

MODELLING AND MICROSTRUCTURAL ANALYSIS ON DEPOSITION OF AISI316 STAINLESS STEEL OVER EN24 MEDIUM CARBON STEEL BY FRICTION SURFACING METHOD

Submitted in partial fulfillment of the requirements for the award of

Bachelor of Engineering degree in Mechanical Engineering

By

Y VENU GOPAL (Reg. No.37150223)

S S SATYA NARESH (Reg. No.37150180)



DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL ENGINEERING

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade “A” by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI – 600119

MARCH 2021



SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)

Accredited with "A" grade by NAAC
Jeppiaar Nagar, Rajiv Gandhi Salai, Chennai - 600 119
www.sathyabama.ac.in



DEPARTMENT OF MECHANICAL ENGINEERING

BONAFIDE CERTIFICATE

This is to certify that this Project Report is the Bonafide work of **Y Venu Gopal (Reg. No. 37150223)** and **S S Satya Naresh (Reg. No. 37150180)** who carried out the project entitled "**Modelling and microstructural analysis on deposition of aisi316 stainless steel over en24 medium carbon steel by friction surfacing method**" under my supervision from Dec 2020 to March 2021

Internal Guide

Mr. DILLIP KUMAR SAHOO, M.E., (Ph.D.),

Head of the Department

Dr.G. ARUNKUMAR. M.E. PhD

Submitted for Viva Voice Examination held on _____

Internal Examiner

External Examiner

DECLARATION

We, **Y Venu Gopal (Reg. No. 37150223)** and **S S Satya Naresh (Reg. No. 37150180)** hereby declare that the Project Report entitled “**Modelling and microstructural analysis on deposition of AISI316 stainless steel over EN24 medium carbon steel by friction surfacing method**” done by us under the guidance of **Mr. DILLIP KUMAR SAHOO, M.E., (Ph.D.)**, is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree in Mechanical.

1.

2.

DATE:

PLACE:

SIGNATURE OF THE CANDIDATE

ACKNOWLEDGEMENT

I am pleased to acknowledge my sincere thanks to Board of Management of **SATHYABAMA** for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

I convey my sincere thanks to **Dr. S.PRAKASH. M.E. PhD.** Dean, School of Mechanical Engineering and **Dr. G.ARUNKUMAR. M.E. PhD.**, Head of the Department, Dept. of Automobile Engineering for providing me necessary support and details at the right time during the progressive reviews.

I would like to express my sincere and deep sense of gratitude to my Project Guide **Mr. DILLIP KUMAR SAHOO.M.E.(PhD)**, for his valuable guidance, suggestions and constant encouragement paved way for the successful completion of my project work.

I wish to express my thanks to all Teaching and Non-teaching staff members of the Department of mechanical Engineering who were helpful in many ways for the completion of the project.

ABSTRACT

The present study shows the modelling and microstructural analysis on deposition of AISI316 stainless steel over EN24 medium carbon steel by friction surfacing techniques. A 3D-FE model of friction surfacing process was prepared using ABACUS software and the results obtained were compared with the experimental value. Various Friction surfacing process parameters like axial load, rotational speed and transverse speed were taken into account very precisely which are considered as supreme aspect for good bonding integrity. The interface temperature was measured by a non-contact infrared thermometer. The microstructural attributes and interfacial characteristics of the coatings were analysed by using high amplification FE-SEM image, which disseminate the presence of delicate gritty martensitic features at interface. The EDX and XRD analysis showed the existence of oxygen, chromium and cobalt at interface, which indicate the emergence of oxide compounds which leads to acceptable metallurgical bonding between the materials

Keywords: ***Friction surfacing, AISI 316 stainless steel, EN24 carbon steel, FE-SEM, EDAX, ERD.***

LIST OF CONTENTS

CHAPTER NO.	TITLE	PAGE NO.
	ABSTRACT	v
	LIST OF CONTENTS	vi
	LIST OF FIGURES	ix
	LIST OF TABLES	x
	LIST OF ABBREVIATIONS	xi
1	INTRODUCTION	1
1.1	SURFACE ENGINEERING	1
1.2	TYPES OF MODIFICATION PROCESS	2
1.3	WHY FRICTION SURFACING	2
1.4	FRICTION SURFACING	4
1.5	IMPORTANCE OF FRICTION SURFACING	6
1.6	APPLICATION OF FRICTION SURFACING	6
2	LITERATURE SURVEY	8
3	AIM AND OBJECTIVE	20
3.1	AIM	20
3.2	OBJECTIVE	20
3.3	PROBLEM IDENTIFICATION	20
4	MATERIALS, MODELLING AND EXPERIMENTAL PROCESS	21
4.1	MATERIALS	21

4.1.1	EN24 MEDIUM CARBON STEEL	21
4.1.2	AISI 316 STAINLESS STEEL	22
4.1.3	PROPERTIES OF AISI 316 STAINLESS STEEL	22
4.2	MATHEMATICAL MODELLING OF FRICTION SURFACING PROCESS	22
4.2.1	MODEL OF FRICTIONAL HEAT GENERATION AT MECHTRODE	22
4.2.2	MODEL OF FRICTIONAL HEAT SOURCE AT SUBSTRATE	25
4.3	MODELLING OF FRICTION SURFACING	26
4.4	EXPERIMENTAL WORK	29
4.4.1	NC-IR INFRARED THERMOMETER.	30
5	RESULTS AND DISCUSSION	32
5.1	CHARACTERISTICS OF DEPOSIT	32
5.1.1	MEASUREMENT OF DEPOSIT DIMENSIONS	32
5.2	MECHANICAL TEST	35
5.2.1	VICKERS HARDNESS TEST	35
	5.2.1.1. SAMPLE PREPARATION	36
	5.2.1.2. VICKERS HARDNESS	36
5.2.2	BENDING TEST	38
5.3	MICROSTRUCTURAL ANALYSIS	40
5.3.1	FE-SEM (FIELD EMISSION SCANNING ELECTRON MICROSCOPY)	40

5.3.2	EDAX SPECTROSCOPY (ENERGY DISPERSIVE X-RAY ANALYSIS)	42
5.3.3	X- RAY DIFFRACTION (XRD)	45
5.3.4	MEASUREMENT OF COATING INTERFACIAL THICKNESS	47
5.4	COMPARISON OF EXPERIMENTAL AND SIMULATED RESULTS	48
6	CONCLUSION	50
	REFERNCE	51

LIST OF FIGURES

FIGURE NO	DESCRIPTION	PAGE NO
1.1	Scope of surface engineering	1
1.2	various solid state joining processes	3
1.3	Principle of Frictional surfacing	5
4.1	Frictional interface of mechtrode rod.	23
4.2	Heat source model of substrate	25
4.3	Modelling of friction surfacing process	26
4.4	Meshing structure of the friction surfacing process	27
4.5	Simulation of the friction surfacing process with process parametric combination	28
4.6	Friction surfacing (a) experimental set up (b) during experimental work.	30
5.1	Hardness profile at (a) longitudinal and (b) Transverse direction	37
5.2	Samples obtains after (a) face and(b) root bent condition	39
5.3	Bending test report of (a) sample 6 and (b) sample 8	40
5.4	Microstructural view of the different samples at 500x and at 1500x	42
5.5	EDAX test report obtained from Sample (a) S1, (b) S6, (c) S8	44
5.6	Xray Diffraction at (a) Sample S1 (b) Sample S6 (c) Sample S8	46
5.7	Interfacial thickness measurement of the samples obtained from (a) S6 and (b) S8 combinations.	47
5.8	Comparison of simulated and experimented results of obtained coating geometry of (a) coating width (b) coating thickness (c) interface temperature	48

LIST OF TABLES

TABLE NO	DESCRIPTION	PAGE NO
4.1	Chemical composition of AISI 316 stainless steel	21
4.2	Chemical composition of EN24 medium carbon steel	21
4.3	Material properties used for simulation work	27
4.4	Friction surfacing process parameters	28
4.5	Coating geometry obtained from the simulation work	29
5.1	Experimented value of coating geometry obtained from friction surfacing process	32
5.2	Appearance of the coating and consumable rod during experimental work.	34

LIST OF ABBREVIATIONS

FS	FRICTION SURFACING
SE	SURFACE ENGINEERING
AA	ALUMINIUM ALLOY
LCS	LOW CARBON STEEL
MCS	MEDIUM CARBON STEEL
SS	STAINLESS STEEL
UDF	USER DEFINED FUNCTION
PLC	PROGRAMMED LOGICAL CIRCUITS
UDF	USER DEFINED FUNCTION
NDT	NON-DESTRUCTIVE TECHNIQUES
FE-SEM	FIELD EMISSION SCANNING ELECTRON MICROSCOPE
EDAX	ENERGY DISPERSIVE ANALYSIS
XRD	X-RAY DIFFRACTOMETER

CHAPTER 1

INTRODUCTION

1.1 SURFACE ENGINEERING

Surface engineering involves altering the properties of the solid surfaces which could be different from those of the core material to reduce the degradation over time. These are also used to impart a wide range of functional properties, including physical, chemical, electrical, electronic, magnetic, mechanical, wear-resistant and corrosion-resistant properties at the required substrate surfaces. Almost all types of materials, including metals, ceramics, polymers, and composites can be coated on materials, similar or dissimilar. This is accomplished by making the surface robust to the environment in which it will be used to protect from wear and corrosion to prolong its life and also enhance aesthetic appearance of the substrates.

Surface engineering techniques are being used in the automotive, aerospace, missile, power, electronic, biomedical, textile, petroleum, petrochemical, chemical, and steel, power, cement, machine tools, and construction industries. The scope of surface engineering basically involves four broad aspects:

- Designing the surface to be developed,
- Developing or modifying the substrate using suitable approach,
- Characterizing the engineered or modified surfaces,
- Putting them in application for the purpose

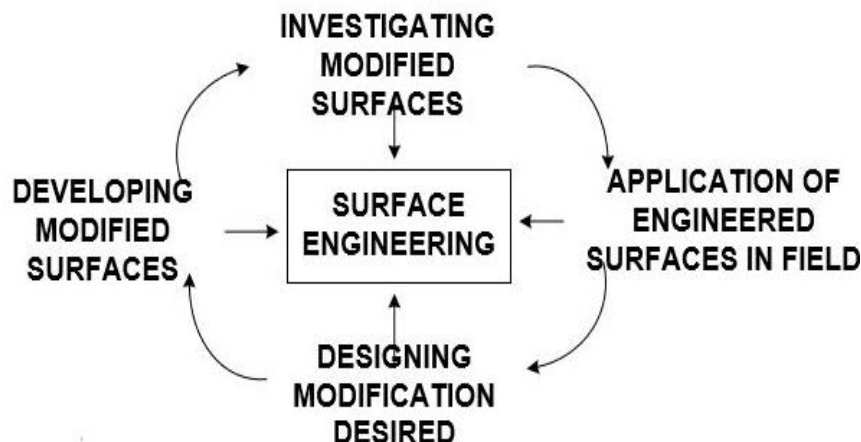


Fig.1.1: Scope of surface engineering

1.2 TYPES OF MODIFICATION PROCESS

Surface treatments give the desired properties to the base materials to enhance the corrosion resistance or their tribological properties. These are grouped into three broad categories namely

- i) Modify the surface without altering the chemical constitution of the substrate,
- ii) Modify the surface without altering the chemical constitution of the substrate,
- iii) coating with different materials.

Other innovative processes include solid-state processes such as roll bonding, explosive cladding and friction surfacing which are widely employed to protect the surfaces. The Techniques and capabilities describes the various method of coating of one material with respect to their need of coating thickness (mm).

1.3 WHY FRICTION SURFACING:

Generally, surface modification are divides into three categories, that is modification done without changing the material chemically, modification by altering surface chemistry and modification by adding new material onto the surface i.e., by coating. The Techniques and capabilities describe the various method of coating of one material with respect to their need of coating thickness (mm). From Fig 1.2 we can see that only some coating methods has the ability to create a coating with more than 1 mm. Among them friction surfacing can produce a coating of 0.3mm to 4mm thickness. It is a solid phase process where relatively low maximum temperatures are reached and consequently it has important advantages over other surfacing methods which are performed at high temperature. It has the potential to be used on a wide range of materials and application. For example, wear resistant metals containing hard carbide particles can be deposited without the carbide particles being lost to the solution in the metal matrix due to high temperature. Corrosion resistant cladding can be performed on steel without the formation of brittle inter-metallic compounds and cladding of steel can be performed underwater without the risk of hydrogen cracking. The process is not

sensitive to environmental condition and unlike other process, produces no toxic fumes, gases or environmental contaminants. During the process small pieces of plastic or metal will be forced out of the flash mass, the flash carries the debris and dirt.

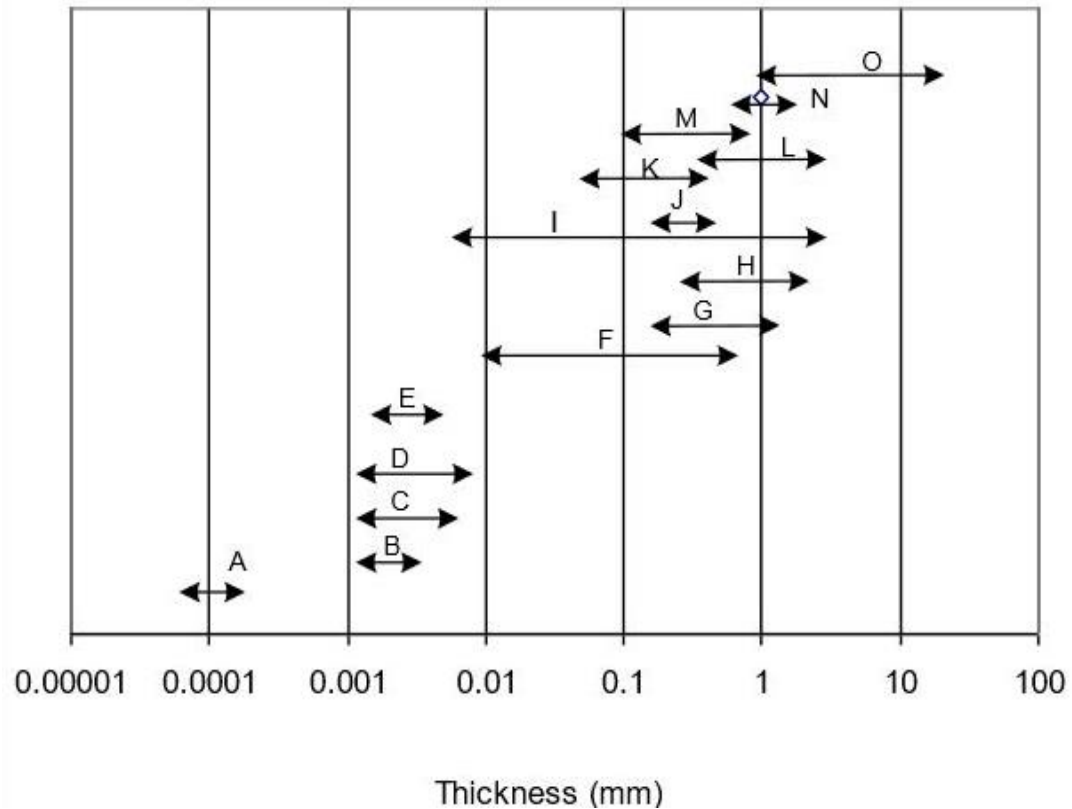


Fig. 1.2: various solid state joining processes

- A: Ion Implantation,
- B: PVD,
- C: CVD,
- D: Electrolytic Plating,
- E: Electro-less Plating,
- F: Hot Dipping (Galvanizing/Aluminizing),
- G: Laser Surface Alloying,
- H: Transformation Hardening,
- I: Mechanical Working,

J: Nitriding,
K: Carbonitriding,
L: Carburizing,
M: Thermal Spraying,
N: Friction Surfacing,
O: Weld Overlays.

