

INVESTIGATION ON DEPOSITION OF MAGNESIUM OVER CARBON STEEL BY FORCED SHIELDING FRICTION SURFACING PROCESS

Submitted in partial fulfilment of the requirements for the award of

Bachelor of Engineering degree in

Automobile Engineering

By

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INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade "A++" by NAAC

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of ANSHUL MALATHKAR (Reg. No. 40860006) and ALLA YASWANTH GANESH (Reg. No.40860005) who carried out the project entitled **"INVESTIGATION ON DEPOSITION OF MAGNESIUM OVER CARBON STEEL BY FORCED SHIELDING FRICTION SURFACING PROCESS"** under my supervision from November 2023 to April 2024.

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DECLARATION

We, ANSHUL MALATHKAR (Reg.No.40860006) and ALLA YASWANTH GANESH (Reg.No.40860005) hereby declare that the Project Report entitled "INVESTIGATION ON DEPOSITION OF MAGNESIUM OVER CARBON STEEL BY FORCED SHIELDING FRICTION SURFACING PROCESS" done by me under the guidance of Dr. DILLIP KUMAR SAHOO, M.E., Ph.D., is submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering degree in Automobile.



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ABSTRACT

Friction surfacing is an advanced manufacturing process, which has been successfully developed over the past decade. The process is used for corrosion and wear resistant coatings and for reclamation of worn engineering components. The major requirement is for flexibility to enable rapid changes of process parameters in order to develop new applications, with variations of materials and geometries in term of cost and reliable manner. The present work deals with the solid-state deposition by friction surfacing process where Magnesium AZ91 is coated over IS2062 Low carbon steel substrates. This investigation elaborates the excellence acquired by different combination of the process parameters used in friction surfacing specifically traverse speed, speed of rotation and the axial load. Suitable parameters were selected based on suitable design of experiment (DOE) approach. The parameters were chosen based on the results obtained from the analysis such as total deformation of mechtrode and temperature distribution during friction surfacing. Mechanical test like hardness and bending test were conducted to evaluate the bonding strength of the depositions. High amplification SEM, EDAX and XRD reports were used to analyze the interfacial characteristics of the deposition. Sem results shows the proper molecular interlocking between magnesium and iron particles. EDAX results revealed the chemical composition of magnesium rod with low carbon steel after deposition. Interference roughness was evaluated at the coating interface and was found to be in uniform condition. A detailed corrosion analysis has been done to analyze the corrosion behavior of the depositions.

Keywords: ***Friction Surfacing, micro hardness, bending test, SEM,EDAX, XRD, Potentiodynamic Polarization test.***

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LIST OF ABBREVIATIONS

FS-Friction Surfacing

FESEM-Field Emissions Scanning Electron MicroscopeEDAX-Energy

Dispersive X-Ray Analysis

EIS-Electrochemical Impedance SpectroscopyRPM-Rotation Per Minute

KN-Axial Load

DOE-Design Of Experiment

CHAPTER 1

INTRODUCTION

1.1 SURFACE ENGINEERING

Surface engineering is sub-discipline of materials science which deals with the surface of solid matter. Solids are made of bulk material covered by a surface. The surface which bounds the bulk material is called surface phase. It acts as an interface to the surrounding environment. The interaction of the surface with environment can degrade the surface over time. Degradation can be caused by wear, corrosion, fatigue, and creep by the environment. Surface engineering involves altering the properties of surface phase in order to reduce the degradation over time. This is accomplished by making the surface robust to the environment in which it will be used. It provides a cost-effective material for robust design. An engineering component usually fails when its surface cannot adequately withstand the external forces or environment to which it is subjected. The choice of material with appropriate thermal, optical, magnetic and electrical properties is crucial to its functionality. Tribology performance governing the life of components subjected to wear is dictated by various physical, mechanical, chemical, and dimensional properties of the surface materials. Improving the functionality of the product by improving the property is the only aim of surface engineering. The surface properties of any component are solely determined by its application and purpose, which is ascertained based on the combination necessary for building the component. For example, a combination of toughness and hardness, corrosion resistance and smoothness will be important for developing pump parts that have good cavitation resistance

1.1.1 Surface and sub-Surface zones:

The purpose of any component made of crystalline materials is characterized in two ways one is the nature of surface irregularity which is quantified in terms of surface roughness and other is the sub-surface region which is generally composed of the five distinct zone as shown in Fig 1.1.

