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Deposition of Steel over Steel by Friction Surfacing Technique and Investigation of its Physical Geometry

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ABSTRACT

Friction surfacing (FS) is a coating technique inspired by friction stir welding. FS is a solid-state, thermo-mechanical process providing excellent wear and corrosion resistance properties. Frictional heating elevates the temperature of the consumable rotating tool (mechtrode) up to the softening of the material, the tool is traversed along the length of the plate, and the material gets deposited onto the substrate plate with good mechanical properties and excellent corrosion resistance properties, FS process may have wider application in the mining industry to provide an adequate coating on excavator's teeth, shovel teeth, and dragline teeth. This paper has an experimental approach to investigate the coating integrity during the FSed deposition of AISI4140 (consumable rod) over EN24 plate on a conventional milling machine. Various tests like wear test, XRD analysis, hardness, IR thermography, surface roughness, FESEM images have been analysed. Experiments have shown that at a low travel speed of 16mm/min, the coating is non-uniform and an excessive increase in travel speed will not give proper time for softening of the material, resulting in a discontinuous coating so the optimum travel speed must be chosen for better quality coating. Also, one more approach has been made to explore the effect of mechtrode shapes on the flash formation of the consumable tool while deposition of mild steel over mild steel on the milling machine where conical cylinder tool shape was more efficiently worked.

1. INTRODUCTION

Friction surfacing (FS), is a novel coating technique of friction surface processing where the joining of similar and dissimilar materials takes place. This is a solid-state process in which dynamic recrystallization of the material by shearing and stirring action (Seidi *et al.*, 2021) of the tool rod, decides the proper adhesion between metal-to-metal bonding. This process has 3 main stages as shown in Figure1, in the first stage a rotating consumable tool is used that is in contact with the substrate plate, and an axial load is applied continuously on it. Preheating takes place and the elastoplastic zone appears. The second stage is the deformation stage where the temperature rises suddenly due to frictional heating between the substrate plate and the consumable tool. Interdiffusion between the plate and coating material occurs, leading to metallic bonding formation. A viscoplastic shearing interface forms between the deposited layer and tool material that flash away later. In last with the travel movement of the consumable, the viscoplastic material is deposited onto the substrate surface in a continuous process. This stage is known as the diffusion zone (Gandra *et al.*, 2012) and the process ends with tool retraction. This process is mainly used in industries for delamination/coating, to repair worn parts in the marine industry, and where corrosion-resistant and wear-resistant properties are predominant factors. Also used for hard-facing of metals, and deposition on knife cutting edges of different categories such as dies, tools, punches, and blades required for chemical, medical, food processing, and agricultural industries (Raju *et al.*, 2016). In cladding applications, FS is also used for multilayer deposition. FS has wider application in the mining industry to provide a better coating to excavator's teeth, shovel teeth, and dragline teeth. Material with low thermal conductivity is more suitable for this process. This technique has the advantages of cladding harder material, providing a localized heating zone and dilution of the metal is almost negligible, preventing defects in the coating. Failure to consolidate between two adjacent depositions limits the use of the FS process.

Close control of process parameters is required to obtain a good quality coating. Sometimes postprocessing is also required (Dilip *et al.*, 2013). They discovered the possibility that this procedure might be used as a substitute for depositing single-layer or multi-layer solid-state coating using the additive manufacturing process to create three-dimensional parts. Friction Surfacing (FS) is used in the construction of chemical pumps and petrochemical pressure vessels (Rao *et al.*, 2013) To increase the effectiveness of FS technique many factors comprise like physical properties of the material (melting point, surface roughness,) and thermo-mechanical properties (hardness, yield strength, thermal conductivity).

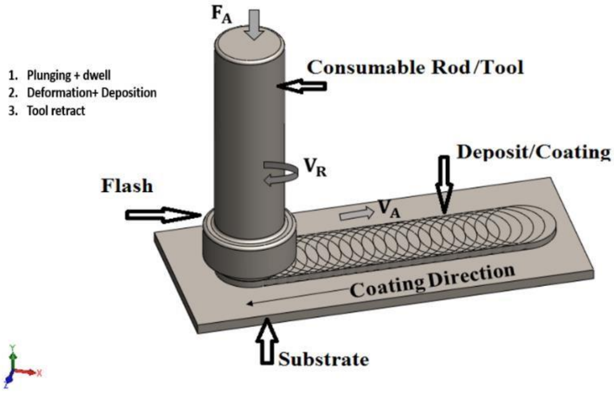


Figure 1: Interpretation of friction surfacing process

FS process parameters include the geometry of the plate (thickness of the plate and rod diameter, rod length) and machining parameters including axial load, rotational speed, travel speed, tilt angle, etc. play a vital role in a better quality of a final product. In addition, atmosphere and inductive heating may become essential in FS. The efficiency of the FS process can be predicted by the coating geometry, consumption rate, deposition rate, and tool efficiency. The amount of heat generation during the process will decide the bonding quality, microstructure, and mechanical properties of the final coating. To obtain sound coating, process temperature needs to be carefully monitored (Kallien *et al.*, 2020)(Aravinda *et al.*, 2021).

Many researchers investigated the impact of process parameters on coating quality. The relation among coating width, thickness, and bonding strength is examined so it is found that as coating thickness decreases and coating width increases, the bonding strength of FS coating improves. It has been observed that with the increase in forging load, coating thickness reduce also with an increase in rotational speed, width of the coating increase and provide good bonding strength to the coating. Traverse speed has not much influence on the thickness of the coating and the bond strength (Rethnam *et al.*, 2021; Barnabas, 2014). In the experiment of friction surfaced deposition of Inconel 718 over AISI 1045 carbon steel it has been examined that the thickness and width of the coating is strongly affected by the combination of rotational speed and traverse speed. The wider coating was noticed at the combination of high RPM and low tool travel speed, while at a higher transverse speed and higher RPM, a thinner coating was seen. Thinner coatings give high bonding strength to friction-surfaced coatings as compared to thicker coatings. Due to the formation of martensite at the interface of the coating, it provides higher hardness to the coating (Sahoo *et al.*, 2020).