1.4 FRICTION SURFACING

Frictional surfacing is a solid-state metal bonding process which uses frictional energy and temperature created during the process to plasticize the consumable rod which in turn is subjected to relative transverse motion to form a layer of coating over the substrate. In this process the base metal substrate is fixed in between two clamped plates, the consumable rod is pressed against the substrate with axial load, rotates at certain rotational speed and moves along the substrate with specific transverse speed. Heat is created due to friction between the interface of two materials which in turn causes the consumable rod to plasticize and deposit on the base metal surface. The undeposited plasticized part forms mushroom like structure on the surface of consumable rod. Axial load (KN), rotational speed (rpm), transverse speed (mm/s) and consumable rod diameter are the general process parameters that highly influence the physical properties, mechanical properties and bonding quality of frictional surfacing coating. The coating width, coating thickness and intermetallic bonding strength between the coating and substrate depends upon the selection of proper parameters. The Fig. 1.3 shows the schematic diagram of parameters and process principle involved in friction surfacing process.

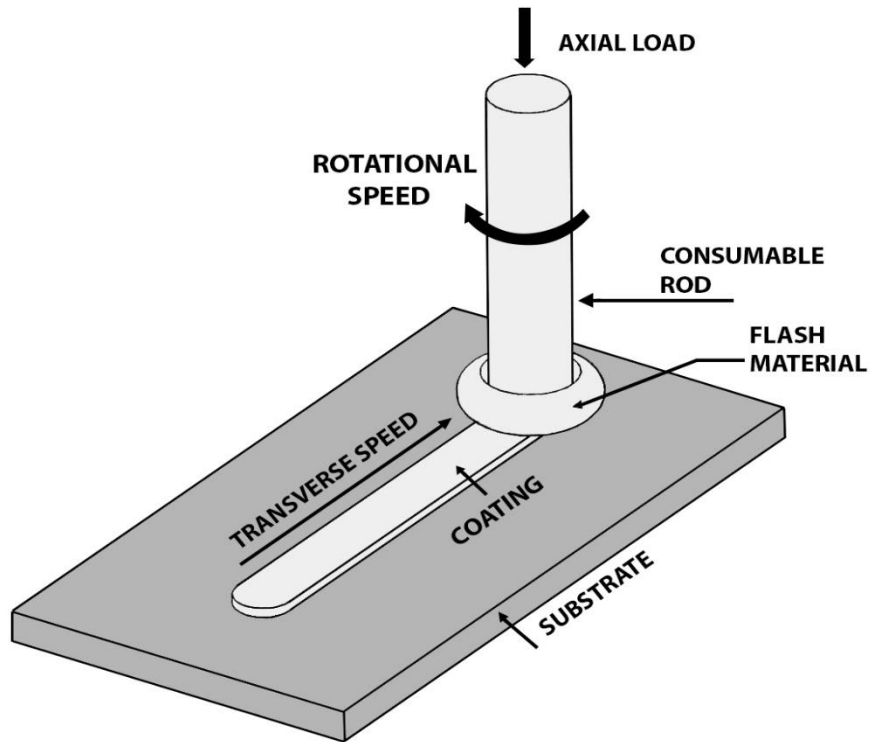


Fig 1.3: Principle of Frictional surfacing

When the consumable tool travels along the substances the viscous plastic material is transferred onto the substance surface. At the same time, pressure and thermal conditions at the interface promote an interdiffusion process that strongly dissipates the substrate with the coating material. Thus, a fine-grained microstructure is produced through dynamic recrystallization on the consumable rod. The material undergoes a thermomechanical process. The deposited layer has an excellent metallurgical adhesion due to diffusion. Friction surfacing enables dissimilar material combination reducing substrate distortion and loss of material properties. Friction surfacing eliminates hot cracking, segregation and dilution associated with fusion-based techniques. In friction surfacing, the mechtrode force, mechtrode rotational speed and substrate traverse speed are of critical importance for the final quality of the coating and bonding. The main objective of this study is to characterize the friction-surfaced SS316 overlaid on EN24 carbon steel.

1.5 IMPORTANCE OF FRICTION SURFACING:

Friction surfacing has the distinctive ability to produce coating without any dilution. It is a solid-state method utilized for producing corrosion and wear resistant coatings. It is based on strong plastic deformation resulting from a collective action of frictional heat and axial pressure. The method can be used for repairs to the surface cracks created by thermal fatigue. Heat treatment procedure meant for filling up cracks can, unlike fusion welding techniques, be dispersed with. This reduces processing period and helps enhanced metallurgical properties of the materials. Heat produced by frictional dissipation resulted in the viscoplastic deviation at the top of the consumable rod. In the course of travel along the substrate, the consumable rod material is transferred to the substrate surface. Simultaneously, pressure and thermal conditions at the interface trigger an inter diffusion process which strongly dissipates the substrate with the coating material, producing a fine-grained microstructure. Through dynamic re-crystallization on the consumable rod, the material undergoes a thermomechanical process. The deposited layer has an excellent metallurgical adhesion arising from diffusion. Friction surfacing promotes different material combination creating a reduction in and loss of material properties. Friction surfacing eliminates segregation, hot cracking and melting connected with fusion-based techniques.

1.6 APPLICATIONS OF FRICTION SURFACING

Several applications have been conceived for this unique process. A wide range of component sizes and shapes have been surfaced for critical end use. Friction surfacing is the unique solid phase bonding process that facilitates metallurgical bonds, with applications in the areas of wear resistance, protection against corrosion, aesthetic appearance to the surfaces, homogeneous repairs to valuable components and to achieve desired thermal/electrical properties. The development of the friction surfacing also leads to cladding of pressure vessels with titanium, aluminium and stainless steel.

The critical areas of application include depositing hard facing materials on cutting edges of knives of various categories, punch, die, tools and blades required for food processing, chemical, agriculture and medical industries. Friction surfacing is most

suitable for reconditioning of worn-out shafts, in-situ reclamation of worn-out railway points and good anti-corrosion overlay of slide valve plates.

Friction surfacing not only gives good bond on plane surfaces but also on other contours by design of special purpose machines using CNC technology. Since bond strength is very good, these deposits are expected to serve better during service. There is also some advancement in using robots for wear and corrosion resistant deposits on 3D complex geometric surfaces. Friction surfacing is being developed to use under water for marine propulsion system. This process though has enormous potential, it is yet to be commercialized on a large scale in many countries including India.

CHAPTER 2

LITERATURE SURVEY

1. M.J.R. Stegmueller, R.J. Granta, P. Schindele: Quantification of the interfacial roughness when coating stainless steel onto aluminium by friction surfacing, *Surface & Coatings Technology*, 375, 2019, 22-33.

The rotational speed of and load on the coating rod influenced the bond strength significantly with low rotational speeds and high load values producing a good bond quality. An image recognition software tool was used to generate an interfacial roughness profile graph which described the coating-substrate interface. Large roughness values can be related to high coating push-off strengths (up to 107 MPa), and also were a result of low rotational speeds and high load values during friction surfacing. Dovetail shaped mechanical interlocks identified in the profile produced both high push-off and shear strength when compared with wedge shaped interlocks; which, overall, provided good shear strengths up to 126 MPa.

2. Seyedeh Marjan Bararpour, Hamed Jamshidi Aval, Roohollah Jamaati: Modeling and experimental investigation on friction surfacing of aluminum alloys, *Journal of Alloys and Compounds* 805, 2019, 57e68.

A three-dimensional finite element software known as ABAQUS was employed to anticipate the materials thermo-mechanical behaviour over this procedure. At that point, in order to investigate the mechanical and microstructures characteristics of the coated samples, the experimental observations and model predictions have been implemented. The results clarified that the strain rate and temperature values are not high at the interface of the substrate and coating layer, also, we observed their maximum values in a layer nearby the upper surface of the coating in the advancing side (AS).

3. Zahra Rahmati, Hamed Jamshidi Aval, Salman Nourouzi and Roohollah Jamaat: Modeling and experimental study of friction surfacing of AA2024 alloy over AA1050 plates, *Mater. Res. Express* 6, 2019, 0865g2.

The results revealed that as the rotating velocity of the consumable rod is increased, the axial feeding rate or the traverse velocity is declined. Moreover, if the other two parameters are kept constant, the maximum temperature and heat generation increase. In strains more than 20, the temperature leads to an increase in the grain size by basically enhancing the grain growth phenomenon, however, the mechanism of grain growth is not dominant with respect to the other values of strain. The maximum ultimate shear strength occurs in the plastic strain more than 20 and the temperature around 395 °C in the coating.

4. Parisa Pirhayati, Hamed Jamshidi Aval, Effect of silver on non-isothermal aging of friction surfaced AA2024-16wt%Ag composites, Surface & Coatings Technology, 2019.

The severe plastic deformation and the heat applied during the friction surfacing process result in the formation of ultrafine grains within the coating. The presence of silver can stimulate the formation of the T (Al₆ (Cu, Ag) Mg₄) precipitate, concerning the formation of the θ precipitate. Adding silver during friction surfacing results in thermal stability of the coating. The formation of the T' phase in the coating, containing silver, can result in higher hardness and ultimate shear strength compared to a silver free coating during the aging process up to 260 °C.

5. Seyedeh Marjan Bararpour, Hamed Jamshidi Aval, Roohollah Jamaati: Effects of Zn powder on alloying during friction surfacing of Al–Mg alloy, Journal of Alloys and Compounds, 2019.

The addition of Zn powder greatly increases the thermal stability of the coating and reduces kinetic of grain growth Based on the XRD results in pre heat treatment condition of sample containing Zn powder, in addition to the iron-rich particles and Mg₂Si, the MgZn and Mg₇Zn₃ particles formed. The long-time solid solution and aging treatment result in the AlMg₄Zn₁₁ precipitates in the coted sample. After 8 hours heat treatment, the coating hardness reaches 70.14 BHN, which shows an increase of 14% as compared to before heat treatment.

6. Hongjun Li, Wei Qin, Alexander Galloway, Athanasios Toumpis, Friction Surfacing of Aluminium Alloy 5083 on DH36 Steel Plate, 2019.

Seven friction surfaced plates with different combinations of parameters were examined. the substrate. The results show that the deposition surface quality decreased as the feed rate, travel speed and axial force increased. However, the bond strength increased with higher feed rate, higher rotation speed and lower travel speed. Elemental diffusion of Fe to AA5083 was established, and the intermetallic compound FeAl₃ was produced in the interface.

7. Mingrun Yu, Zili Zhang, Hongyun Zhao, Li Zhou, Xiaoguo Song: Microstructure and corrosion behavior of the ultra-fine grained aluminum coating fabricated by friction surfacing, Materials Letters, 250, 2019, 174–177.

The grain size and the fraction of low angle boundaries significantly declined. The A1* and A2* shear textural components were found in the FS coating. Furthermore, the corrosion current of the coating was less than that of the base materials, and the passive potential of the coating increased. The corrosion resistance of the passive file and aluminum alloy were both promoted after FS according to the electrochemical impedance spectroscopy.

8. D. Guo a, C.T. Kwoka, S.L.I. Chan, strengthened forced convection – A novel method for improving the pitting corrosion resistance of friction-surfaced stainless-steel coating, Materials and Design, 182, 2019, 108037.

In the present study, it is demonstrated that the resistance of the friction surfaced coating to pitting corrosion could be further improved using strengthened forced convection (SFC) with argon shielding. Restoration and further growth of dynamically recrystallized grains under SFC relieve the elastic strain in {111} grains, decrease the dislocation density, and hence reduce the metastable pit initiation probability effectively and suppress the stable pit transition susceptibility slightly.

9. Mohammed Shariq, Madhulika Srivastava, Rupam Tripathi, Somnath Chattopadhyaya, Pedro Vilaca, Espoo,Finland, Nenad Gubeljak,

Maribor, Slovenia, and Grzegorz Krolczyk, Optimization and characterization of friction surfaced coatings of ferrous alloys, *Wear Testing*, 60, 2018, 7-8.

The scientists were successful in obtaining a friction surfaced coating of mild steel over mild steel, mild steel over stainless steel (AISI 304) and stainless steel over stainless steel using a low-cost conventional milling machine. The results showed that, with an increase in rotational speed and table feed rate, width and thickness of the coating decreases, while temperature increases. An infrared (IR) camera provided thermographs that elaborated the distinct stages of heat dissipation during the process of coating formation. The bond integrity and strength of the coating was analysed by bend tests and Vickers micro hardness test. The results revealed that a higher hardness value was obtained at the interface of the coating as compared to coating and interface.

10. A.V. Sreenu, Aluminium-boron nitride nano composite coating by friction surfacing on low carbon steel substrate – a feasibility study, *Materials Today: Proceedings* 5, 2018, 26829–26835.

Optical microscopic studies reveal that there is no gross porosity or cracks presents at the interface. Scanning electron microscopy of the coating indicated that there is uniform. EDS analysis and Micro hardness survey across the interface showed that there are no traces of dilution and intermetallic compound formation across the interface. X-ray diffraction studies at the coating also confirmed the presence of boron nitride phase in the coating and there is no intermetallic compound formation between aluminium matrix and boron nitride particles. It was observed that there is no significant increment in the hardness of the aluminium before and after the friction surfacing process.

11. Samuel Silvério, Hennin Krohn, Viktoria Fitseva, Nelson Guedes de Alcântara, Jorge Fernandez dos Santos, Deposition of AA5083-H112 Over AA2024-T3 by Friction Surfacing, *Soldagem & Inspeção*, 23(2), 2018, 225-234.

The present study addresses the deposition of AA5083-H112 coatings over AA2024-T3 substrates focusing on the influence of the main process parameters

such as axial force, rotational speed and deposition speed, in the mechanical properties of the deposits. A performance and geometric analysis of the depositions are also presented. Sound aluminum coatings were produced; plastic deformation and heat generation promotes a dynamic recrystallization of the anisotropic consumable rod, resulting in a fine and homogeneous deposit. The coating presented an increase in ultimate tensile strength and failure deformation of 9% and 6%, respectively. Deposition efficiency between 25 and 50% were obtained, with a maximum of 48% average efficiency observed with 800 RPM, 12 kN and 16 mm/s.