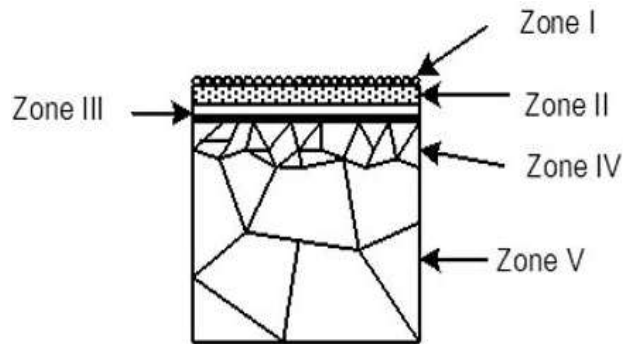


Fig 1.1: Surface and Sub-Surface region

- Zone I: Comprises a very thin layer of few nanometres called contamination layer which retains absorbed gases, hydrocarbons, and moisture etc.
- Zone II: Constitutes impurities such as oxides, nitrides, etc., which are formed as a result of interactions between atmospheric or ambient gases and substrate surface
- Zone III: Involves a layer usually thinner than 1 micrometre with badly damaged crystalline structure
- Zone IV: Consists of layer of thickness ranging from few microns to hundreds of micrometres with grain structure deformed by the application of external stresses during manufacturing or residual stresses
- Zone V: Involves normal structure of bulk materials as per thermal and mechanical stresses which is experienced by the material during manufacturing

1.1.2 Scope of Surface Engineering:

Surface engineering is perhaps the most powerful function which helps us to modify existing surfaces, create new coatings, formulations, understand the mechanism of surface degradation and its improvement. 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

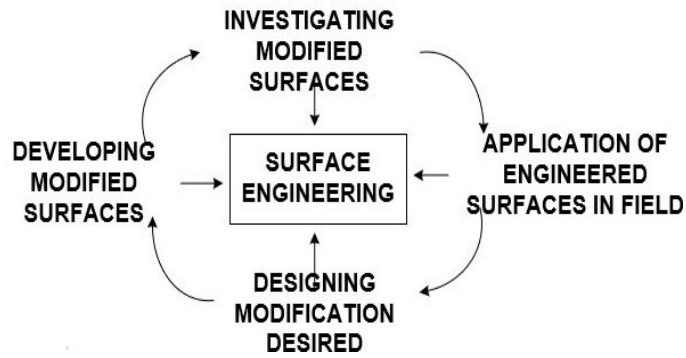


Fig 1.2: Flow of Surface engineering process

Process of SE is a cyclic process as shown in Fig 1.2. Surface properties desired for the fulfilment of the service life required are determined by the service conditions with respect to load, environment, and reliability. Tribological components are subjected to different environments and stress conditions, hence, there is the requirement for these components to possess varying set of properties for longer life. These properties are corrosion resistance for those working in moist environment, hardness for low stress abrasion condition, fracture toughness and fatigue resistance for fluctuating load condition such as gear tooth surfaces, etc. For the designing, the compatibility of materials and approach with substrate material, configuration, and location must be kept in mind.

1.1.3 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).