Friction surfacing of AISI316 stainless steel on EN24 plate has been examined and the effect of process parameters on the physical geometry of coating was inspected. The results showed the impact of axial load, rotational speed, and travel speed on the thickness of the coating and width of the coating. Also, the combined effects of traverse speed, axial load, and consumable speed on the coating geometry were investigated. The results showed that the width of the coating increased and the thickness of the coating decreased as the traverse speed and consumable speed increased (Nixon *et al.*, 2018). Using the different consumable speeds of the tool 316 stainless steel, FSed on 304 plates has been experimented with to study the impact of speed on crystallography, hardness, and corrosion resistance. A higher strain rate and a higher temperature have been seen on the advancing side of FS coating which makes a stronger bonding on the advancing side. Due to the MnS fragments found in a coating, pitting corrosion resistance is higher in FSed coating as compared to 316 rods. Coating geometry is enhanced at increased rotational speed (Guo *et al.*, 2019). During the deposition of AA1100 over mild steel the deposit comes with greater thickness at increased RPM because more deformation in the tool takes place due to high torque in the spindle at a MIJST Hemlata Jangid et.al (Deposition of Steel Over Steel by Friction Surfacing Technique and Investigation of its Physical Geometry) 3 higher rotational speed.

Uniform thick coating over a length can be achieved if the RPM is higher, and the effect of axial load on thickness of the coating is decreased. At low travel speed and RPM, uniform coating attains also width of the coating decreased with higher travel speed and rotational speed (Sugandhi & Ravishankar, 2012). The flash formation during the friction surfacing process can be controlled by using different tool geometry and by drilling holes into the consumable rod. The axial loading between the rotating tool and substrate plate, induced localized flow stress which should be equivalent to the flow stress of plasticized material, the flash formation will be more if the flow stress of plasticized metal is higher than localized flow stress. If the flow stresses are similar then only the material will be resistant to the adhesion and easily mingle with the base metal to form a well-bonded coating (Gandra *et al.*, 2014).

According to (Troysi *et al.*, 2018) the effectiveness of FS coating on a CNC machine can be increased by modifying the 0.5 ratio between vertical and horizontal motions. This will provide high precision and accuracy and allow for the quicker production of complex and delicate items (Singh *et al.*, 2023). Experimental results suggest that the optimum method for coating steel with steel for significant applications is friction surfacing. Through microstructural studies, the shear action and combination of the coating and substrate material at the interface were further investigated. The author stated from the regression equation that the width of the deposit obtained is proportional to the axial load, rotational speed, and their interactions but inversely proportional to welding speed, and the thickness of the deposit is directly proportional to axial load and inversely proportional to welding speed and their interactions (Govardhan *et al.*, 2012). This paper aims to achieve better results in terms of good bonding strength and better hardness of the final FSed coating of AISI4140 on EN24 substrate plate by optimising process parameters, varying the tool geometry, and making a blind hole in the consumable rod, and its impact on the mechanical properties of the coating, flash formation, and coating geometry of the FS process will be observed. Both AISI4140 and EN24 medium-carbon steel have many uses in the mining, automotive, and agricultural industries.

2. EXPERIMENTAL PROCEDURE

Two experimental approaches were made in FS coating process, performed on a conventional milling machine, first approach was done by using the plate of medium carbon steel EN24 and the consumable rod of AISI4140 along with constant rotational speed and varying travel speed, and the second approach was carried out by FSed of mild steel over mild steel with varying tool shapes. Material EN24 contains more carbon and possesses high strength, wear, corrosion resistance property, and better toughness property, with greater application in the fabrication of excavator's teeth, and shovel teeth. Stud rod AISI4140 has high chromium, and Cr makes steel more hardened and increases the corrosion resistance of steel. Mild steel was used because it is more susceptible to flash generation during FSed process due to its softness and ductile nature compared to other steel grades. The chemical composition of the rod and substrate is shown in Table 1.

Table 1
Chemical composition of rod and substrate materials

Material (%) C	Si	Mn	P	S	Cr	Mo	Ni
EN24: 0.36/.044	0.10/0.30	0.45/0.70	0.04 max	0.04 max	1.00/1.40	0.20/0.35	1.30/1.7
AISI4140: 0.38/0.43	0.15/0.30	0.75/1.0	0.035	0.040	0.80/1.10	0.15/0.25	0.17
Mild Steel: 0.22	0.20	0.70	0.06	0.07	0.06	-	0.03

In the first experiment, a consumable rod of 15.5mm diameter and 100mm length was used for FS coating on EN24 plate with dimensions of 15 × 200 × 100 mm. Feed was given manually, with a constant rotational speed of 2000rpm and different travel speeds were used on the vertical milling machine as shown in table2. To avoid contamination with oxides the mechtrode and substrate plate were cleaned with acetone. For XRD, 3D profilometer, FESEM tests, polishing, and etching were done. The samples were subjected to a progressive polishing procedure using 12" sic paper 400 to 2000 grit emery papers, followed by diamond polishing with a 0.05-micron particle size. For EN24, etchant (10ml HCL+ 5ml HNO_3+ 1ml HF) with additional glyceryl was used with a holding time of 5-10sec.

Table 2
Process parameters for experiment-1 with average response values

Sample combinations	Process parameters		Average response values		
	Rotational speed (RPM)	Travel speed(mm/min)	Coating thickness(mm)	Coating width (mm)	Quality of the coating
S1	2000	16	3.8	12.0	Non-uniform coating
S2	2000	25	3.5	14.0	Discontinuous deposition
S3	2000	40	3.0	15.0	Better bonding

Table 3
Process parameters for experiment-2

Sample combinations	Rotational (RPM)	Travel speed (mm/min)	Tool shape	Tool dimension	Coating thickness (mm)	Coating Width (mm)
C1	2000	40	Conical cylinder	Large diameter-15.00mm Small diameter-12.00mm Length of the tool-80mm	2.8	14
C2	2000	40	Drilled a blind hole in a solid cylinder	Diameter-15.50mm Length-80mm Diameter of drilled hole-5mm Length of drilled hole-40mm	3.0	18
C3	2000	40	Square	Average side-12mm Length of the tool-55mm	3.5	12
C4	2000	40	Hexagonal	Average side-14mm Length of the tool-55mm	3.3	15

In the Experiment-2, mild steel was taken as both substrate and stud rod material. Tool shape variability was considered in this work to minimize flash formation by using different tool profiles as shown in Figure 2 and Table 3. The substrate plate thickness was 15mm. A constant Spindle speed of 2000rpm and a travel speed of 40mm/min were used, and the feed rate was given manually. The etchant used for the mild steel was nital (ethanol+2%nitric acid). The experiment of the friction surfacing process was performed on a conventional milling machine; the setup is presented in Figure 3.