12. Juan Carlos Galvis, Pedro Henrique Fernandes Oliveira, Juliana de Paula Martins, André Luis Moreira de Carvalho, Assessment of Process Parameters by Friction Surfacing on the Double Layer Deposition, Materials Research, 2018, 1-11.

The friction surfacing process of two deposited layers on two deposition surface conditions, i.e., a smooth interface and a rough interface, was investigated. The interface strength of the substrate/deposit1 (smooth) and deposit1/deposit2 (rough) was evaluated by bending tests and the micro-hardness profile along the transverse section of the substrate/deposit1 and deposit1/deposit2. The bending tests revealed the presence of small delaminations with no evidence of fracture at the rough deposit1/deposit2 interface (D1/D2) with less predominance in the deposition condition 3B. This suggests that the combination of the travel speed of 5.5 mm/s and an increase in the consumable rod feed rate of (≥ 5.5 mm/s) increases the adhesive strength of the two produced interfaces

13. Márcio Maciel da Silva, Michel Lenhago Beneducci Afonso, Stephanny Lohanny Nunes Silva, Fernanda Christina Teotônio Dias Troysi, Ítalo Bruno dos Santos, Pedro Paiva Brito: Application of the friction surfacing process in a CNC machining center: a viability assessment for producing Al-alloy coatings on low carbon steel, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2018, 40:14.

In the present work, the viability of employing the friction surfacing process in a machining center with computerized numerical control was investigated. The

surface finish of the substrate plate was found to influence heat generation during the deposition process and impacted coating deposition. The results demonstrated that, although parameters must be carefully tuned, the process can be feasibly applied under the experimental conditions investigated, and a maximum push-off force value of 4250 N could be achieved

14. Abhishek Sharma, Shiwendu Sagar, Raju Prasad Mahto, Baidehish Sahoo, Surjya Kanta Pal, Jinu Paul, Surface modification of Al6061 by graphene impregnation through a powder metallurgy assisted friction surfacing, *Surface & Coatings Technology*, 337, 2018, 12–23.

In the present work, authors demonstrate a surface modification of Aluminium by graphene impregnation through a novel powder metallurgy assisted friction surfacing (PMAFS) process. This modified friction surfacing technique involves two stages. In the first stage, an Aluminium-graphene composite tool is fabricated through a powder metallurgy route. In the second stage, this consumable tool is utilized for FS to obtain a composite coating layer on Aluminium surface. Experimental results show that the surface composite prepared by this modified friction surfacing technique does have impregnated graphene successfully in Al matrix. Morphology and damage to graphene are studied by using Raman spectroscopy. Nanoindentation study was conducted for a various set of processing parameters with variation in graphene content. Further, the influence of graphene percentage and processing parameters on mechanical properties and microstructural changes were also studied. Composites prepared at relatively lower tool rotational speed with low content of graphene in the tool is found to have optimum mechanical properties with a homogeneous distribution of graphene in Al substrate. The nano-hardness of the surface composite is increased by 100% after impregnation of graphene nano platelets (GNP) with an optimum set of parameters.

15. J.C. Galvis, P.H.F. Oliveira, M.F. Hupalo, J.P. Martins, A.L.M. Carvalho: Influence of friction surfacing process parameters to deposit AA6351-T6 over AA5052-H32 using conventional milling machine, *J. Mater. Process. Technol.* 245, 2017, 91–105.

Superficial and microstructural characterization of the deposits was investigated. The substrate/deposit interface resistance was also investigated by bending tests and evaluating the microhardness profile. Friction surfacing produced microstructural deposits of refined grains with 24.1% lower hardness values than those of the consumable material as received. The bending tests revealed delamination presence in the deposit/substrate interface with lower predominance for the 1A deposition process.

16. Michael, JR. Stegmüller., Richard J Grant, Paul Schindele: Improvements in the process efficiency and bond strength when friction surfacing stainless steel onto aluminium substrate, *Journal of Materials: Design and Applications*, 0(0), 2017, 1–12.

Friction surfaced specimens produced by the application of inductive heating and utilising a flash-reducing tool were compared with those obtained through the classical approach. It was found that the use of inductive heating resulted in an increased consumption of the coating material; however, the push-off strength could be more than doubled when compared with the classical process with high shear strength values of up to 111 MPa. Temperature measurements with thermocouples taken during the coating process showed that the melting temperature of the aluminium substrate was reached at the substrate–coating interface.

17. Capt. B. Kiruthi Murugan, V. Balusamy, R. Padmanaban, R. Vairav Vignesh, Study of the effect of parameters in friction surfacing of Monel over Mild Steel using linear – radial basis function model, 2017.

This paper investigates suitability of friction surfacing (FS) for cladding AISI 1012 with Monel K500. FS trials were conducted by varying the spindle speed, axial pressure and the horizontal feed rate. The thickness and width of the coating were measured and the data were used to develop radial basis function network model relating the FS process parameters with the coating thickness and width. The model was used to analyse the variation of coating thickness and width. The coating thickness and width decreased with increase in spindle speed and horizontal feed rate, while they increased with increase in axial load

- 18.S. Ravi Sekhar, V. Chittaranjandas and D. Govardhan, Friction Surfacing process of Stainless-steel alloys, International Journal of Mechanical Engineering and Technology, Volume 8, Issue 7, 2017, pp. 613–626.

In the present work, the weldability of the stainless steel with the low carbon steel by friction surfacing has been investigated experimentally. With 23 designs of experiment, the optimum parameters are determined for obtaining the desired mechanical and physical properties. This coating is investigated for bond strength using primary tests and mechanical tests. Metallographic examination, micro hardness distribution and bend tests are also conducted to estimate the qualitative properties of the deposit. The corrosion test is also performed to discuss applications deposited sheets in the areas of chemical pumps, pressure vessels and joining of dissimilar metals

- 19.Mohammed Shariq, Madhulika Srivastava, Rupam Tripathi, Somnath Chattopadhyaya, Amit Rai Dixit, Feasibility Study of Friction Surfaced Coatings over Non-Ferrous Substrates, Procedia Engineering. 149, 2016, 465 – 471.

The present work examines the feasibility of getting friction surfaced coatings on different combinations of consumable rods and non-ferrous substrates. Aluminium (AA1050A), Copper, Stainless Steel (AISI 304), Mild Steel were used as substrates and commercially pure Copper and Stainless Steel (AISI 304) were used as consumable rods. The formation of coating is influenced by the coefficient of friction as well as material properties, such as, thermal conductivity and stability at high temperature.

- 20.S. Madhu, M. Balasubramanian, Rathesh Sivakesan, Finite Difference Modelling on the Temperature field of Aluminium and Low carbon steel in Friction Surfacing, ARPN Journal of Engineering and Applied Sciences, Vol 11(16), 2016, 10065-10071.

In this work, the temperature model of mechtrode in friction surfacing is established. Using finite element method, the temperature field of consumable-rod during the friction surfacing process is simulated. In this work low carbon steel (EN1A) is used

as a Substrate Material and Aluminum 6061 Alloy is used as a Mechtrode. Mechtrode rotation speed is varying from 900 to 1500 rpm and the axial load applied is 10 KN.

21. D. Govardhan, K. Sammaiah, K.G.K. Murti, G. Madhusudhan Reddy, Evaluation of bond quality for stainless steel-Carbon steel friction surfaced deposits, Materials Today.Proceedings.2, 2015, 3511 – 3519.

Friction surfacing was carried out by using Stainless steel as mechtrode and Low carbon steel as substrate. This paper is an attempt to give review details of the variants of friction surfacing techniques, bonding mechanism, factors selection of process parameters to apply on different combinations of materials and confirming the same with experimental test results. Effect of process parameters on the responses like width, height, surface roughness, tensile strength shear strength and ratio of tensile strength and shear strength are discussed in details.

22. H. Krohn, S. Hanke, M. Beyer, J.F. dos Santos, Influence of external cooling configuration on friction surfacing of AA6082 T6 over AA2024 T351, Manufacturing Letters. 5, 2015, 17–20.

This concept has been investigated by depositing Al alloy AA6082 T6 on AA2024 T351 substrate. The efficiency of the process was increased from 19% to 31% without influencing the properties of the deposited material. Temperature measurements revealed that the intensity and chosen location of cooling also affect the process characteristics and allow modifying the coating geometry.

23. Ashok Kumar U, Laxminarayana. P, Friction Surfacing Process of Aluminium alloys, 2014.

The present work deals with the solid-state coating by friction surfacing process of various materials coated over substrate materials. The effects of traverse speed on the geometry, interfacial bond characteristics and mechanical properties of coatings are studied

24.D. Pereira, J. Gandra, J. Pamies-Teixeira, R.M. Miranda, P. Vilaca, Wear behaviour of steel coatings produced by friction surfacing, J. Mater. Process. Technol.214, 2014, 2858–2868.

Friction surfacing was performed to produce multi-layer coatings of AISI 1024, AISI 1045 and AISI H13 overmild steel substrates. Microscopic and hardness characterization revealed the presence of bainitic and martensitic microstructures which influenced the hardness of the coatings. The analysis suggested that AISI 1024 presents the least wear, both in terms of friction coefficient and wear rate.

25.R. George Sahaya Nixon, Dr. B.S. Mohanty, Friction Surfacing of Metal Coatings on Stainless Steel AISI 304 Over Spheroidal Graphite Iron Substrate, Advanced Materials Research Vols. 816-817 (2013), pp 271-275

This work explains the perfection obtained through various combination of the parameters used in friction surfacing namely traverse speed, rotational speed and the applied load. Mechanical tests like bending test, microhardness test and corrosion test were conducted. Appreciable hardness values (200 HRC) have been obtained in micro-hardness test. Bend test performed on the surface revealed good strength and reliability of the bonding. The Corrosion test was conducted to find the suitability of these deposits for chemical pumps, pressure vessels and joints of dissimilar metals.

26. Gandra J., Pereira D., Miranda R.M., Vilaça P., Influence of process parameters in the friction surfacing of AA 6082-T6 over AA 2024-T3. Procedia CIRP. 7, 341 – 346(2013).

The present study addresses the deposition of AA 6082-T6 coatings on AA 2024-T3 substrates, while focusing on the effect of process parameters, such as, axial force, rotation and travel speed. It was observed that low travel and rotation speeds contribute to an increase of coating thickness and width. Bonding at coating edges deteriorates for faster travel speeds. The axial force is determinant in achieving a fully bonded interface.

27. Gandra J., Vigarinho P., Pereira D., Miranda R.M., Velhinho A., Vilaça P., Wear characterization of functionally graded Al–SiC composite coatings produced by Friction Surfacing. *Materials and Design*. 52, 373–383(2013).

SiC particles with a median size of 118.8, 37.4 and 12.3 μm were packed inside AA6082-T6 aluminium rods and used as consumables. AA2024-T3 plates were used as substrates. Results indicate that the smaller particles were more easily embedded in the aluminium matrix during deposition. The multi-layer coating presents a composition gradient, as SiC area fraction gradually increases from 5% to 30%.

28. Sekharbabu R., Khalid Rafi H., Prasad Rao K., Characterization of D2 tool steel friction surfaced coatings over low carbon steel. *Materials and Design*. 50, 543-550(2013).

In this work D2 tool steel coating is produced over a low carbon steel substrate using friction surfacing process. A lower rotational speed of the consumable rod and higher translational speed of the substrate is found to result in thinner coatings. Friction surfaced D2 steel coating showed fine-grained martensitic microstructure compared to the as-received consumable rod which showed predominantly ferrite microstructure. The infrared thermography studies showed the peak temperature attained by the D2 coating to be about 1200 °C.

29. Prasad Rao K., Veera Sreenu A., Khalid Rafi M., Libin H.N., Balasubramaniam K., Tool steel and copper coatings by friction surfacing – A thermography study. *J. Mater. Process. Technol.* 212, 402-407(2012).

Infrared thermography was used to record thermal profiles during friction surfacing. Thermal profiles for different sets of consumable rod/substrates (tool steel/steel; copper/steel and copper/copper) were recorded and analysed. It was found that a metallurgically bonded coating can be obtained if the flow stress of the plasticized material is comparable with the localized stress developed due to axial loading.

30. Ramesh Puli, G.D. Janaki Ram, Corrosion performance of AISI 316L friction surfaced coatings, *Corrosion Science*, 62, (2012) 95–103

In this work, the corrosion behaviour of AISI 316L stainless steel coatings made using friction surfacing and manual metal arc welding processes was comparatively evaluated. Friction surfaced coatings exhibited superior general and pitting corrosion resistance compared to manual metal arc coatings, while both the coatings were found to be immune to intergranular corrosion. Compared to alloy 316L bulk material, friction surfaced coatings showed better pitting corrosion resistance, but considerably lower general corrosion resistance.

CHAPTER 3

AIM AND SCOPE OF PRESENT INVESTIGATION

3.1. AIM

To obtain the solid-state coating between medium carbon steel and stainless steel by friction surfacing and analyse its microstructural features of the coatings which gives better corrosion resistance and good mechanical strength compared to the base material.

3.2. OBJECTIVE

The aim objective of this study is to analyze the microstructural features and characterization study of the coating of AISI 316 stainless steel over EN24 medium carbon steel using friction surfacing process. A 3D-FE model of friction surfacing process will be prepared using ABACUS software and the coating geometry like coating width, coating thickness will be predicted. The friction surfacing will be carried out by considering the process parameters like axial load, rotational speed and transverse speed and the obtained coating geometries will be compared with the predicted value. Series of microstructural study like FE-SEM, EDAX and XRD will be performed to know the bonding behaviour of these two coating materials. Mechanical tests like Vickers hardness test and bending test will be carried out to know the bonding strength of the coatings.

3.3. SCOPE OF THE PRESENT INVESTIGATION

After gone through the present literature review, it has been noted that the modelling of friction surfacing process and finding the coating geometry on both mathematical and experimental ways are limited and not effectively analysed for the material combination of AISI 316 stainless steel and EN24 medium carbon steel by friction surfacing process. The present work deals with evaluating the microstructural attributes of the deposition of AISI316 stainless steel over EN24 medium carbon steel. A successful coating of AISI316 stainless steel over EN24 medium carbon steel has offered improved mechanical properties and also high machinability having wide commercial applications.

CHAPTER 4

MATERIALS, MODELLING AND EXPERIMENTAL PROCESS

4.1. MATERIALS

Stainless steels are most notable for their corrosion resistance, which increases with increasing chromium content. Additions of molybdenum increase corrosion resistance in reducing acids and against pitting attack in chloride solutions. Thus, there are numerous grades of stainless steel with varying chromium and molybdenum contents to suit the environment the alloy must endure. Stainless steel's resistance to corrosion and staining, low maintenance, and familiar luster make it an ideal material for many applications where both the strength of steel and corrosion resistance are required. The chemical compositions of EN24 Medium Carbon Steel and AISI316 stainless steel are displayed in Table 4.1 and 4.2 respectively.