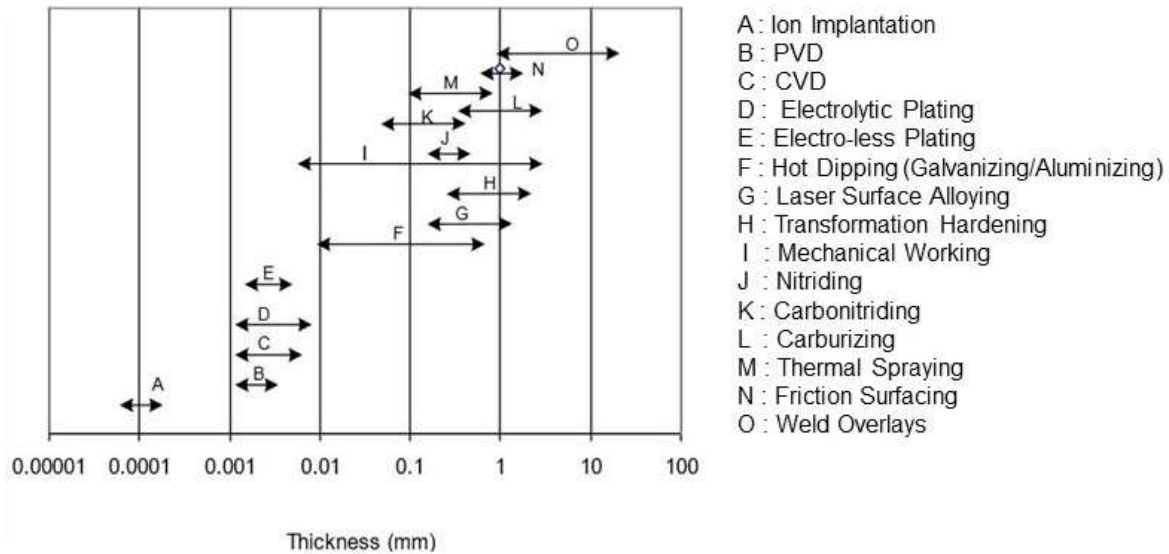


Fig 1.3: Method of coating and their coating thickness

From Fig 1.3 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.

The process of coating similar or dissimilar metals on another metal by the application of friction from the workpiece is called as friction surfacing. The result will be a plasticized layer deposited on the surface of the base metal with properties of both metals combined in the substrate surface. Friction surfacing can be utilized to create long-life, components which are wear resistant, anti-corrosion bonding. It can

also be used in the treatment of damaged parts such as, farming equipment's and turbine cutting edge. Surface treatments carried out in liquid state will have defects like cracks and improper solidification. However, these defects are not encountered in friction surfacing since it is carried out in solid state. Friction surfacing being a non-dilution method, the defects connected with fusion based coating techniques like dilution, solidification cracks and formation of intermetallic compounds are avoided or very negligible. Friction surfacing can also be used in rigid facing of valve seating with stellite and press tools such as punches and dies.

1.2 FRICTION SURFACING:

Friction surfacing is a solid state technology with increasing applications in the context of localized surface engineering. It uses the frictional energy dispersed among the operation and induces a molten state metal without the participation of the extraneous heat source, and that generates the high strength and high-quality linkages with fewer deformations in an extensive variety of material lengths and thickness. FS is investigated mainly for producing fine grained coatings, which exhibit superior wear and corrosion properties. Since no bulk melting takes place, this process allows dissimilar joining of materials that would be otherwise incompatible or difficult to deposit by fusion based methods. Several studies also emphasis its energy efficiency and low environmental impact as key advantages when compared with other alternative technologies. A wide range of material combinations have been deposit by FS, mainly alloy and stainless steels.

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 called as Flash mass. Axial load (kN), Rotational speed (rpm), Transverse speed (mm/min) 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, surface roughness and temperature distribution between the coating and substrate depends upon the selection of proper parameters. The Fig 1.4 shows the schematic diagram of parameters and process principle involved in friction surfacing process.