The IR thermography was done with Chauvin Arnoux CA 1888 IR thermal camera. In the beginning, the process was in a dry friction state condition and an unsteady state system. After the process starts in a very short period, the temperature rises rapidly with a minor dilution of the mechtrode, in a few minutes steady state condition takes place and transforms the dry friction into lubricated frictional heat generation and the temperature remains constant with a very small drop. The temperature during the process observed was around 484 ºc for Experiment 1 and 426 ºc for Experiment 2 shown in Figure 4.

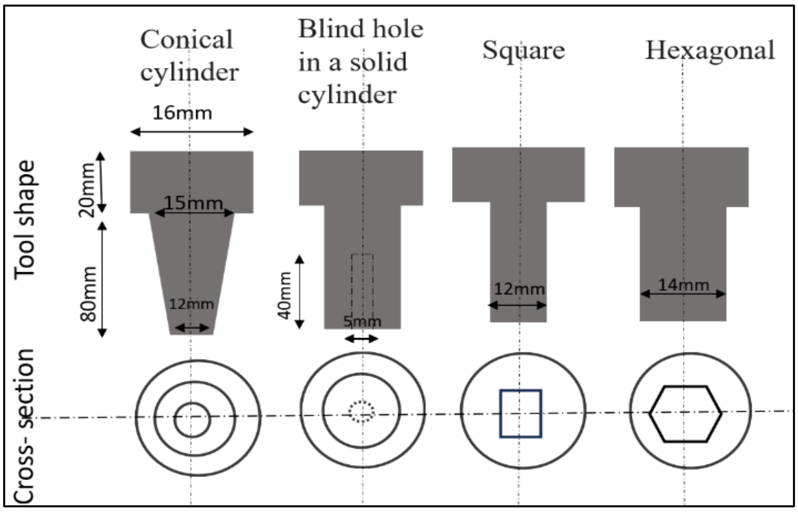


Figure 2: Variable tool shapes used in friction surfacing process

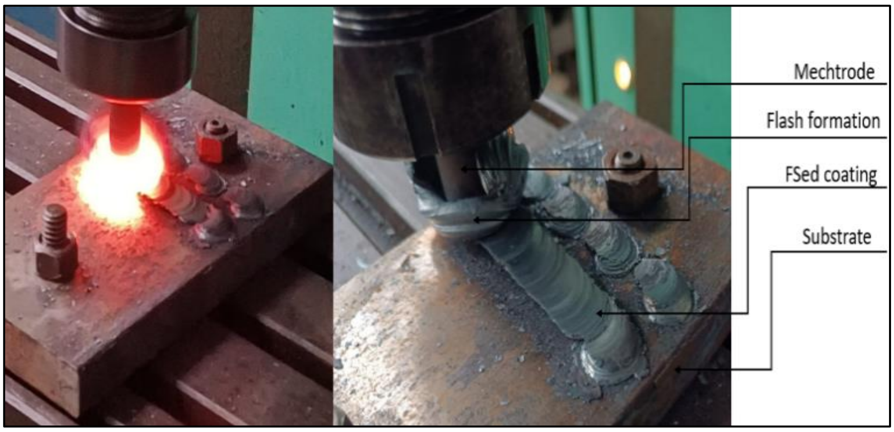


Figure 3: Experimental setup for friction surfacing

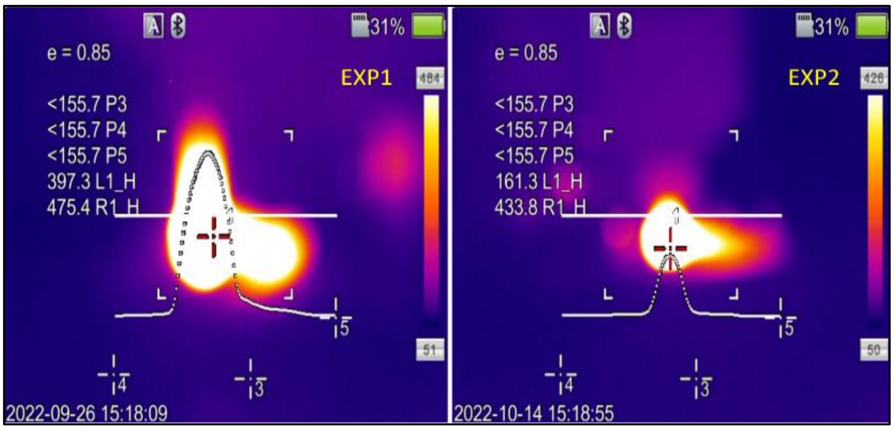


Figure 4: IR thermography images (a) AISI4140 over EN24, (b) mild steel over mild steel coating

3. RESULTS

A. Quality of Deposition and Appearance

Coating quality and appearance have been examined with both visual inspection and 3D profilometer. The quality of the deposit includes roughness, and coating characteristics like thickness, width, and strength of the coating. A vernier caliper was used to measure the thickness of a deposition layer by measuring the difference in thickness between the coated substrate and the uncoated substrate at three different points and its average.