Table 4.1 Chemical composition of AISI 316 stainless steel

Material	Cr	Ni	Mo	Mn	Si	N	C	P	S
Composition (%)	18	14	3	2	1	0.10	0.08	0.045	0.03

Table 4.2 Chemical composition of EN24 medium carbon steel

Material	C	Si	Mn	S	P	Cr	Mo	Ni
Composition (%)	0.4	0.25	0.55	0.04	0.035	1.2	0.27	0.5

4.1.1 EN24 medium carbon steel

Medium carbon steels include grades with carbon contents ranging from 0.25% to 0.60% of the steel mass. Medium carbon grades are typically employed in conjunction with alloys such as chromium, nickel and molybdenum to produce high strength, wear resistance and toughness. Products using medium grades of carbon steel

include gears, axles, studs and other machine components that require optimal combinations of strength and toughness.

Medium carbon steels have good machining characteristics, and one of the more popular grades used in machined steel product is AISI 1045. AISI 1045 can also be hardened by heating the material too approximately 820-850C (1508 -1562 F) and held until the material reaches a uniform temperature. It should be soaked for one hour per 25 mm section of material and subsequently cooled in still air.

4.1.2 AISI 316 stainless steel

Stainless steels are most notable for their corrosion resistance, which increases with increasing chromium content. Additions of molybdenum increase corrosion resistance in reducing acids and against pitting attack in chloride solutions. Thus, there are numerous grades of stainless steel with varying chromium and molybdenum contents to suit the environment the alloy must endure. Stainless steel's resistance to corrosion and staining, low maintenance, and familiar luster make it an ideal material for many applications where both the strength of steel and corrosion resistance are required.

4.1.3 Properties of AISI 316 stainless steel

- Density: 0.799g/cm³
- Electrical resistivity: 74 micro m-cm (20 degrees Celsius)
- Specific Heat: 0.50 kJ/kg-K (0–100 degrees Celsius)
- Thermal conductivity: 16.2 W/m-k (100 degrees Celsius)
- Modulus of Elasticity (MPa): 193×10^3 in tension
- Melting Range: 2,500–2,550 degrees Fahrenheit

4.2 MATHEMATICAL MODELLING OF FRICTION SURFACING PROCESS

4.2.1 Model of frictional heat generation at mechtrode

To analyse the frictional behaviour of mechtrode during friction surfacing, it should be assumed that the pressure and heat produced at the interface region should be uniform and as per the assumption, the frictional heat developed at substrate-mechtrode interface should be derived from the following mathematical expression. Before that an

elemental annulus with inner radius r_p and width dr_p was defined at frictional interface displayed in figure 1.

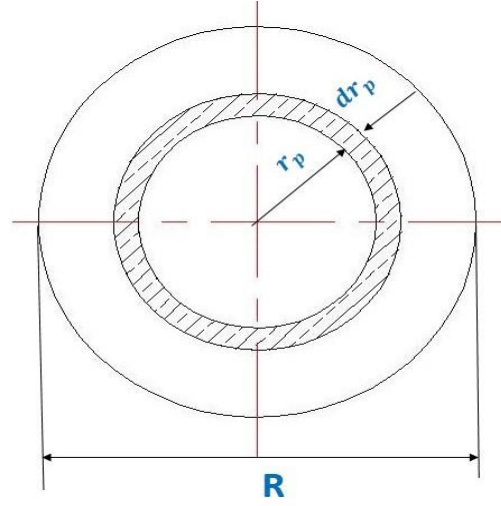


Fig.4.1: Frictional interface of mechtrode rod.

Throughout the contact surface of the mechtrode, a constant pressure (p_c) is acting. Therefore the area of the elemental annulus should be calculated as $dA_p = (2\pi r_p).dr_p$. By converting the pressure equation into a differential representation of the area dA_p . The differential force dF_r which is acting on area dA_p can be rewritten by the following equation.

$$dF_r = p_c dA_p = 2p_c \pi r_p dr_p \text{----- (1)}$$

Let dF_d be the differential frictional force which is equivalent and opposite of the normal force acting on dA_p . The dF_d can be written as

$$dF_d = \mu dF_r = 2\mu p_c \pi r_p dr_p \text{----- (2)}$$

Where μ is considered as coefficient of friction. It can be called as the tangential velocity, V_t which is same at any point on the elemental section and can be expressed as

$$V_t = r_p \omega_a \text{----- (3)}$$

Where ω_a is called as the angular velocity and the differential power (dp_c) which is developed during the rotation of mechtrode is defined as

$$dp_c = dF_d(V_t) \text{-----} (4)$$

By putting the value of dF_d and V_t in equation (4) and integrating with respect to r , integrating Eq. (4) with respect to r , the designation of frictional heating power (p_c) developed at mechtrode interface can be derived as

$$P_c = \int_0^R 2\mu p_c \pi r_p^2 \omega_A dr_p = \frac{2}{3} \mu p_c \pi (R^3) \omega_A \text{-----} (5)$$

The frictional heat flux (Qr_p) developed at the mechtrode interface can be calculated as

$$Q(r_p) = \frac{dp_c}{dA_p} = \mu p_c \omega_A r_p \text{-----} (6)$$

During plastic deformation of materials, the temperature fluctuation will enhance the physical and mechanical properties of the material. During deformation analysis, the established relationship among material and induced thermal strain will vary based on the temperature distribution during the process of heat transfer stage. The material deformation will also influence the heat transfer space, energy transition and the boundary condition of the mechtrode.

The power required for plastic deformation or the rate of internal energy (q_h) available for the ductile mechtrode like aluminium which is away from the contact interface can be written as

$$q_h = \beta_{eq} \sigma_{eq} \epsilon_{eq} \text{-----} (7)$$

Where β_{eq} is called as the thermal efficiency during plastic deformation, σ_{eq} is the equivalent stress and ϵ_{eq} is the equivalent strain rate respectively. Based on the plastic deformation theory, maximum amount of plastic deformation converts into heat so the thermal efficiency β_{eq} , usually set as 0.9. The remaining amount of energy is mainly stored as dislocations and vacancies. For the aid of simplicity, during this computational

analysis, the internal energy value was neglected as its value is very low compared to the frictional heat development during the process.

4.2.2 Model of frictional heat source at substrate

In friction surfacing, the total process is divided into two consecutive stage i.e. the initial frictional preheating stage and steady deposition stage. At beginning of the friction surfacing, the development of the frictional heat at the surface of the substrate is the prime source for recrystallization of mechtrode material (refer figure 4.2). After the preheating stage, the mechtrode experience a severe plastic deformation and the frictional interface was transferred to coating layer position.

During substrate simulation, the total substrate thickness is taken as $M_t + S_t$ by considering coating thickness (M_t) and substrate thickness (S_t). A transient flux of local heat transfer can be applied over the total substrate thickness and shown in figure 2. The thermal exchange between the substrate and the surrounding atmosphere are also taken in to account for simulation and expressed in the following terms.

$$-\lambda \frac{\partial T}{\partial n} = \alpha(T - T_a) \text{----- (8)}$$

Where, λ , T and T_a are the thermal conductivity, temperature attained by substrate and atmospheric temperature respectively.

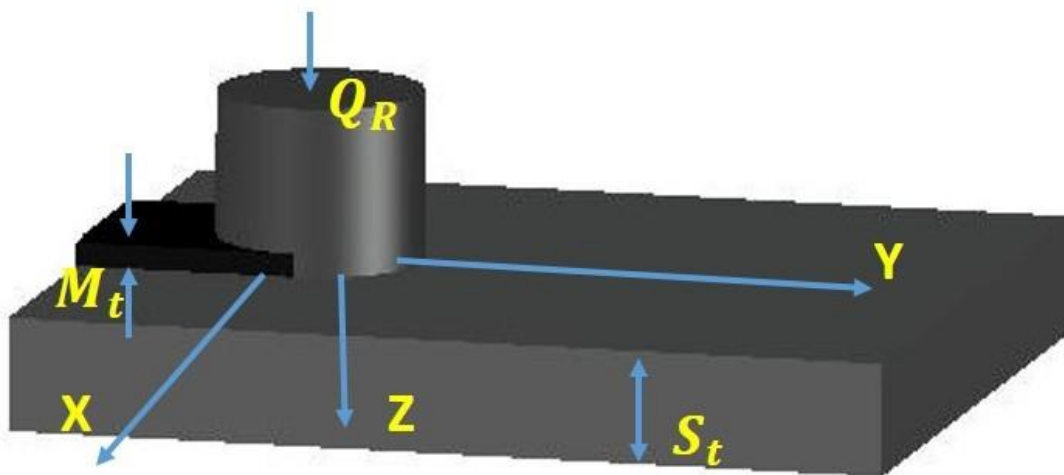


Fig. 4.2 : Heat source model of substrate

4.3 MODELLING OF FRICTION SURFACING

The CAD modeling of the friction surfacing process was done using ABACUS software. The dimensions are obtained from scrap FE mesh. Surfaces were extracted from the scrap mesh and smoothening of surfaces was done. Mechtrode and substrate plate was modelled separately and assembled together which shown in figure 4.3

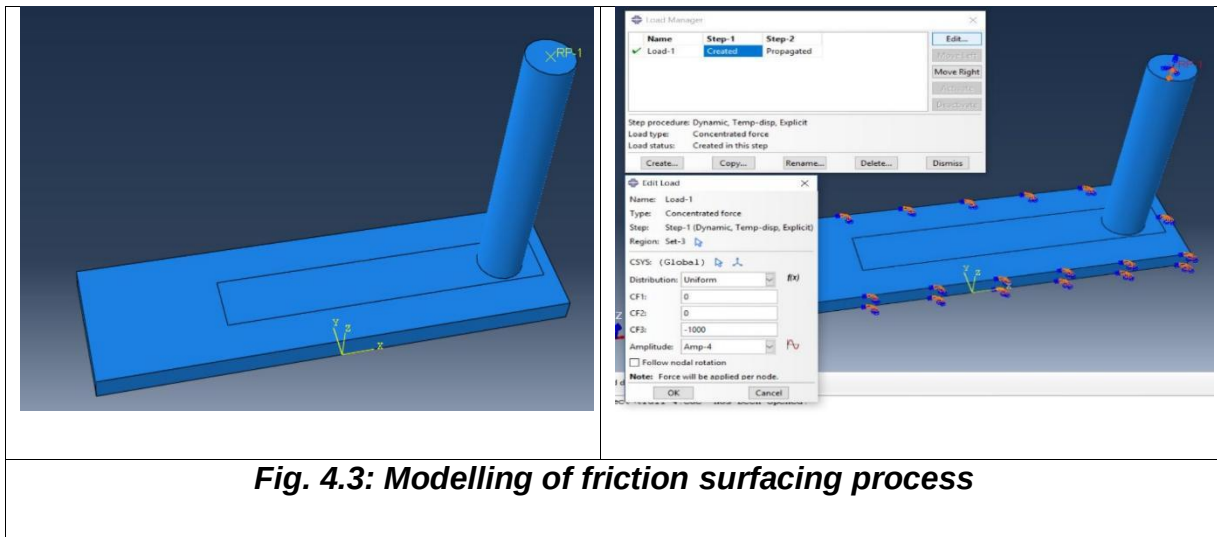


Fig. 4.3: Modelling of friction surfacing process

After the creation of geometry the next step was discretisation of the component named as finite element modeling. Two models were created one for the Temperature flow analysis and the other for the strain rate analysis. The tool used for meshing was Abacus software. Meshing of components was done using a global element length of 5mm. Tria elements were used as the element type for both mechtrode and substrate materials. The meshing was done on the outer and inner surface of the friction surfacing process. Water tightness must be ensured to create volume elements out of tria elements.

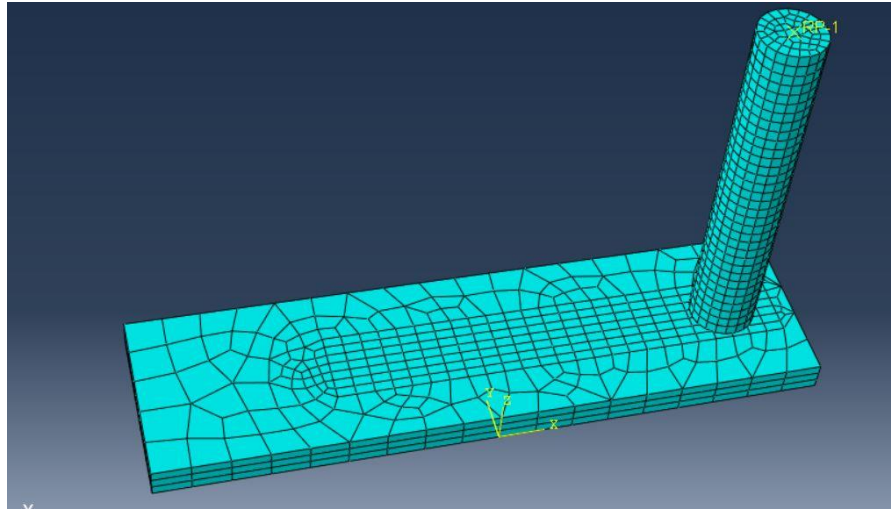


Fig. 4.4 Meshing structure of the friction surfacing process

After completion of the meshing part, the complete friction surfacing structure under gone for simulation process. The simulation work was carried out on ABACUS software. The material properties for both mechtrode and substrate materials are taken for simulation work are displayed in table 4.3. The process parameters were taken as same value for both simulation and experimental work. The fundamental process parameters were taken based on the literature survey and displayed in Table 4.4.

Table 4.3 Material properties used for simulation work

Material Properites	AISI 316 Stainless steel	EN24 Medium Carbon steel
Density (kg/m ³)	7190	7850
Thermal Expansion (10 ⁻⁵ /°k)	1.24	0.59
Thermal Conductivity (W/m°C)	96.6	45.1
Heat capacity (J/g°C)	2.13	2.3
Young's Modulus (GPa)	207	192

Table 4.4 : Friction surfacing process parameters

Sample Combinations	Axial Load (KN)	Rotational speed (rpm)	Transverse Speed
S1	6	1500	75
S2	6	2000	150
S3	6	2500	200
S4	8	1500	75
S5	8	2000	150
S6	8	2500	200
S7	10	1500	75
S8	10	2000	150
S9	10	2500	200

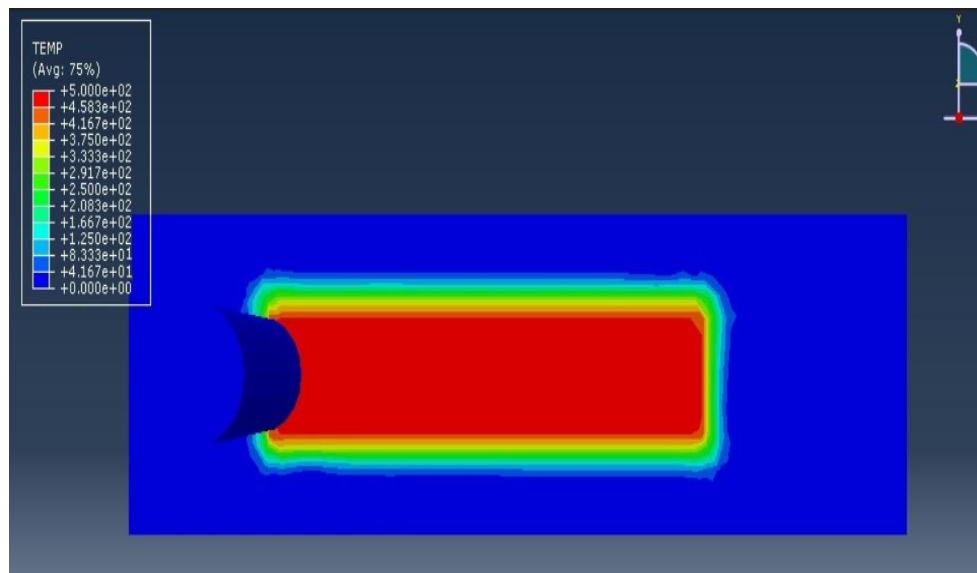


Fig. 4.5 Simulation of the friction surfacing process with process parametric combination of Axial force 8 kN, rotational speed 2500 rpm and Transverse speed 200 mm/min.