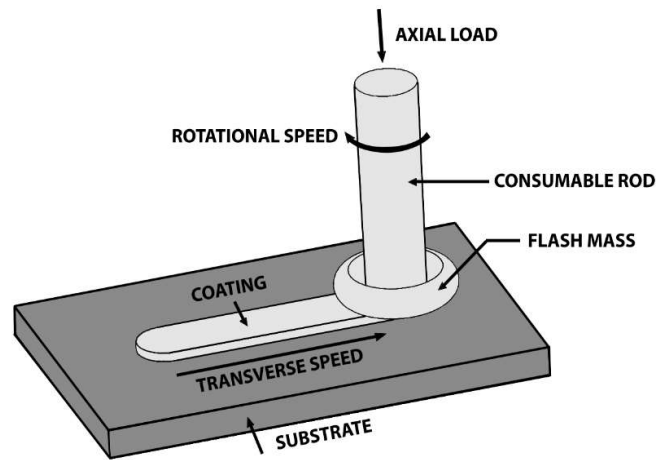


Fig 1.4: Schematic representation of Friction surfacing

The interface region usually remains intact, even after resisting loads equal to the ultimate tensile strength of the weaker material. However, the bond quality at the edges of the deposit is generally poor, and this area may need to be removed. With high strength surfacing materials, the thickness of the deposit is generally small. The surface appearance of the substrate and mechtrode depends on the material deposited, and the parameters used. Parameters and process principle involved in friction surfacing process disclosed the application of the friction surfacing process used in producing of long-life industrial blades, anticorrosion coating deposition, wear components, and in the recuperation of worn and damaged parts such as industrial turbine blades tip and agricultural machinery. Observed that superior bonding quality of the friction surfaced coatings can be achieved by higher ratios between feed rate and travel speed of mechtrode.

1.2.1 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.

1.2.2 Advantages of Friction surfacing

Friction surfacing techniques are generally melt-free, which mitigates grain growth in engineered materials such as high-strength heat-treated steels. Another advantage is that the motion tends to clean the surface between the materials being welded, which means they can be joined with less preparation. During the welding process, depending on the method being used, small pieces of the plastic or metal will be forced out of the working mass (flash). Another advantage of Friction surfacing is that it allows dissimilar materials to be joined. This is particularly useful in aerospace, where it is used to join lightweight aluminium stock to high-strength steels. Normally the wide difference in melting points of the two materials would make it impossible to weld using traditional techniques and would require some sort of mechanical connection. Friction surfacing provides a full-strength bond with no additional weight. Other common uses for these sorts of bi-metal joins is in the nuclear industry, where copper-steel joints are common in the reactor cooling systems; and in the transport of cryogenic fluids, where Friction surfacing has been used to join aluminium alloys to stainless steels and high-nickel-alloy materials for cryogenic-fluid piping and containment vessels. Friction surfacing is also used with thermoplastics, which act in a fashion analogous to metals

under heat and pressure. The heat and pressure used on these materials is much lower than metals, but the technique can be used to join metals to plastics with the metal interface being machined. For instance, the technique can be used to join eyeglass frames to the pins in their hinges. The lower energies and pressures used allows for a wider variety of techniques to be used.

1.2.3 Disadvantages of friction surfacing

There are certain limitations and disadvantages to Friction Surfacing process like:

- Working piece dimensional limitations
- FS is restricted mostly for round bars with similar cross-section and pieces of other forms are still possible to weld but it is quite harder
- Workpiece needed to be stationary and fixed
- Joint design have certain limitations
- Impossibility to forge workpieces consisting of non-forgeable materials and certain difficulties associated with experimental materials
- Cost of FRW equipment is high, high initial capital costs

1.2.4 Application of Friction Surfacing:

Experimental results show that friction surfacing is as an alternate method for obtaining coatings of dissimilar materials and base material combination depends on specific applications. Friction surfacing has very large potential applications in industries due to improved reliability and productivity, suitability for batch production, reduction in cost, superior quality which was previously impossible. This process can also be attempted in the robotics for full automation. Friction surfacing is the solid-state welding process and it is confirmed that the problems associated with fusion welding are eliminated like porosity, inclusion and other defects normally formed while solidification of weld. The deposit has refined micro structure and with little distortion. This method is suitable for repair and reclamation of worn and damaged parts. This process also can be performed under water without a sealing mechanism. Under water Friction surfacing is developed for marine propulsion system. This process, has excellent potential, and requires commercialization on a large scale. This process can be performed in open air and not require any inert gases to prevent oxidation. This process is most suitable for the consumables which are having less thermal

conductivity than substrate and poor sliding characteristics. The deposit has refined micro structure and with little distortion. It is a clean welding process, does not require fluxes or other consumables and produces no fumes or spatters or harmful radiation. Low thermal conductivity of mechtrode and poor sliding characteristics are required for performing friction surfacing.

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 Tountis, 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 film 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 Gubelj, 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. Ma'rcio Maciel da Silva, Michel Lenhago Beneducci Afonso, Stephanny Lohanny Nunes Silva, Fernanda Christina Teotonio Dias Troysi, I'talo 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. Stegmuller., 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. Vaira 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 OBJECTIVE

3.1 AIM

To obtain a successful solid-state deposition of Magnesium alloy and to investigate the microstructural analysis between Magnesium alloy AZ91 over IS2062 Low carbon steel by Friction Surfacing which will give better corrosion resistance and good strength compared to the base low carbon steel.