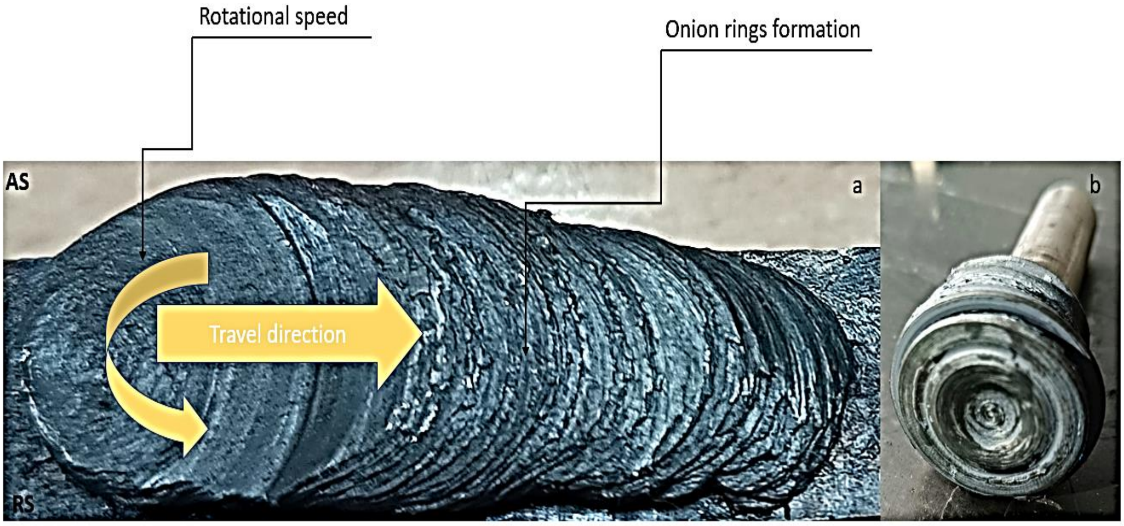


Figure 5: (a) Superficial of the coating and (b) Shape of the mechtrode after FSed coating

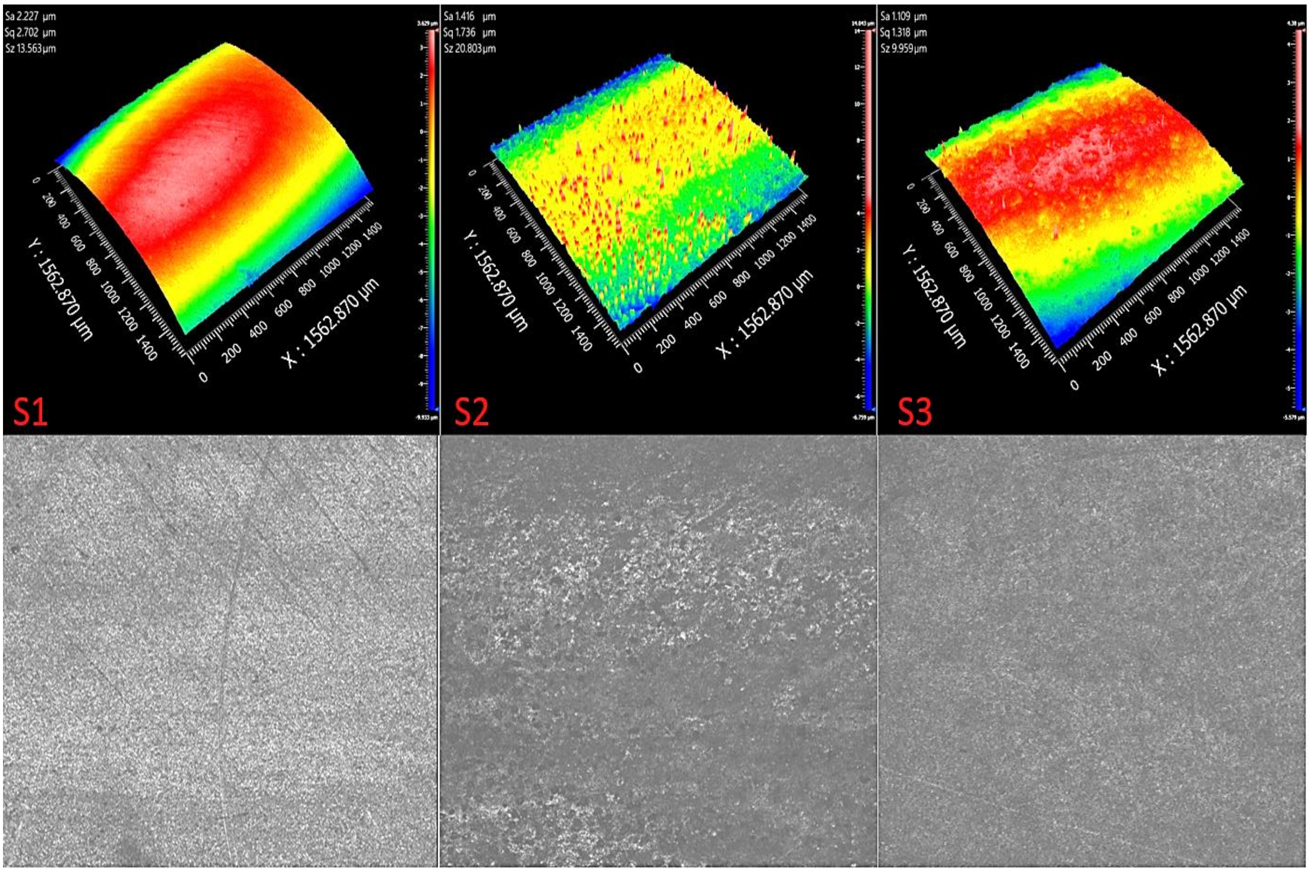


Figure 6: 3D profilometry images for samples S1, S2, and S3 along with 2D images of the coating interface.