During simulation work, the different process parametric combinations were applied on the model of the friction surfacing process. The value of coating geometry like coating width and thickness were obtained during simulation were recorded and shown in table 4.5.

Table 4.5: Coating geometry obtained from the simulation work

Sample Combinations	Simulated Coating width (mm)	Simulated coating Thickness (mm)	Interface Temperature (°C)
S1	13.00	1.79	822
S2	13.42	1.68	838
S3	13.54	1.32	857
S4	12.23	1.62	846
S5	12.56	1.57	869
S6	13.90	1.69	887
S7	12.65	1.60	893
S8	13.96	1.76	921
S9	12.40	1.78	940

4.4. EXPERIMENTAL WORK

An AISI316 stainless steel rod of 16mm diameter and 120 mm length was used as the consumable rod, and an EN 24 medium carbon steel plate of 150 mm length, 120 mm width and 10mm thickness was used as the base metal. The mechtrode and substrate are milled on their surface using a conventional milling machine to ensure flatness at the coating surface. Both materials are then cleaned using acetone to remove contaminated particles. The experiment was carried out in a friction surfacing machine using certain parametric combination. Axial load of 6kN, 8kN, 10kN, rotational speed of 1500rpm, 2000 rpm, 2500 rpm and transverse speed of 75mm/min, 150mm/min and 200mm/min were used during the FS process. The Friction surfacing process has the parameter values to create the coating such as rotational speed, transverse speed and

axial load of the mechtrode. The coating is done when the flash region starts to create, then the road moves forward direction to deposit the coating layer on the substrate. The mechtrode and substrate are milled on their surface using a conventional milling machine to ensure flatness at the coating surface. Both materials are then cleaned using acetone to remove contaminated particles. These processes are carried out using the L9 orthogonal array values. Stainless steel coatings were overlaid on medium carbon steel for 100 mm in length. A total of 9 coating was done according to the suitable parameters chosen as per the Taguchi L9 orthogonal array. Fig. 4.6 shows the pictorial view of the experimental work and during experimental work (Figure 4.6b)

4.4.1. NC-IR Infrared Thermometer.

The interface temperature of the consumable rod and substrate were recorded by using a NC-IR thermometer IRX-68 HTC, Taiwan. The thermometer was calibrated by the manufacturer to measure the temperature ranging from -50°C to 1850°C . It was operated with optical resolution 50:1 with adjustable emissivity from 0.1 to 1. The emissivity value for AISI 316 stainless steel and EN24 carbon steel were taken as 0.6 and 0.26 respectively and the thermometer was placed at an appropriate distance of 1 m from the surfacing zone



(a)



(b)

Fig.4.6: Friction surfacing (a) experimental set up (b) during experimental work.

CHAPTER 5

RESULTS AND DISCUSSION

5.1. CHARACTERISTICS OF DEPOSIT

The quality of mechtrode AISI 316 deposit over the EN24 medium carbon steel substrate was analyzed by visual inspection and by using low magnification tools. All the 9 coatings achieved continuous and uniform deposit with the combination of axial force, rotational speed and transverse speed. It was observed that the coating width (Cw) increases with increase in rotational speed (rpm) and coating thickness (Ct) increases with decrease in transverse speed (mm/min) of the mechtrode. The coating width and coating thickness ranges from 12.23 to 13.96 and 1.79 to 1.32 respectively.

5.1.1 Measurement of deposit dimensions

The width, height and surface roughness of the deposits are not same for all treatment combinations. For each treatment combinations, width and height of the deposit is maximum at initial stage and remains constant while process continues. At the end of the process the mechtrode is automatically detached from substrate by moving upwards. Width of the deposit is small when compared with the remaining length. The surface roughness is also uniform over entire length. Uneven portion of the deposit is removed from both sides and is discarded. The remaining length is taken for testing purpose. Remaining length of the deposit is divided in to eight equal parts. These segments are useful for determining average values of the width, height and surface roughness. Similarly mark eight divisions in all deposits. The dimensions of the coating geometry obtained from the experimental work are displayed in Table 4.3.

Table 5.1 : Experimented value of coating geometry obtained from friction surfacing process

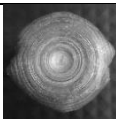
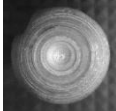
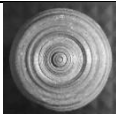
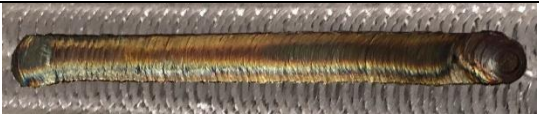
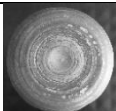
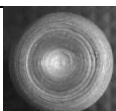
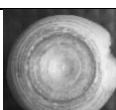
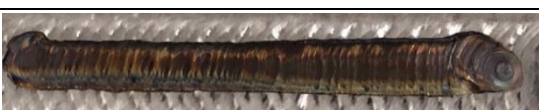
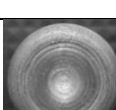
Sample Combinations	Experimented Coating width (mm)	Experimented coating Thickness (mm)	Interface Temperature (°C)
S1	14.12	1.88	829
S2	14.17	1.68	846
S3	14.04	1.46	866
S4	13.23	1.71	854
S5	13.36	1.68	879
S6	14.54	1.77	912
S7	13.35	1.68	923
S8	14.71	1.83	941
S9	13.26	1.86	956

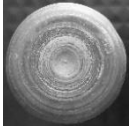
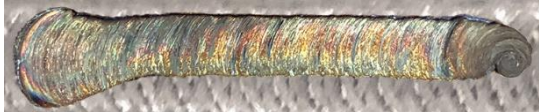
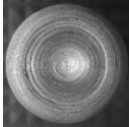
5.1.2. Visual examination of deposits

Visual examination reveals surface flaws and is a valuable indication in weld quality. It is a simple, accessible, low-cost inspection method, but it requires a trained inspector. Further, it can be an excellent process control tool, help to avoid subsequent fabrication problems and evaluate workmanship. Visual examination only identifies surface discontinuities. A conscientious program of visual inspection before and during welding may reduce costs by exposing surface defects early in the fabrication process. At the end of the process the mechtrode is automatically detached from substrate by moving upwards. Width of the deposit is small when compared with the remaining length. The width, height and surface roughness of the deposits are not same for all treatment combinations. For each treatment combinations, width and height of the deposit is maximum at initial stage and remains constant while process continues. The surface roughness is also uniform over entire length. Uneven portion of the deposit is removed from both sides and is discarded. The remaining length is taken for testing purpose. Remaining length of the deposit is divided in to eight equal parts. The following features

are required to perform visual inspection method. The most important instrument in visual testing is the human eye. The Visual Testing was conducted for all deposits after the completion of friction surfacing to detect gaps, lack of bond, surface cracks, pores etc with eye and using magnifier.

Table 5.2 Appearance of the coating and consumable rod during experimental work.

Sample	Consumable rod		Coating deposit
S1			
S2			
S3			
S4			
S5			
S6			
S7			

S8			
S9			

5.2. MECHANICAL TEST

A series of mechanical test has been conducted in order to find the tensile strength, coating strength, and bonding strength of the coating. The test carried out are Vickers hardness test, bending and ram tensile test.

5.2.1. *Vickers hardness test*

In 1925, Smith and Sand land of the United Kingdom developed Vickers Hardness Test which is used for an indentation tests that employs a square-based pyramidal-shaped indenter made from diamond. In this test the force is applied smoothly, without impact and held in contact for 10 to 15 seconds known as dwell phase. The force must be known as precisely according to ASTM E384 for tolerances.

Vickers micro hardness tester shown in figure 8, consists of the micrometer which works in conjunction with the eyepiece to measure the indentation dimensions. The time of indentation can be set using a knob on the front panel of the micro hardness tester.

The sample whose micro hardness is to be measured is mounted in phenolic powder and fixed securely on the table. The eyepiece is used to locate the point where the measurement is to be taken and the height of the table is adjusted until a clear image of the specimen is seen in the eyepiece then the table is locked in this height and the eyepiece is removed and the indenter is put in place above the sample.

The time of indentation and the load on the specimen are set to the desired numbers and the start button on the front panel of the instrument is turned on. The indenter

indents the material and leaves the rhombus shaped dent on the surface of the sample. The indenter is then pushed back so that the eyepiece is right on the sample.

For the Vickers test, both the diagonals are measured, and the average value is used to compute the Vickers pyramid number. ASTM specification E384, states that the load range for microhardness testing is 1 to 1000 gf. For loads of 1kg and below, the Vickers hardness (HV) is calculated with an equation, where in load (L) is in grams force and the mean of two diagonals (d) is in millimeters.

5.2.1.1. Sample preparation

The parametric study was taken, and the material is cut into longitudinal and transverse direction as shown in the fig 3.8 and 3.9. The indentation points were selected accordingly with 1mm distance from each point and 10mm distance from each set as shown (fig 3.8&3.9). Two points on the aluminium material and two points on the stainless-steel material and one on the interface.

5.2.1.2. Vickers hardness

One of the methods to find the strength of the coated material is by conducting a hardness test. Hardness is the property of a material that enables it to resist penetration, plastic deformation, indentation and scratching. Vickers hardness method is suitable for low level loads for any type of surface treatment process. The Vickers hardness tester has a diamond shaped indenter and fisheye lens placed above the indenter to measure the micro hardness of the specimen. The load is applied on the indenter using a nob handler. Indentations were made on the specimen at five different places along the longitudinal and transverse direction to get the micro hardness value of the coating. The indentations were made at the coating layer, interface of the coating and substrate with a load of 10 Kgf and dwell time period of 18 seconds. The test was carried on all the coating samples with different parametric combination. The values and graph obtained from the micro hardness test shows that the hardness value at the interface is higher compared to both substrate and mechtrode. The increase in hardness at the interface is due to the molecular bonding and microstructural shape formed during the friction surfacing process. It has been noted that the hardness value

at the interface increases with increase in rpm of the mechtrode and minimally affected by the transverse speed of the mechtrode. Fig. 8a and fig. 8b shows the longitudinal graph and transverse graph of the hardness test respectively. The test was carried on all the coating samples with different parametric combination. The results of the Vickers micro-hardness test across the overlaying are shown. From the aforementioned results, it is found that at the center of coating—that is at the point of contact between the substrate and the overlay—the hardness value was found to be higher than the individual hardness value of the two alloys. As the size of the grains decreases, the hardness value increases. Hardness value is inversely proportional to the size of the grains. Thus, the materials bonded by the process of friction strength have a higher hardness at the point of contact of the two materials

$$HV = 185.4 \times L/d^2$$

L Load in kgf

d Arithmetic mean of the two diagonals, d1 and d2 in mm

HV Vickers hardness.

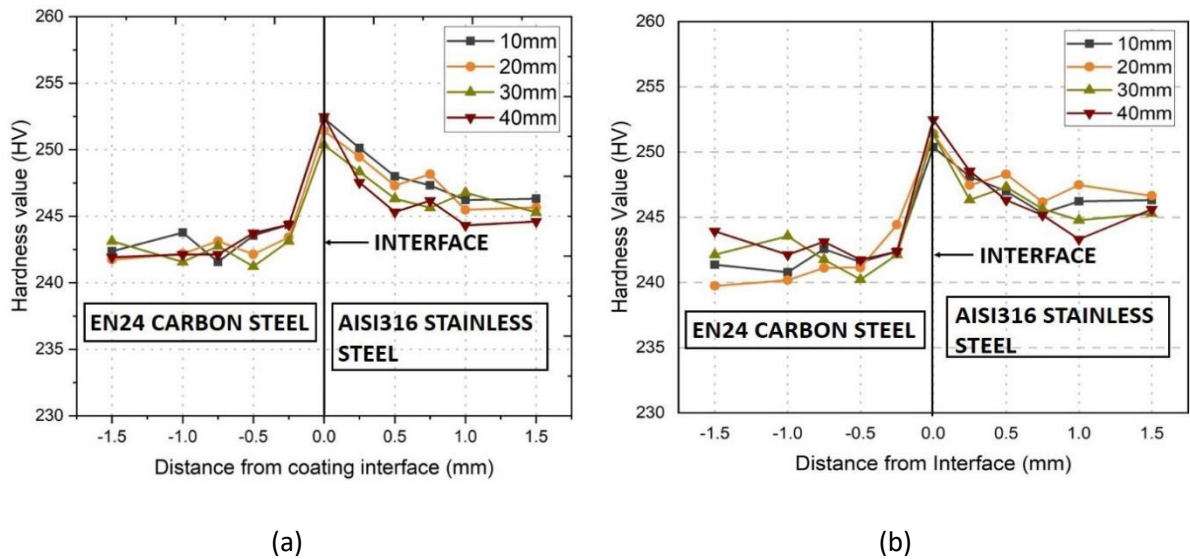


Fig.5.1: Hardness profile at (a) longitudinal and (b) Transverse direction.