3.2 OBJECTIVE

The main objective of this study is to find the suitable process parameters for deposition of Magnesium alloy AZ91 over low carbon steel by friction surfacing. The friction surfacing will be carried out by considering and optimizing the process parameters like axial load, rotational speed and transverse speed. In this study, Magnesium alloy AZ91 will be taken as the consumable rod or mechtrode and Low carbon steel (IS 2062) taken as the base metal or substrate. The process parameters are selected by selecting appropriate Design of Experiment approach (DOE). Microstructural features were analysis by conducting SEM, EDAX and XRD test was carried out to find the chemical composition and structure after friction surfacing.

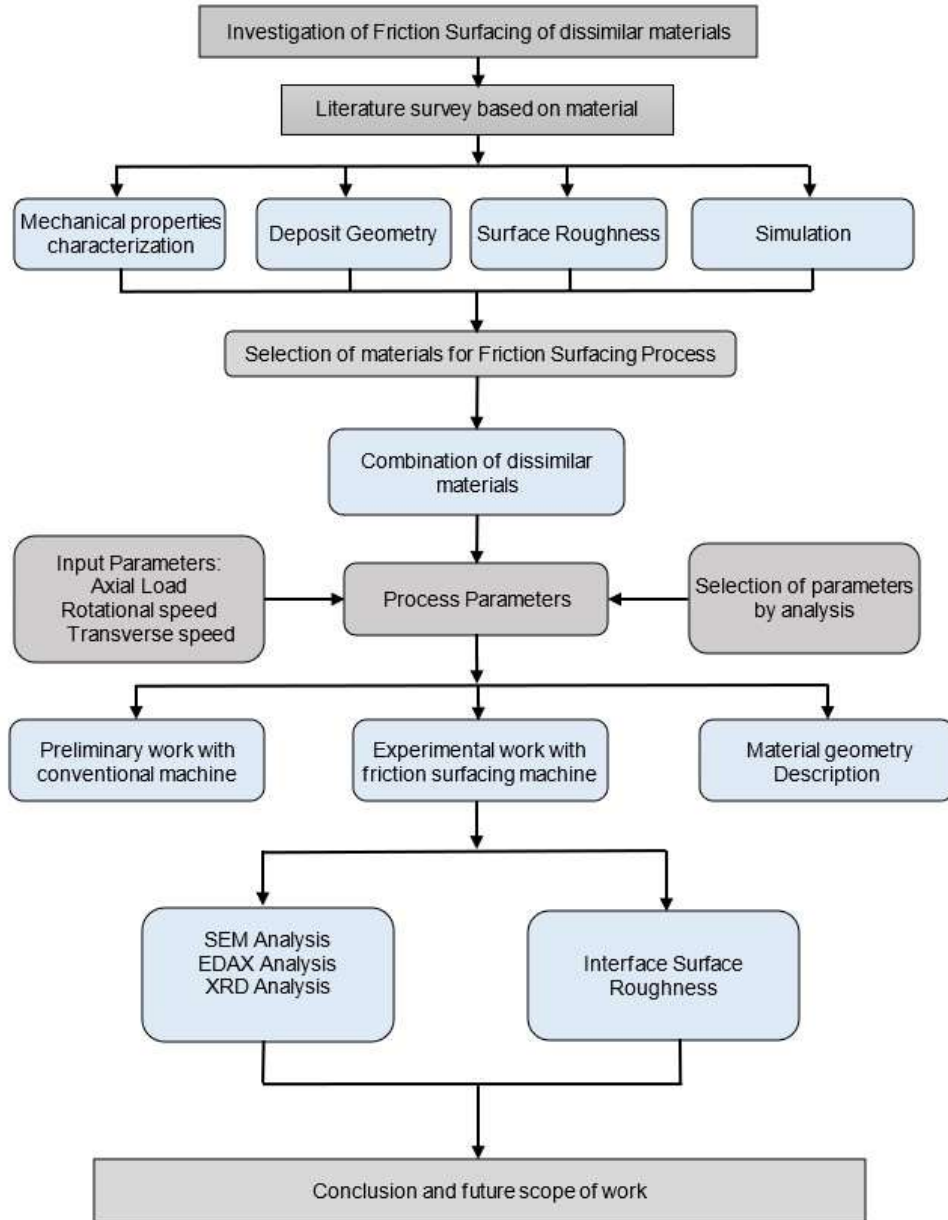
3.3 PROBLEM IDENTIFICATION

By analysing the present literature survey, it has been found that many researcher and scientist has done the friction surfacing with different material combination to improve the mechanical, tribological and corrosion properties of the parent materials. There are different experimental methods adopted in friction surfacing between carbon steels and magnesium for getting good bonding strength which also improves the corrosion resistance. It has been found that, limited work was carried out for finding the appropriate process parameters for getting successful deposition of Magnesium over carbon steel.

The present experimental work was carried to find the most appropriate process parameters for successful deposition of magnesium. Mechanical test like bending, hardness test to be conducted to find the mechanical strength of the coating. Microstructure analysis to be done be conducting the FE-SEM and EDAX test. A

detailed corrosion test was carried out to know the corrosion behaviour of the deposition.

3.4 METHODOLOGY OF THE PROJECT WORK



CHAPTER 4

MATERIALS AND EXPERIMENTAL PROCESS

4.1. MATERIAL

Magnesium is notable for its light weight and high corrosion resistant and in same way carbon steel and its alloys are the most used metals in present day. Magnesium is used as the consumable rod or mechtrode with a diameter of 18 mm and length of 100 mm. Low carbon steel is used as the substrate or base metal. All three substrates have same dimensions which is 6mm thickness, 100mm in width and 150 mm in length. The materials are chosen based on the literature review and because of the high usage of these metals in the industry. Substrate plate was prepared as 9 samples from substrate material as mentioned in Table 4.1. and 27 samples of aluminium were prepared as mechtrode.

