different combinations of the rotational speed and the axial force for different diameter of the rotating rod. But, at a higher level of this combination, the coating thickness was around 1.95 mm under the constant transverse speed.

B. NC-IR infrared thermometer

During FS, the frictional heat generated by the rubbing between the rotating consumable rod and the substrate is the key factor for successful formation of coating. A non-contact type infrared (NC-IR) thermometer was used for the measurement of the interface temperature of the consumable rod and the substrate. The temperature–time plot showed in Figure 7 gives a thermal profile for the different rod diameters starting from the consumable rod rotation to the end of the deposition process. There was a steady increase in the temperature during the initial phase (a dwell phase). There was a rapid increase in temperature aft the dwell phase and during the starting period of the deposition. This was due to the generation of high frictional heat by molecular diffusion. The recorded maximum peak temperature was 358°C, 389°C, and 422°C for the consumable rod diameters of 12 mm, 18 mm, and 24 mm, respectively. The temperature distribution during the deposition phase was steady in the case of the 12-mm and 18-mm rod diameters, and a continuous coating was formed in this phase. On the other hand, although the 24-mm rod diameter gave the highest peak temperature, the temperature distribution at the interface was unsteady and not uniform. As a result, a large quantity of consumable material was accumulated at the tool face to form an extensive mushroom shaped structure during the deposition phase (Figure 6). The axial force and the rotational speed were seen having a great influence on temperature formation at the interface. A higher
range of its combination produced a higher peak temperature compared to its lower range of combination.

The development of the interface temperature is normally depending on an applied axial force, a rotational speed, a contact frictional surface area at the interface, and a coefficient of friction between the mechtrode and the substrate. At the beginning of the deposition process, a larger mechtrode diameter makes a bigger contact friction surface area at the interface, resulting in an increase in the interface temperature. This is the reason why the 18 mm mechtrode diameter produced the higher interface temperature than the 12 mm mechtrode diameter. Brittle intermetallic layer formation is mainly due to the presence of excessive temperature at the interface and due to the nonuniform heat distribution between the mechtrode and the substrate. In case of the 18 mm mechtrode diameter, the temperature at the advancing side and the retreating side of the coating was nearly the same. This indicates a uniform heat distribution between the mechtrode and the substrate and is validated through the shape of the mechtrode face after the FS process (Figure 5).

C. FE-SEM

Field emission scanning electron microscopy (FE-SEM) images were taken from the sample obtained from aluminium cladding over EN24 carbon steel with different consumable rod diameters. COXEM PX 200 optical microscope was used for taking the images on the longitudinal sections of the sample having 15 mm in length and 15 mm in width. The result showed the coating deposition as a mechanical mixture of aluminium and iron particles. This was the results of the occurrence of dynamic recrystallization between them during the process. The aluminium particles were niggardly distributed on the iron layer. A thin composite layer formation was found between aluminium and carbon steel and was almost similar to the material transfer during the frictional condition. Figure 8 shows the FE-SEM analysis at the coating interface of different diameters of the consumable rod. Figure 8(c) displays the microstructural view at the interface of the 12 mm rod diameter. A separate line observed indicates less material transformation during the process. Figure 8(d) illustrates the interface of the 18 mm rod diameter, showing a perceptible quantity of material transferred towards the steel side and a gritty martensite features at interface. The microstructural features for the 24 mm rod diameter have been explained in Figure 8(e), which shows aberrant mass transfer at the interface due to jerky temperature distribution between the consumable rod and the substrate material.

Both carbon steel and aluminium surfaces have asperities in nature at the beginning of FS. These asperities have
different measurement scales. Very limited asperities form a contact pair by contact between each other. The effectual stress is very high at the contact point of asperities compared to the approximate stress using a normal load. Asperities face plastic deformation during a relative sliding between the two surfaces and it was much more towards the aluminium side as aluminium is a weaker material than carbon steel.

D. EDAX

During FS of aluminium 6063 over EN24 carbon steel, the deposition of the consumable rod involves the formation of compounds like chromium, cobalt, silicon. Figure 9(a) shows an energy dispersive X-ray analysis (EDAX) of the 12 mm rod diameter over stainless steel. The carbon percentage at the interface increased by 4.64% compared with the original substrate having 0.42% carbon. Figure 9(b) shows the EDAX of the 18 mm rod diameter over carbon steel, which contains 6.65% of carbon at its interface, indicating a stronger bonding between carbon steel and aluminium compared to the 12 mm rod diameter. Figure 9(c) provides the EDAX report of the 24 mm rod diameter. The carbon percentage at interface was 5.08%, which was slightly less than that of the 18 mm rod diameter. There was a reduction in the carbon percentage as a result of the uneven temperature distribution during the deposition phase that led to a lesser degree of oxidation at the interface. A high temperature with a uniform distribution rate during the deposition phase was the prime reason for obtaining a high percentage of carbon at the interface. Consequently, an increase in the hardness of the coating was demonstrated by microhardness tests. This was due to the re-condensation of the carbide particles during the plastic deformation.