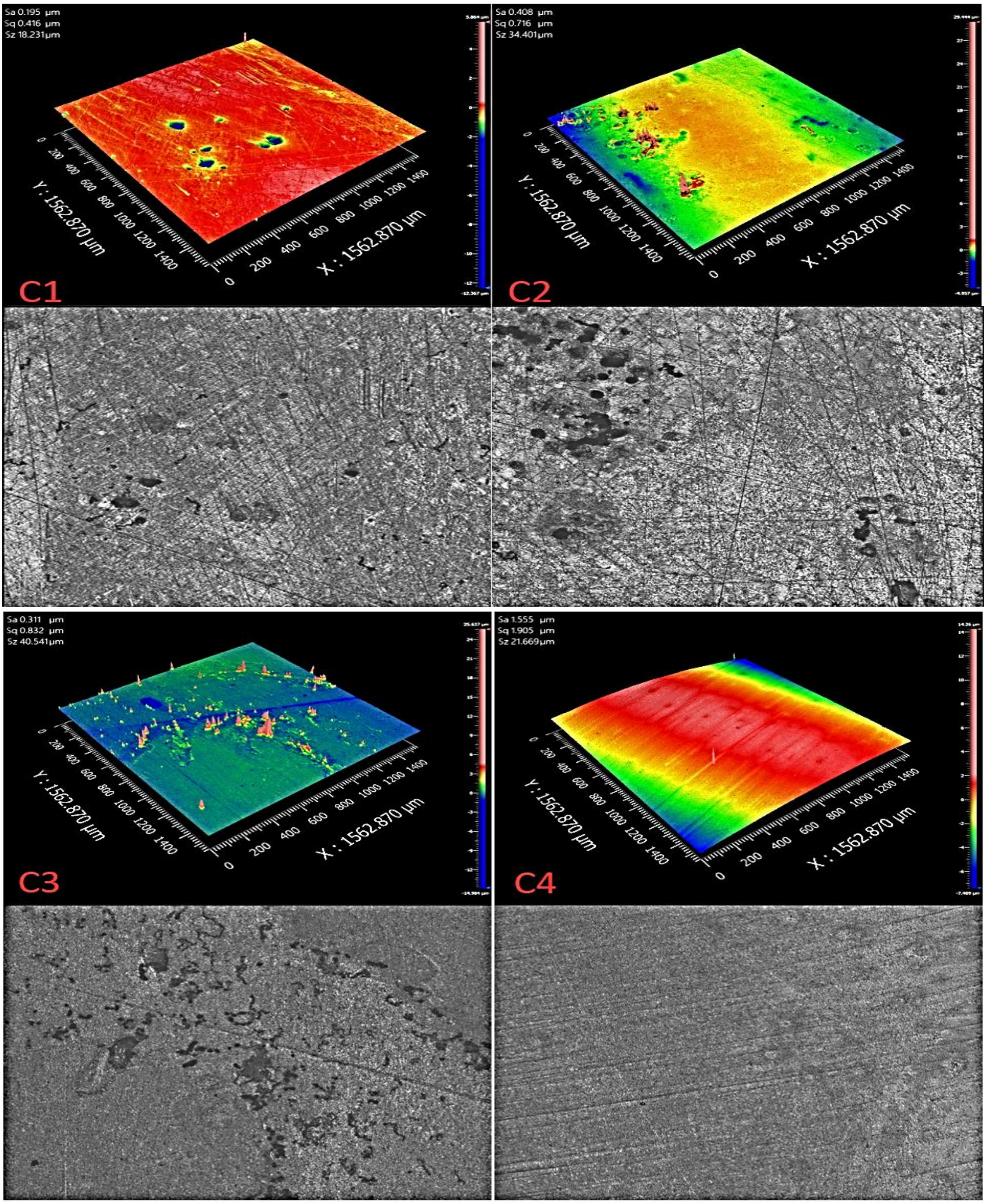


Figure 7: 3D profilometry image for samples C1, C2, C3, and C4 along with 2D images of the coating interface

B. Interface of Coating

FESEM images have been collected from a measurement device model named SUPRA55, Zeiss Germany, which showed the FSed coating interface images along with some cracks, black pits, and flakes(due to poor adhesion) as shown in Fig 8,9. Due to the dry friction between mating surfaces, the temperature during the FS process reached suddenly very high, followed by rapid cooling of the metal, availing the presence of martensite structure and some intermetallic laves phase in the coating microstructure, which results in high hardness due to fine-grained microstructure and provides good wear resistant property to the coating. A discontinuous dynamic recrystallization (dDRX) has been seen while friction surfacing of austenite steel AISI 316L rod on mild steel plate, under moderate Zener–Hollomon, parameter conditions. It has been noticed that the grain size increases when we move toward the coating corner from the coating interface(Sahoo & Mohanty, 2019). Bonding at the interface has been affected by the process parameters.

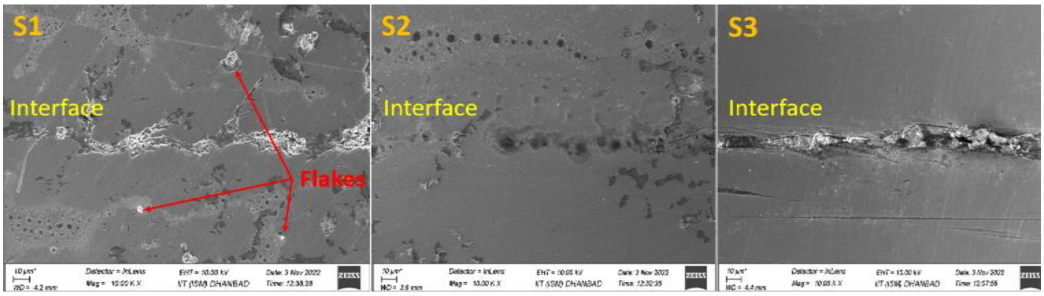


Figure 8: FESEM images of coating interface forExperiment-1

Dynamic recrystallization is a combined effect of plastic deformation and temperature rise due to frictional heat in the FS technique, which plays an important role in grain refinement and gives a fine, equiaxial, and homogeneous quenched microstructure (Puli & Janaki Ram, 2012). FS coating of steel may achieve martensite, pearlite, and ferrite along with a full austenitization process with finer grains distribution as the temperature rises in the process accordingly. In XRD data, a compound like Cr0.06Fe1.92, Cr0.7Fe0.3, Cr, and α-ferrite have been detected in both experiments. Cr is a strong alloying element that provides hardenability and improvement in corrosion resistance in an oxidizing medium. Mo is also present in IMC which gives profitability to the metal in a marine environment for better performance against corrosion resistance. It is also noted that excessive heating of the substrate may increase the formation of oxide compounds that may lead to pores and cracks at the coating interface.