Table 4.1: Mechtrode and Substrate materials

Mechtrode	AZ91 Magnesium Alloy
Substrate	IS2062 Low carbon steel

4.2 MATERIAL DESCRIPTION

4.2.1 *Magnesium Alloy*

Magnesium alloy AZ91Mg is a mid-strength alloy that comes under the medium range of magnesium alloys commonly referred to as architectural alloy. It is normally used in intricate extrusions to be précised in dimensions. It is very light in weight, has a very smooth surface finish, relatively high corrosion resistance, and is readily suited to welding and can be easily formed and melted to any state. Chemical composition and properties of Magnesium Alloy AZ91 is given in Table 4.2 and 4.3.

Table 4.2: Chemical composition of Magnesium Alloy AZ91

Elements	Al	Zn	Si	Mn	Cu	Fe	Mg
% of composition	8.25	0.63	0.035	0.22	0.003	0.014	Balance

Table 4.3: Properties of Magnesium Alloy AZ91

Density	2.38 g/cm ³
Tensile Strength, Ultimate	160 MPa
Tensile Strength, Yield	140 MPa
Specific heat	700 J/Kg °C
Thermal conductivity	180 W/m °C
Modulus of Elasticity	53.3 GPa
Melting Point	590°C

Applications of Magnesium AZ91:

- Used in Precision Tubing in motor vehicles, refrigerators, air conditioning, solar panels etc.
- Used in automobile for reducing the weight of the vehicle this decreases the fuel consumption.
- Aluminium reacts with the oxygen in the air to form a microscopically thin layer of oxide. This layer is only 4 nanometres thick but provides excellent protection against corrosion. It even repairs itself if damaged.

4.2.2 Low Carbon Steel

Low carbon steel IS 2062 has low amount of carbon content. IS 2062 contains silicon, manganese, Sulphur and Phosphorus with the majority of the composition being manganese and silicon. Low carbon steel contains approximately 0.05–0.25% carbon making it malleable and ductile. Low carbon steel has a relatively low tensile strength, but it is cheap and easy to form. The low carbon material is relatively soft and weak, but has outstanding ductility and toughness. In addition, it is machine able, weld-able, and is relatively inexpensive to produce. Chemical composition and properties IS2062 Low carbon steel is displayed in Table 4.4 and 4.5.