5.2.2. Bending Test

Bending test is done on the coated material to determine the material ductility, bend strength, bonding strength, fracture strength and resistance to fracture. Fine coated specimens have been selected for face bend and root bend test for different specimens depending on their parametric combination. The procedures were followed according to Bureau of Indian Standards IS 1599 and the sample preparations are made accordingly. Fig. 10(a) and fig. 10(b) shows the image of root bend and face bend respectively. The specimen is supported at the ends and load is applied in the middle of the specimen. In the first specimen, different loads of 6.1 tons, 6.5 tons and 7.1 tons were applied to bend the specimen to 30°, 60° and 120° angle in root bending respectively. There was no visible crack or peeling of the coating seen in root bending. This shows the good interlocking of molecules at the interface. The second specimen is taken to conduct face bending with loads of 6.3 tons, 7.2 tons and 7.8 tons was required to bend the specimen at 30°, 60° and 90° respectively. Here also there was no visible crack or peeling of the coating which ensures good interlocking of molecules at the interface. Both bend test specimens are observed under stereo microscope and it was noted that the coating deposit on the surface was not separated, cracked or torn. It has been observed that low level of welding speed and low frictional pressure gave best results. Therefore, the plates that are coated with stainless steel over medium carbon steel by friction surfacing process can be deformed to required shape. The bend test results of the coated samples are shown. The three-point bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material. The bend test uses a coupon that is bent to a specified angle at three points. The bend tests were conducted on the friction surfaced specimens with the coating on the compressed side. The coated samples were found to survive a 180° bend without any coating delamination. Only some small voids were observed at the coating/surface interface. The specimen obtained by using higher axial load has comparatively a smaller number of cracks than the specimens obtained by using lower axial load. This shows the fact that bonding integrity is a function of axial load applied. The coating is not separated from the substrate after bend testing. This shows that both SS316 and EN24 have bonded effectively. As the axial load increases,

the bonding integrity between the substrate and the overlay is formed. Therefore, the bonding integrity depends on the axial load. Results for the bend test on max load and max displacement from trail3a are shown in Fig.4. The investigation shows that the strength of a workpiece has increased after the coating because the overlaying surface provides resistance towards bending

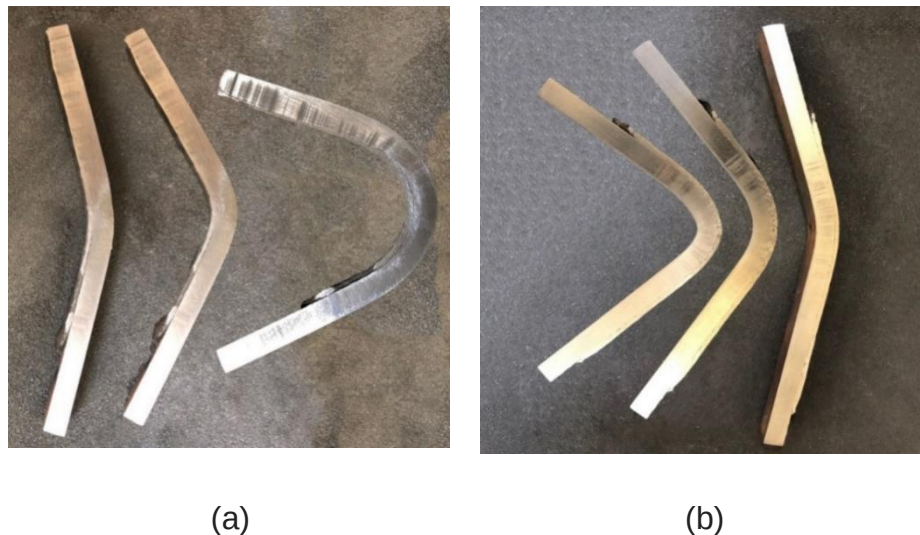
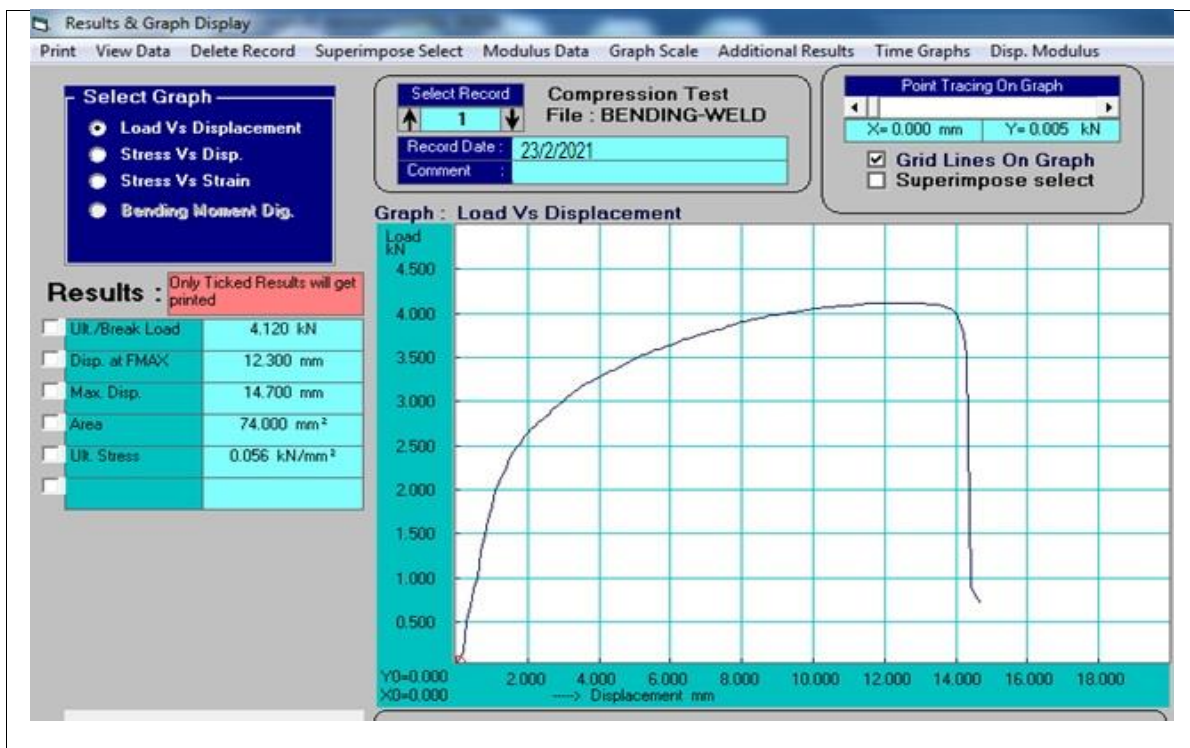
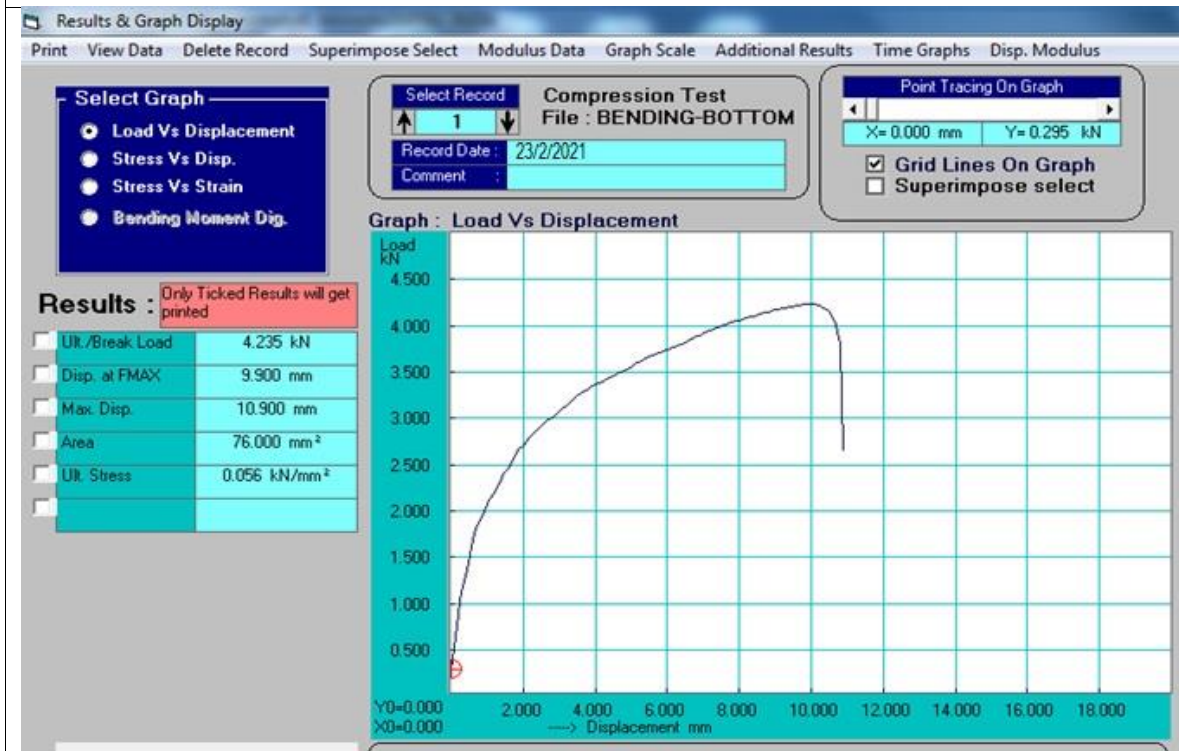


Fig. 5.2: Samples obtained after (a) face bent and (b) root bent condition.



(a)



(b)

Fig. 5.3 Bending test report of (a) sample 6 and (b) sample 8

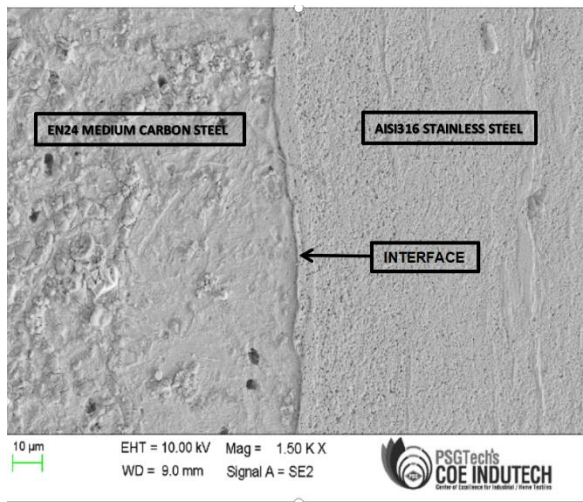
5.3. MICROSTRUCTURAL ANALYSIS

The chemical and microstructural analysis is done to find the bonding nature and interface composition of the coating. This is found by undergoing SEM, EDAX, XRD and interfacial thickness test. Three samples S1, S6, S8 from different parametric combination is taken for testing shown in Fig.

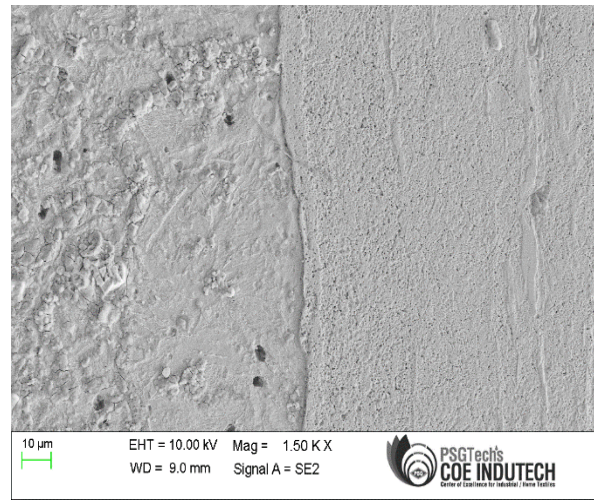
5.3.1 FE-SEM (Field Emission Scanning Electron Microscopy)

The SEM images here are taken from the interface of stainless steel and medium carbon steel coating using frictional surfacing method, it is done to ensure the flawless bonding between the two different metals and minimum existence of oxidization, pores and cracks. The process was carried out in a CARL ZEISS SIGMA WITH GEMINI COLUMN microscope with a resolution of 1.5nm, the samples have been cut longitudinally into 5 x 5mm length and breadth respectively and viewed in to get the

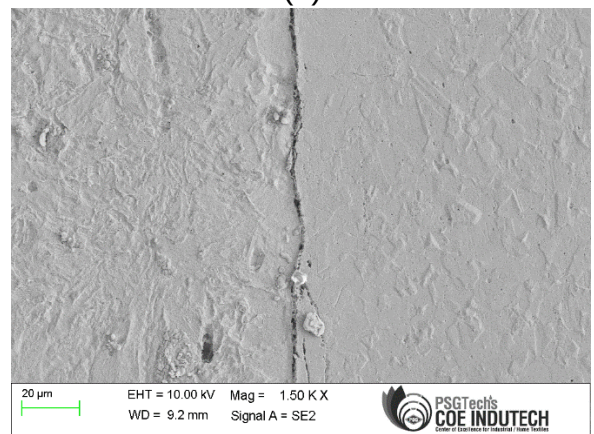
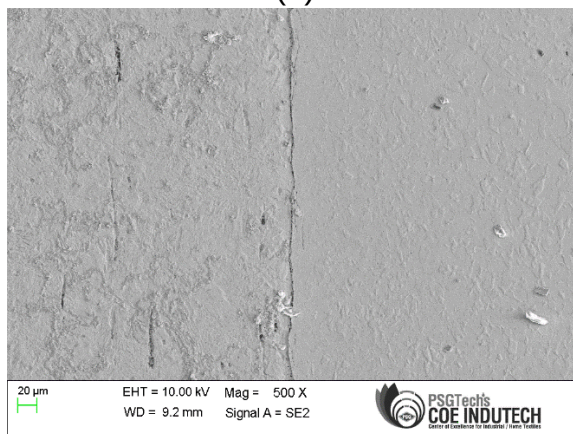
following images (Fig 5). Due to the extensive heating stainless steel gets melted and forms a layer over the medium carbon steel, the interface is clearly shown in the below image. Due to the formation of heat during friction surfacing the specimens gets mixed with each other and the active recrystallization occurred and leads to the mixture of chemical composition like cobalt, chromium, nickel and other compounds at the interface. The surface has occasional micro fillings on the flat surface. The deposition thickness is uniform, and the interface is macroscopically smooth, without any profiles created during friction surfacing. A clear interference line is visible. The process is carried out by the microscope, zooming and taking pictures in different resolutions (500x and 1500x) on the sample to get a clear visual of the mechtrode, bonding and substrate material.