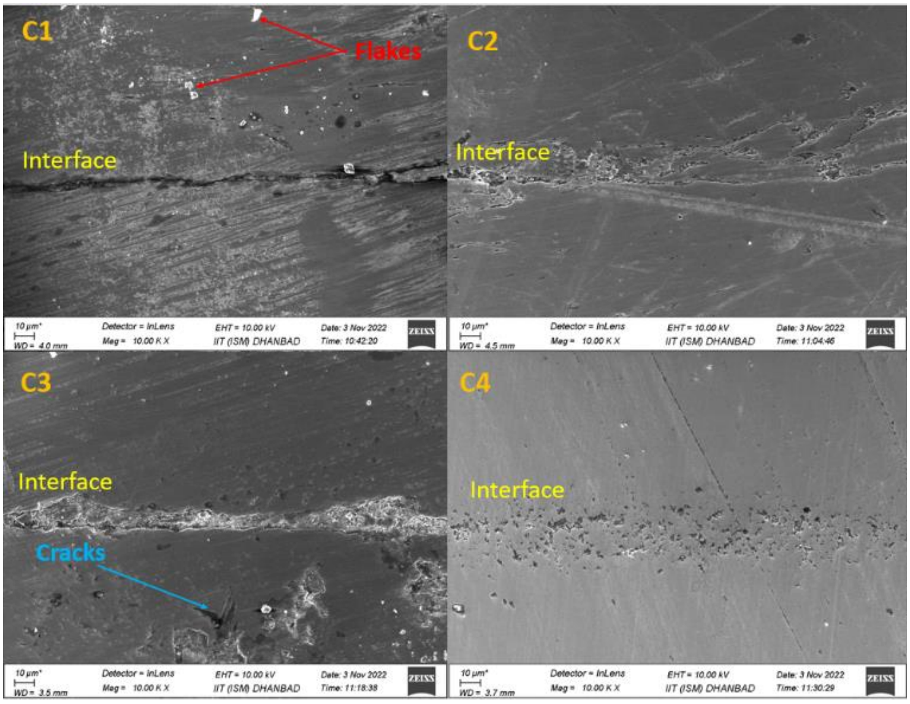
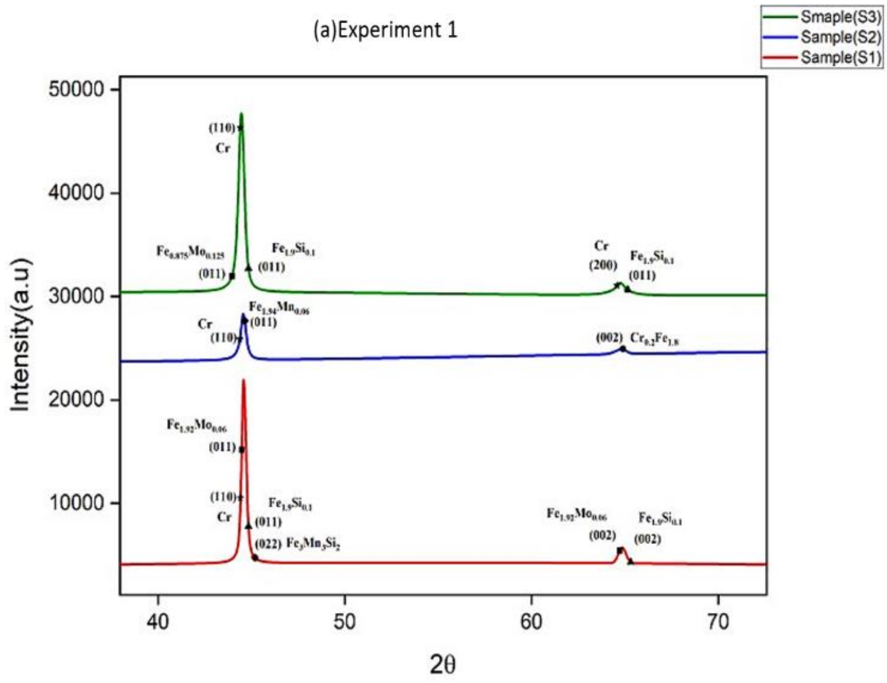


Figure 9: FESEM images of coating interface for Experiment-2

C. XRD Analysis:

This test has been accessed to know about the compound formation during FSed technique and for the identification of the plane orientation. The XRD analysis was done through Rigaku Oxford Diffraction model Supernova smart lab using; Cu Kα X-Ray radiation. The X-ray diffraction data analysis was done using the software X'Pert High Score Plus to identify the peaks and phases of the diffraction pattern. Compound Fe1.9Si0.1 has been detected in samples S1, and S3 in a plane (011) at angles 45º, and 65º. Iron-silicon compounds possess good resistance to abrasion and good corrosion resistance properties. Fe1.94Mn0.06 has been found in sample S2 in a plane (011) at an angle of 45º because the temperature of the process was around 484 ºc which is below the austenitization temperature. In this test, intermediate compounds have been detected in a plane (011) with the highest peak at a 45º angle and a small peak also observed at an angle of 65º can be seen in Figure10(a). Cr peak is also found in all three above samples in a plane (110) because EN24 metal is used for the base plate which emphasizes excellent corrosion properties due to the presence of Cr. Figure10(b) represents the XRD graphs for samples C1, C2, C3, and C4. In mild steel as a base plate, the presence of α-ferrite has been acquired in the deposited plane (110) in sample C4, α-ferrite is considered good for the provision of corrosion properties to the FSed coating but poor for wear resistance properties (Padmavathi *et al.*, 2021). Compound Cr0.06Fe1.92 has been detected in samples C1, and C2 in a plane (011) at 45º due to a temperature of 427 ºc in the friction surfacing process. The highest peak was acquired in sample C2, which reflects the amount of absorption and phase in the mixture.