E. Mechanical Analysis

1. Microhardness test

The Vickers hardness method is applicable for low level loads and is suitable for any kind of surface treatment process. The microhardness tester has a fish-eye piece and a diamond-shaped material called the indenter for the measurement of the microhardness of the specimen. The load on the indenter can be applied using a nob handle on the tester. Indentations were marks at different places along the longi-
The indentations were set perpendicular to the interface of the coating and the substrate with a load of 10 kgf and 18 s dwell time. The graphic and the algebraic representation in Figure 11 shows a higher hardness value at the interface of the coating compared to the consumable materials due to the formation of oxide compounds. The sample of the 18 mm rod diameter gives higher and uniform hardness throughout the coating in both longitudinal and transverse directions. The sample of the 24 mm rod diameter gives better hardness but it is slightly less towards the retreating side because of uneven oxide formation at the interface. The differences in the hardness value at the interface and the mechanism rod were due to the microstructural transformation at the interface and molecular bonding due to the plastic deformation caused during the process. This is a significant aspect for the application that tends to reduce corrosion resistance. The hardness value at the interface was seen high with an increase in the rotational speed of the mechanism and was slightly affected by the transverse speed.

2. Bending test

The fine specimens were selected for different bend tests like face-bend and root-bend tests for different specimens depending on their parametric combinations. The procedures were followed according to Indian Standards 1599, and the preparations were made accordingly. Bent samples are shown in Figure 12. In the sample A4 (12 mm rod diameter), a crack occurred with an applied load of 344 MPa at 90° bend angles in root bending, resulting in poor interlocking of molecules at the interface. Neither a crack nor a peeling was seen on the coating (A1) in the face bending with the same load of 344 MPa at 90° bend angles. The maximum bending strength was achieved with a load of 371 MPa. In the cases of samples B1 and B3 (18 mm diameter), no peeling or crack was observed while the maximum bending strength was achieved at a load of 481 MPa at 120° bend angles. Samples C1 and C3 (24 mm diameter) showed no peeling or crack at the interface with a load of 416 MPa at 90° bend angles. The maximum bending strength was achieved at 437 MPa at 120° angle. Figure 13 shows a relation between the bending strength and the bending angle for all three
diameters of the mechtrode rod. After the bend tests, the specimens were observed under a stereo microscope. It was found that the coating on both the surfaces was neither segregated nor defective on the deformed surfaces. Hence, the plates which were coated with aluminium over the carbon steel by FS can be rolled and deformed to necessitate shape.

IV. CONCLUSIONS

A number of single layer coating samples were obtained between 6063 aluminium alloy over EN24 carbon steel by FS. The effectiveness of the bonding was evaluated by carrying out various analyses like FE-SEM, EDAX, microhardness, and bending tests. The following conclusions are drawn from the experimental results.

1. Good metallurgically single bonded layer of aluminium 6063 over EN24 carbon steel can be obtained using the FS process with the 18 mm rod diameter at both lower and upper level combinations of the axial force and the rotational speed.

2. The width of the coating decreased with an increase in the axial force on the rotating rod, and the thickness of the coating became thinner while the consumable rod experiencing a high rotational speed.

3. The diameter of the consumable rod has a great influence on the generation of the peak temperature at the coating interface. A larger rod diameter (24 mm) produced a high peak temperature (422°C) at the interface but resulted in the brittle intermetallic layer at the interface.

4. SEM images showed good gritty martensite characteristics at the interface of the sample obtained from the 18 mm rod diameter compared to the 12 mm and 24 mm rod diameters.

5. EDAX showed the highest carbon percentage (6.64%) at the interface of the 18 mm rod diameter and also established the presence of oxygen, silicon, chromium, and phosphorus. This designates the formation of oxide compounds at the interface.

6. Results of the microhardness tests indicate an increase in the hardness value at the interface due to oxide formation. Hardness (142 HV) achieved was the highest at the interface of the 18 mm rod diameter and was uniform in both longitudinal and transverse directions.

7. Thus, it is appropriate to use effectually the 18 mm rod diameter of aluminium 6063 to produce single track coating over EN24 carbon steel by the FS process which can enhance the corrosion resistance of the substrate material.
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