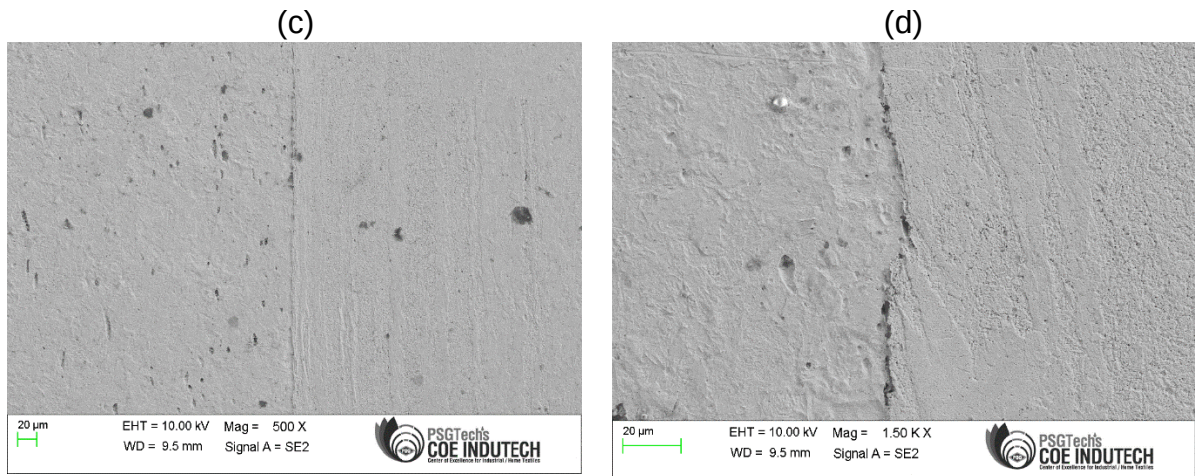


(a)



(b)



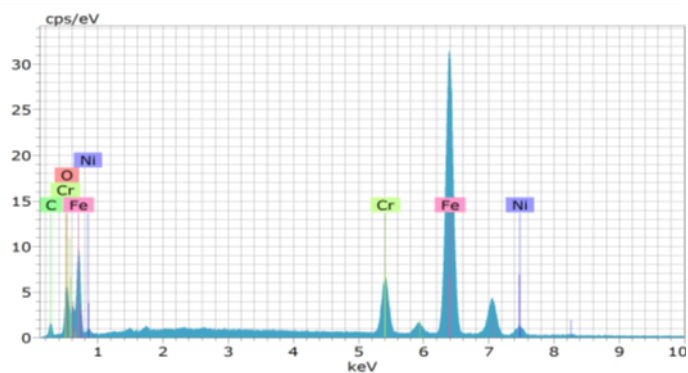
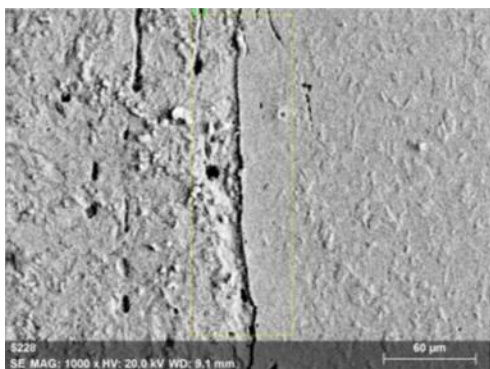


(e) (f)

Fig. 5.4: Microstructural view of the different samples at 500x (a,c,e) and at 1500x (b,d,f)

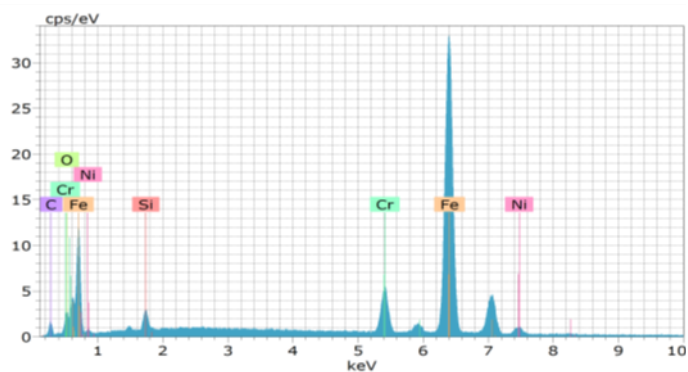
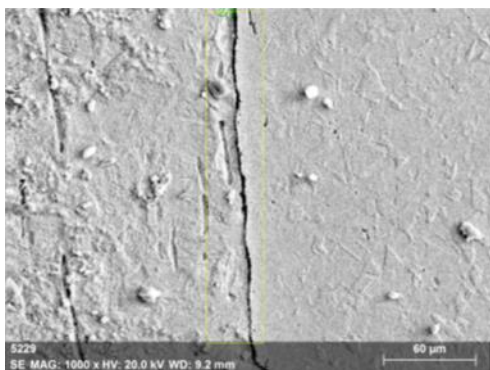
5.3.2 EDAX Spectroscopy (Energy Dispersive X-ray Analysis)

The EDAX test is taken in three different locations (Fig: 5.5(a), 5.5(b) and 5.5(c)) at the interface to find the chemical composition of the sample. The chemical compositions of Medium carbon steel (EN24) and stainless steel (AISI 316) are already known, whereas during the friction surfacing process due to the extensive heating the composition of existing material changes considerably. It is noted that before friction surfacing the chromium percentage of EN24 carbon steel is less than 0.74% in the case of sample 1 but after the surfacing the chromium percentage increases to 8.07% which obviously leads to the increase in the resistance against corrosion. In the case of sample S6 and S8, the percentage of chromium has increased to 6.16% & 7.43% respectively with is much more higher than to the received substrate material. The weight of chromium is more compared to the other particles so during the surfacing process, it precipitates and settles in the top layer of the substrate which grants a boost to the corrosion resistance and it is also evident that there is an increase in hardness of the coating which is validated in hardness test.



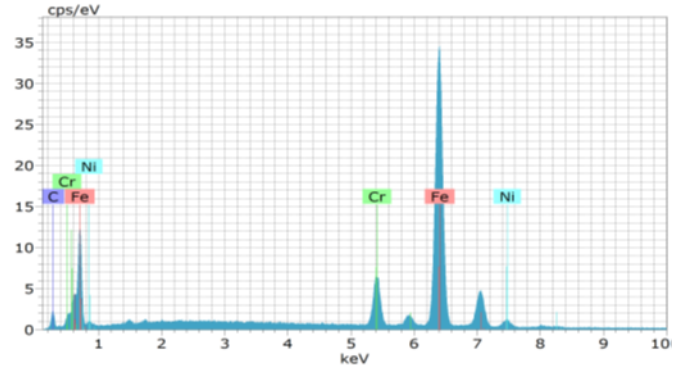
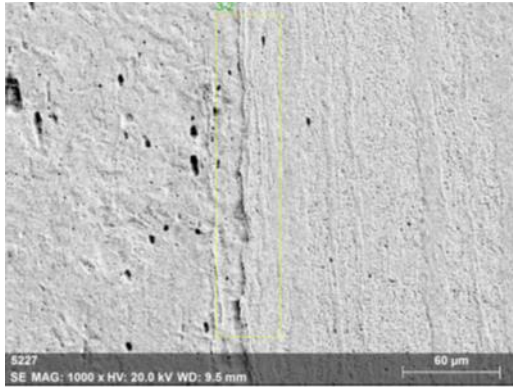
Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom .C [at.%]	(3Sigma) [wt.%]
Iron	K-series	74.29	76.78	57.17	6.03
Chromium	K-series	7.81	8.07	6.45	0.74
Oxygen	K-series	5.75	5.94	15.45	2.77
Carbon	K-series	5.07	5.24	18.12	3.19
Nickel	K-series	3.84	3.97	2.81	0.46

(a)



Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom .C [at.%]	(3Sigma) [wt.%]
Iron	K-series	78.37	81.54	64.10	6.35
Chromium	K-series	6.16	6.41	5.42	0.60
Carbon	K-series	5.50	5.73	20.93	3.45
Nickel	K-series	3.11	3.24	2.42	0.40
Oxygen	K-series	1.88	1.96	5.37	1.21
Silicon	K-series	1.08	1.13	1.76	0.24

(b)



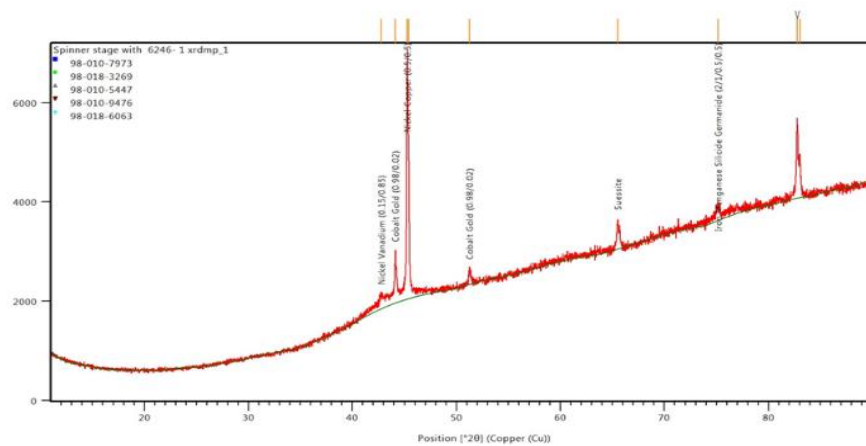
Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom .C [at.%]	(3Sigma) [wt.%]
Iron	K-series	77.11	81.01	63.26	6.25
Chromium	K-series	7.43	7.81	6.55	0.71
Carbon	K-series	7.21	7.58	27.51	4.81
Nickel	K-series	3.43	3.60	2.68	0.43

(c)

Fig. 5.5: EDAX test report obtained from Sample (a) S1, (b) S6, (c) S8

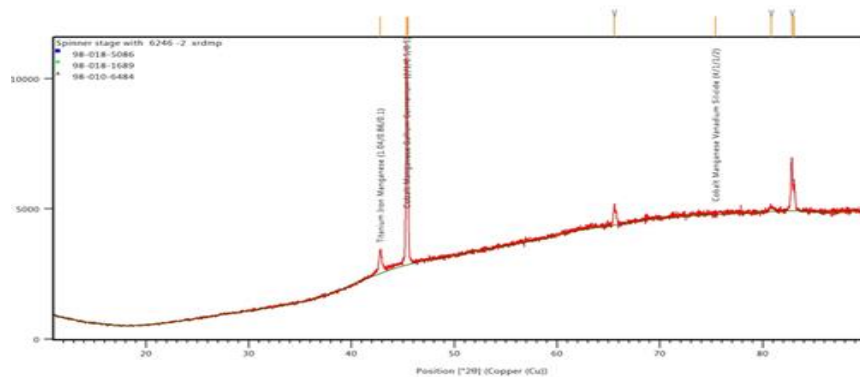
5.3.3 X- ray diffraction (XRD)

The XRD analysis is carried out in stainless steel coated over medium carbon steel for 3 specimens. XRD plot shows that the bonding molecular structure of the mechtrode and the substrate materials. XRD readings were undergone to evaluate the presence of α -ferrite in the deposited area. Fig 5.6 depicts that the presence of α -ferrite in the friction surfaced stainless steel deposit over medium carbon steel. When the temperature is above 550° α -ferrite is found which helps in the increase in corrosion resistance of substrate material.



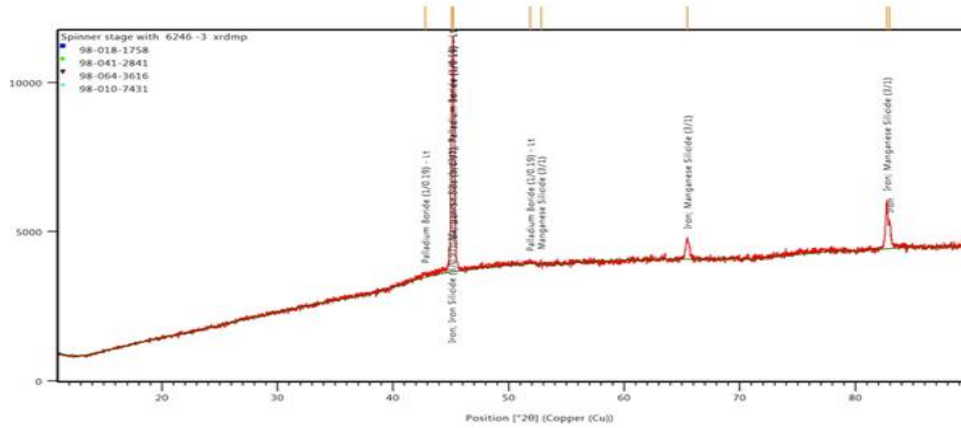
Pos. [°2θ]	Height [cts]	FWHM Left [°2θ]	d-spacing [Å]	Rel. Int. [%]
42.7825	277.78	0.3070	2.11369	5.45
44.1208	1040.80	0.0640	2.05264	20.43
45.2818	5093.35	0.1248	2.00101	100.00
45.4074	2946.44	0.0624	2.00073	57.85
51.2265	290.69	0.1248	1.78188	5.71
65.5234	582.85	0.1248	1.42346	11.44
75.1813	258.59	0.4992	1.26275	5.08
82.7529	1489.84	0.0936	1.16535	29.25
83.0346	877.74	0.0936	1.16500	17.23

(a)



Pos. [°2θ]	Height [cts]	FWHM Left [°2θ]	d-spacing [Å]	Rel. Int. [%]
42.8103	114.80	0.6140	2.11239	1.46
45.0512	5233.69	0.0780	2.01072	66.53
45.2025	7867.14	0.1535	2.00600	100.00
51.8516	70.51	0.6140	1.76332	0.90
52.8024	129.88	0.0768	1.73379	1.65
65.4724	676.98	0.1791	1.42562	8.61
82.6966	1628.90	0.1092	1.16600	20.71
82.9761	867.22	0.1279	1.16374	11.02

(b)



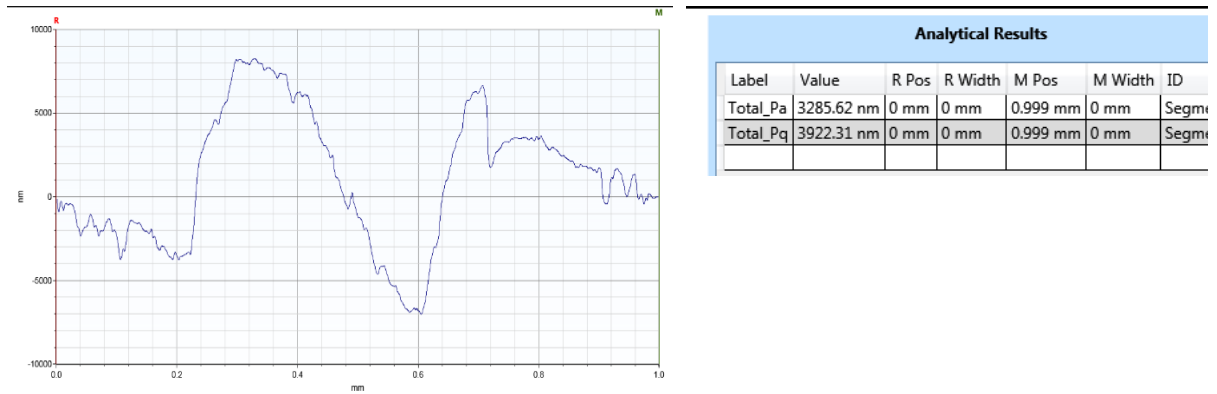
Pos. [°2θ]	Height [cts]	FWHM Left [°2θ]	d-spacing [Å]	Rel. Int. [%]
42.8103	114.80	0.6140	2.11239	1.46
45.0512	5233.69	0.0780	2.01072	66.53
45.2025	7867.14	0.1535	2.00600	100.00
51.8516	70.51	0.6140	1.76332	0.90
52.8024	129.88	0.0768	1.73379	1.65
65.4724	676.98	0.1791	1.42562	8.61
82.6966	1628.90	0.1092	1.16600	20.71
82.9761	867.22	0.1279	1.16374	11.02