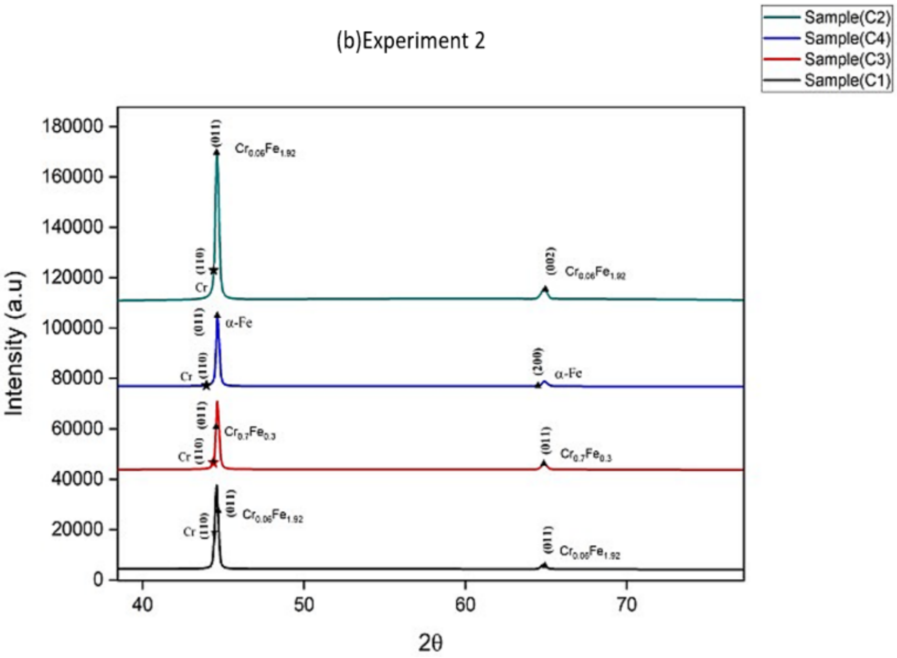


Figure 10: (a) XRD graph for samples S1, S2, S3 (b) XRD graph for samples C1, C2, C3, C4

In sample C3, Cr0.7Fe0.3 compound was found in a similar plane (011) which means intermetallic compound formation made the coating more brittle and harder and enhanced the chance for satisfactory adhesive bonding between interface coating and substrate in the friction surfacing technique. Here embrittlement behaviour of Fe-Cr has been noticed that may exhibit a pronounced increase in hardness accompanied by severe loss of ductility and corrosion resistance if the temperature range goes upto 400-540°C (Sahu *et al.*, 2009).

D. Microhardness

The microhardness survey has been carried out on a digital micro-Vickers hardness testing machine Model HM220, test was conducted in a transverse direction with the application of a 1kg load. It has been seen that the microhardness value of deposited coating was decreasing while moving down from FSed coating to the base metal due to residual stresses or phase formation of martensite in the coating area. For Experiment-1, hardness value on the surfaced coatings w.r.t base plate are increased by 9.4%,11.3%,12.5% in samples S1, S2, S3 respectively. The hardness value for sample S3 achieved is 235HV which is 3% higher than base metal EN24 (228HV). The hardness value of the coatings attained in experiment-2 are increased by 18.95%, 16.63%, 14.6%, and 8.6% in samples C1, C2, C3, and C4 respectively. Coating mild steel over mild steel increased its hardness value by 35%.

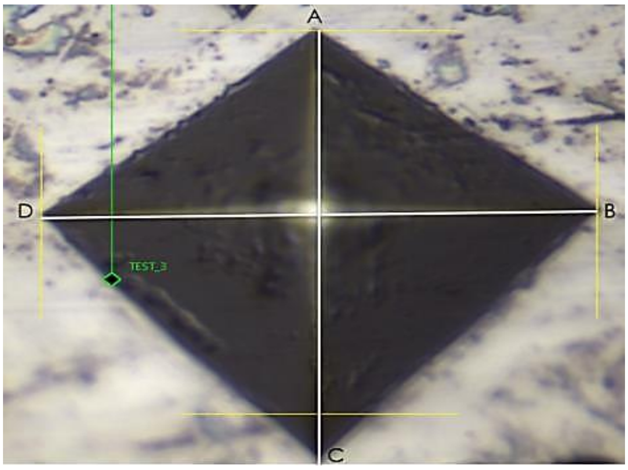


Figure 11: Vickers indentation hardness image

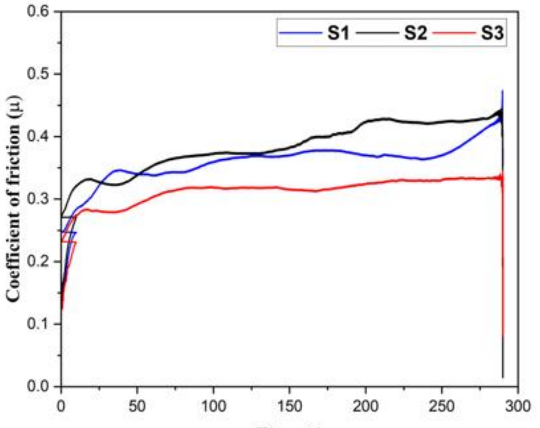
The average microhardness value of FSed coating achieved a value of 238HV, higher as compared to the parent metal mild steel hardness value of 165HV. A rhombus-shaped indentation image while Vickers hardness testing has been present in Figure 11. It has been noticed that while going up from the parent metal to the coating surface, the hardness value is increased.

E. Wear Test Analysis

The wear test analysis for friction-surfaced coating can be done in two types abrasive and adhesive wear. An abrasive type of wear test for FS has been carried out on a universal tribometer machine, model MFT500 made by R-tec Instruments, USA under dry sliding conditions. The wear test observation has conveyed the information in the form of coefficient of friction (μ) here, the coated sample readings have been observed at the load of 10N, with frequency 3HZ for 5min for each sample. The FSed processed coating samples showed better wear properties than the base material, and the value of (μ) for coatings comes lesser than the original metal which represents that FSed coating possessed better wear resistance properties.

Figure 12(a) presents the coefficient of friction for experiment-1, where sample S3 achieved lesser COF than samples S2 and S1. The average of COF has been shown in Table 4 for both experiments. Figure 12(b) Explains that the wear resistance property has been found higher in sample C1 while lesser in sample C4 because the wear resistance property is inversely propositional to the COF value. In XRD data α-ferrite has been found in sample C4, which is undesirable for a wear-resistant property. Martensite formation in FS process leads to better corrosion and wear-resistance (Pereira *et al.*, 2014) along with the greater hardness of coating achieved. Martensite formation in FS process leads to better corrosion and wear resistance (Pereira *et al.*, 2014) along with the greater hardness of coating achieved. The presence of martensite steel in the deposit increased the life of the coating with good strength of the coating. IMC has been seen more in samples S1, S2, and S3 which allows the brittleness of the FSed coating and, as a result, gives great wear-resistance properties.

(a) Experiment-1



(b) Experiment-2

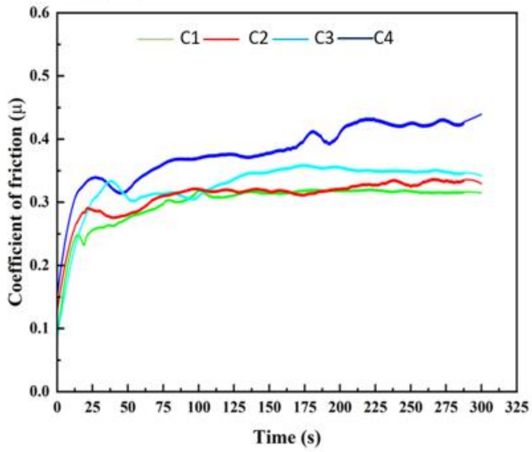


Figure 12: Wear test to develop coefficient of friction (COF) along with time during FS for both experiments

Table 4
Wear results of friction surfacing process in terms of COF

Experiment-1		Experiment-2	
Material	**Coefficient of friction (COF)**	**Material**	**Coefficient of friction (COF)**
EN24	0.55	Mild steel	0.36
AISI4140	0.49	C1	0.30
S1	0.36	C2	0.31
S2	0.38	C3	0.34
S3	0.30	C4	0.38

4. DISCUSSION

Friction surfacing is a promising methodology of material joining with better results and vital applications in aerospace, food processing, mining, agriculture automotive, and chemical industry due to its reliability and great mechanical properties. The friction surfacing process can be utilized for coating purposes, joining, repairing worn parts, and surface modification (Siddesh Kumar *et al.*, 2022). A novel attempt has been made in experiment-1 to overlay the AISI4140 (Mechtrode) on the EN24 substrate plate to uncover the bonding quality between these material combinations and mechanical properties after FSed. The geometry of the FSed achieved feasible results as an increase in the travel speed, the coating thickness decreases and width increases, which can be seen in sample S3, also better bonding can be seen in Figure 8, for S3 with an increment in travel speed. During 3D profilometer, the average surface roughness value came better in sample S3 (1.109µm) at a travel speed of 40mm/min. Cr peak has been found with large intensity in sample S3 in XRD graphs. In hardness testing again sample S3 achieved comparatively better results with a hardness value of 235HV along with an increment of 12.5% coating hardness w.r.t substrate plate EN24. Wear analysis conveyed that wear-resistant property is inversely proportional to the coefficient of friction, sample S3 with COF value of 0.30 showed satisfactory wear-resistant properties respectively.

One more endeavor has been taken in Experiment-2 using mild steel over mild steel with a novel approach using distinct tool shapes to identify flash formation in friction surface processing. The flash formation was observed lesser in sample C2 where a 5mm blind hole drilled mechtrode was used during FS coating, followed by sample C1 which used a conical cylinder tool shape, in sample C2 width of the coating was obtained a bit wider comparatively, and in sample C1 consistency in deposition have been observed. So conical-shaped tool was more efficient followed by a blind hole drilled tool shape. The average roughness value came good in sample C1 (0.195µm) followed by sample C3 (0.315µm) which can be evaluated with FESEM images shown in Fig 8,9 a good coating interface can be seen. During XRD, in mild steel α-ferrite was achieved, at a temperature below 550 ºc so we can assume a partial austenitization process took place due to a FS temperature of 427 ºc attained in this process. Friction surfacing of steel needs to study complex material behaviour at high temperatures and strain rates, and also investigate the steel sensitivity to strain rates that serves the complex material flow during FSed deposition (Hanke *et al.*, 2018). In hardness testing, sample C1 achieved favorable results relatively attaining the average hardness value of 238HV, which is 35% higher than the base plate metal (mild steel). Sample C1 and C2 again give the acceptable wear resistant property for FS coating with 0.30 and 0.31 Coefficient of friction.

5. CONCLUSIONS

The current study leads to the following conclusions:

- This study explores the influence of process parameters and tool shapes on friction-surfaced coatings. Experiments show strong bonding potential and the importance of optimizing process parameters. Tool shapes also impact coating properties.
- In experiments-1 and 2, researchers overlayed AISI4140 (Mechtrode) on EN24 substrate plates to investigate bonding quality and mechanical properties after FSed. Results showed better bonding and better surface roughness values in samples S3 and S2. Samples C1 and C2 showed acceptable wear-resistant properties for FS coating with 0.30 and 0.31 coefficient of friction.
- In Experiments-2, different tool shapes were used to identify flash formation in friction surface processing, with C1 showing better results and C3 showing good coating interface.
- The study suggests that by selecting appropriate parameters and tool shapes, friction surfacing can be tailored to achieve optimal coating characteristics.
- The relationship between temperature evolution and microstructural study should be more inspected to achieve required properties like corrosion-resistant, wear-resistant, a good bonding strength to the FSed coating, etc.

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