(c)

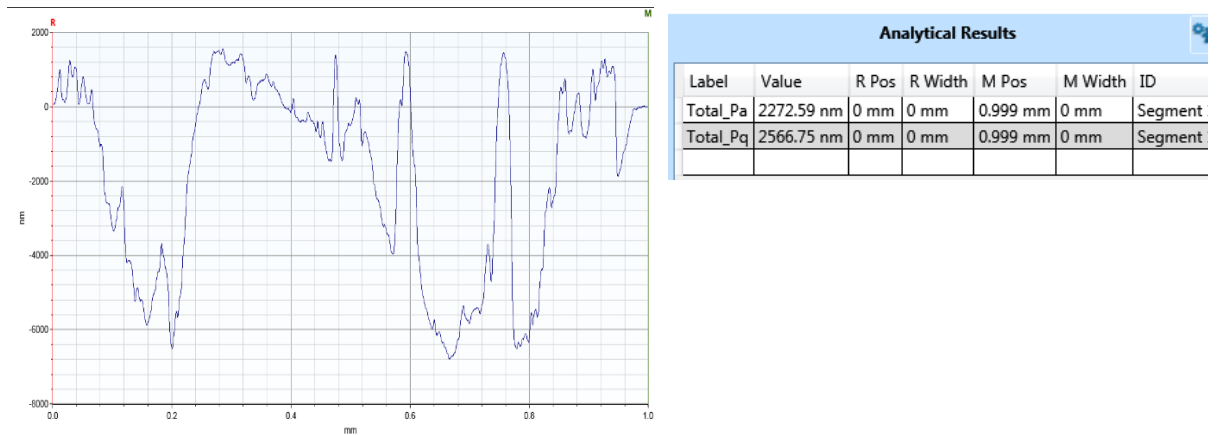
Fig. 5.6: Xray Diffraction at (a) Sample S1 (b) Sample S6 (c) Sample S8

5.3.4 Measurement of coating Interfacial thickness

The interfacial thickness of the coating was measured by ultrasonic thickness measurement (UTM) machine. The sample dimensions for the ultrasonic thickness testing machine is same as FE-SEM testing samples. The thickness obtained at the interface is shown in figure 5.6, which shows that there is multiple formation of coating peak and valley at the interface region. High amplitude of peak and valley implies that there is a occurrence of good microstructural material transformation between substrate and mechtrode material during processing. The thickness measurement has taken for the sample S6 and S8 combinations and their analytical results are shown in figure 5.7 (a) and (b) respectively.



(a)

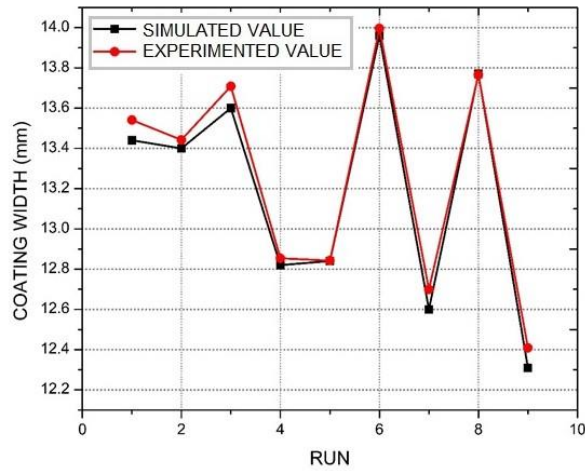


(b)

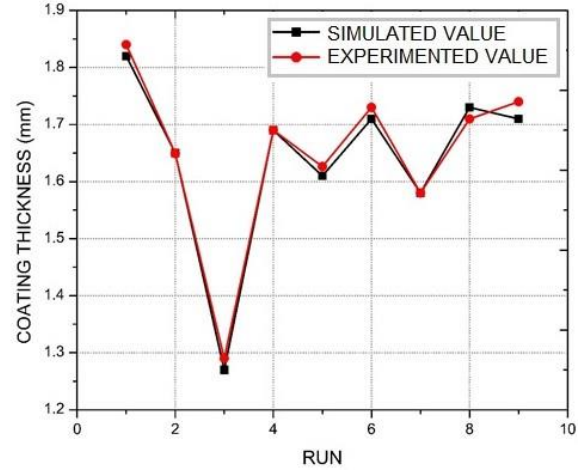
Fig.5.7: Interfacial thickness measurement of the samples obtained from (a) S6 and (b) S8 combinations.

5.4 Comparison of experimental and simulated results

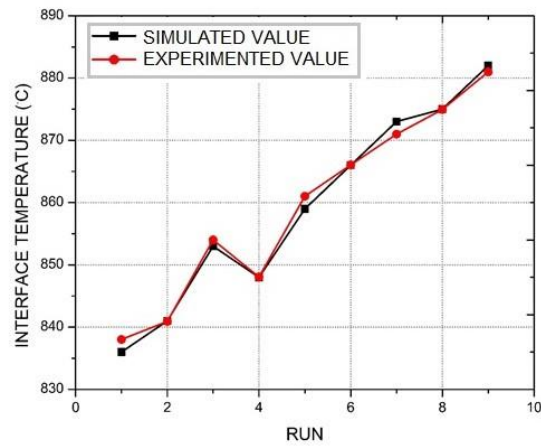
The simulation results and experimental results are compared and displayed in figure 5.8. It has been seen that the both simulation and experimental values are close to each other and an error of less than 10% has been observed from all the obtained samples. A good understanding between the base and coating materials has been seen during the coating process and the achieved coating geometry will be well predicted by the experimental process. Coating geometry like coating width, thickness and interfacial temperature are compared and displayed in figure 5.8.



(a)



(b)



(c)

Fig. 5.8: Comparison of simulated and experimented results of obtained coating geometry of (a) coating width (b) coating thickness (c) interface temperature

CHAPTER 6

CONCLUSION

The simulation and experimental work were carried out for a single layer coating of AISI316 stainless steel over EN8 medium carbon steel by friction surfacing process. Principal parametric relationships of input and output parameters like coating geometry, interfacial bonding and microstructural features are discussed as follows:

1. The deposition of AISI316 stainless steel over EN8 carbon steel has been done by experimentally and computationally by friction surfacing process.
2. The hardness of the mechtrode, substrate and interface are obtained from Vickers hardness test. It is observed that the interface hardness is higher than the substrate and mechtrode which ensures a good bonding characteristic of the coating.
3. The bonding strength of the coating is obtained by performing ram tensile test. The maximum bonding strength obtained is 176.3 MPa which indicates a good nature.
4. The bending test is done to find the bending strength of the coating at different bend angle. The coatings did not break or peel off at any angles during the test which indicates a good strength of the material.
5. The FE-SEM analysis is done to find the microstructural structure at the interface of the coating. It is observed the intermolecular bonding between stainless steel and medium carbon steel is bonded effectively without any gaps or carbon formation.
6. The EDAX analysis is performed at the interface of the coating to find the material composition. It is noted that the majority of material composition at the interface consists of Iron, Chromium and Nickel which indicates a good composition of materials.
7. Finally, from the above results, it is concluded that the coating between AISI 316 Stainless steel and EN 24 Medium carbon steel is successful and can be used for further appliances.

REFERENCE:

- [1] M.J.R. Stegmueller, R.J. Granta, P. Schindele: Quantification of the interfacial roughness when coating stainless steel onto aluminium by friction surfacing, *Surface & Coatings Technology*, 375, 2019, 22-33.
- [2] Seyedeh Marjan Bararpour, Hamed Jamshidi Aval, Roohollah Jamaati: Modelling and experimental investigation on friction surfacing of aluminum alloys, *Journal of Alloys and Compounds* 805, 2019, 57e68.
- [3] Zahra Rahmati, Hamed Jamshidi Aval, Salman Nourouzi and Roohollah Jamaat: Modelling and experimental study of friction surfacing of AA2024 alloy over AA1050 plates, *Mater. Res. Express* 6, 2019, 0865g2.
- [4] Parisa Pirhayati, Hamed Jamshidi Aval, Effect of silver on non-isothermal aging of friction surfaced AA2024-16wt%Ag composites, *Surface & Coatings Technology*, 2019.
- [5] Seyedeh Marjan Bararpour, Hamed Jamshidi Aval, Roohollah Jamaati: Effects of Zn powder on alloying during friction surfacing of Al–Mg alloy, *Journal of Alloys and Compounds*, 2019.
- [6] Hongjun Li, Wei Qi, Alexander Galloway and Athanasios Toumpis, *Friction Surfacing of Aluminium Alloy 5083 on DH36 Steel Plate*, 2019.
- [7] Mingrun Yu, Zili Zhang, Hongyun Zhao, Li Zhou, Xiaoguo Song: Microstructure and corrosion behaviour of the ultra-fine-grained aluminium coating fabricated by friction surfacing, *Materials Letters* 250, 2019, 174–177.
- [8] D. Guo a, C.T. Kwoka, S.L.I. Chan, strengthened forced convection – A novel method for improving the pitting corrosion resistance of friction-surfaced stainless-steel coating, *Materials and Design* 182, 2019, 108037.
- [9] Mohammed Shariq, Madhulika Srivastava, Rupam Tripathi, Somnath Chattopadhyaya, Pedro Vilaca, Espoo, Finland, Nenad Gubeljak, Maribor, Slovenia, and Grzegorz Krolczyk, Optimization and characterization of friction surfaced coatings of ferrous alloys, *Wear Testing*, 60, 2018, 7-8.
- [10] A.V. Sreenu, Aluminium-boron nitride nano composite coating by friction surfacing on low carbon steel substrate – a feasibility study, *Materials Today: Proceedings* 5, 2018, 26829–26835.

- [11] Samuel Silvério, Hennin Krohn, Viktoria Fitseva, Nelson Guedes de Alcântara, Jorge Fernandez dos Santos, Deposition of AA5083-H112 Over AA2024-T3 by Friction Surfacing, *Soldagem & Inspeção*. 23(2), 2018, 225-234.
- [12] Juan Carlos Galvis, Pedro Henrique Fernandes Oliveira, Juliana de Paula Martins, André Luis Moreira de Carvalho, Assessment of Process Parameters by Friction Surfacing on the Double Layer Deposition, *Materials Research*, 2018, 1-11.
- [13] Márcio Maciel da Silva, Michel Lenhago Beneducci Afonso, Stephanny Lohanny Nunes Silva, Fernanda Christina Teotonio Dias Troysi, Ítalo Bruno dos Santos, Pedro Paiva Brito: Application of the friction surfacing process in a CNC machining centre: A viability assessment for producing Al-alloy coatings on low carbon steel, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 2018, 40:14.
- [14] Abhishek Sharma, Shiwendu Sagar, Raju Prasad Mahto, Baidehish Sahoo, Surjya Kanta Pal, Jinu Paul, Surface modification of Al6061 by graphene impregnation through a powder metallurgy assisted friction surfacing, *Surface & Coatings Technology* 337, 2018, 12–23.
- [15] J.C. Galvis, P.H.F. Oliveira, M.F. Hupalo, J.P. Martins, A.L.M. Carvalho: Influence of friction surfacing process parameters to deposit AA6351-T6 over AA5052-H32 using conventional milling machine, *J. Mater. Process. Technol.* 245, 2017, 91–105.
- [16] Michael, JR. Stegmüller., Richard J Grant, Paul Schindele: Improvements in the process efficiency and bond strength when friction surfacing stainless steel onto aluminium substrate, *Journal of Materials: Design and Applications*, 0(0), 2017, 1–12.
- [17] Capt. B. Kiruthi Murugan, V. Balusamy, R. Padmanaban, R. Vaira Vignesh, Study of the effect of parameters in friction surfacing of Monel over Mild Steel using linear – radial basis function model, 2017.
- [18] S. Ravi Sekhar, V. Chittaranjandas and D. Govardhan, Friction Surfacing process of Stainless-steel alloys, *International Journal of Mechanical Engineering and Technology*, Volume 8, Issue 7, 2017, pp. 613–626.

- [19] Mohammed Shariq, Madhulika Srivastava, Rupam Tripathi, Somnath Chattopadhyaya, Amit Rai Dixit, Feasibility Study of Friction Surfaced Coatings over Non-Ferrous Substrates, *Procedia Engineering*. 149, 2016, 465 – 471.
- [20] S. Madhu, M. Balasubramanian, Rathesh Sivakesan, Finite Difference Modelling on the Temperature field of Aluminium and Low carbon steel in Friction Surfacing, *ARNP Journal of Engineering and Applied Sciences*, Vol 11(16), 2016, 10065-10071.
- [21] D. Govardhan, K. Sammaiah, K.G.K. Murti, G. Madhusudhan Reddy, Evaluation of bond quality for stainless steel-Carbon steel friction surfaced deposits, *Materials Today.Proceedings*.2, 2015, 3511 – 3519.
- [22] H. Kroh, S. Hanke, M. Beyer, J.F. dos Santos, Influence of external cooling configuration on friction surfacing of AA6082 T6 over AA2024 T351, *Manufacturing Letters*. 5, 2015, 17–20.
- [23] Ashok Kumar U, Laxminarayana. P, Friction Surfacing Process of Aluminium alloys, 2014.
- [24] D. Pereira, J. Gandra, J. Pamies-Teixeira, R.M. Miranda, P. Vilaca, Wear behaviour of steel coatings produced by friction surfacing, *J. Mater. Process. Technol*.214, 2014, 2858–2868.
- [25] R. George Sahaya Nixon, Dr. B.S. Mohanty, Friction Surfacing of Metal Coatings on Stainless Steel AISI 304 Over Spheroidal Graphite Iron Substrate, *Advanced Materials Research Vols. 816-817 (2013)*, pp 271-275
- [26] Gandra J., Pereira D., Miranda R.M., Vilaça P., Influence of process parameters in the friction surfacing of AA 6082-T6 over AA 2024-T3. *Procedia CIRP*. 7, 2013, 341 – 346.
- [27] Gandra J., Vigarinho P., Pereira D., Miranda R.M., Velhinho A., VilaçaP., Wear characterization of functionally graded Al–SiC composite coatings produced by Friction Surfacing. *Materials and Design*. 52, 2013, 373–383.
- [28] Sekharbabu R., Khalid Rafi H., Prasad Rao K., Characterization of D2 tool steel friction surfaced coatings over low carbon steel. *Materials and Design*.50, 2013, 543-550.

- [29] Prasad Rao K., Veera Sreenu A., Khalid Rafi M., Libin H.N., Balasubramaniam K., Tool steel and copper coatings by friction surfacing – A thermography study. J. Mater. Process. Technol.212, 2012, 402-407.
- [30] Ramesh Puli, G.D. Janaki Ram, Corrosion performance of AISI 316L friction surfaced coatings, Corrosion Science, 62, 2012, 95–103.