Table 4.4: Chemical composition of IS2062 Low carbon steel

Element	C	Mn	P	S	Si	Cr	Ni	Mo	N	Fe
% of composition	0.023	1.50	0.045	0.045	0.4	0.16	0.012	0.25	0.1	Balance

Table 4.5: Properties of IS2062 Low carbon steel

Density	7.85 g/cm ³
Tensile Strength, Ultimate	440 MPa
Tensile Strength, Yield	370 MPa
Specific heat	500 J/kg °C
Thermal conductivity	46 W/mK
Modulus of Elasticity	200 GPa
Meting Point	1,450 °C

Application of IS2062 LCS:

- Used in gears, shafts, axles, bolts, studs, and machine parts.
- Used for hand tools such as screwdrivers, pliers, and similar items
- LCS is used to make clutch housings, bushings and suspension components such as brackets and control arms.
- Mostly used for crankshafts, couplings, and cold headed parts.

With its low carbon levels, low carbon steel has generally less corrosion resistance than other carbon steel. Coating of aluminium over carbon steel protects the steel core from oxidation. The magnesium layer protects the steel from oxidation so the steel core regains its original yield strength and protects the low carbon steel from corrosion and improves other material properties.

4.3 EXPERIMENTAL SETUP

The experimental process was directed in a primarily developed friction surfacing machine. The consumable rod is carried by the spindle which was driven by a synchronous servo motor. The movements of axial load was controlled as a closed loop circuit system with the help of PLC. All the parameters could be obtained from a Personal Computer (PC). The units of process parameters were axial load in kN, rotation speed in rpm, and transverse speed in mm/min. Fig 4.5 (a) shows the friction surfacing machine and (b) shows the friction surfacing process.



(a)



(b)

Fig 4.5: (a) Friction surfacing machine (b) Friction surfacing process

The selection of materials for the FS experiments was to the requirement of developing a thick crack free coating of high corrosion resistance and also have good heat transfer rate. By considering these properties the coating can enhance the life of the substrate. This type of coating can be used on products where the rate of heat transfer is more important like engine exhaust line, cooling fins and many other industrial operations. The process parameters for friction surfacing is shown in Table 4.6. The parameters were chosen based on the analysis results.

Table 4.6: Friction surfacing parameters

Axial load (kN)	Rotation speed (rpm)	Transverse speed (mm/min)
4, 5, 6	1000, 1500, 2000	60,90,120

4.5 EXPERIMENTAL PROCESS AND PARAMETERS

Before starting the experiment, the raw materials of mechtrode and substrate plates are cleaned perfectly by the operation of turning and facing using lathe machine and the substrate is cleaned using milling machine which is used to remove the dust and the rough surfacing including the rust created due to corrosion. Both the material (rod and substrate) were washed with acetone earlier to surfacing to reduce the impurities during the process. The experiment was carried out in a friction stir welding machine using certain parametric combination. Table 4.7 shows the input parameter used for friction surfacing. 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.9 deposition samples were prepared through friction surfacing. The parameters used for preparing coating samples are displayed in Table 4.7.

Table 4.7: Design matrix of the experiments

Experiment No	Axial force (kN)	Rotational speed(rpm)	Transverse speed(mm/min)
E1	4	1000	60
E2	4	1500	90
E3	4	2000	120
E4	5	1000	90
E5	5	1500	120
E6	5	2000	60
E7	6	1000	120
E8	6	1500	60
E9	6	2000	90

CHAPTER 5

RESULT AND DISCUSSIONS

5.1 QUALITY OF DEPOSIT

The quality of mechtrode magnesium AZ91 over IS 2062 low carbon steel substrates was analysed by visual inspection and by using low magnification tools. All the samples achieved continuous coatings and uniform deposit with the combination of axial load, rotational load, and transverse speed. A stable hard layer of coating was obtained, with no dilution being found. The dimensions of the coating formed depends on the parameters used. Thicker and wider coatings were produced in the substrate plate.

5.1.1 Primary inspections

The quality of the deposit is evaluated at the shop floor after deposition. These are for the qualitative analysis, to give status of the deposit, whether it is acceptable or not. The NDT techniques such as appearance and adhesion tests such as impact test and hammer tests are performed for evaluation of bonding and quality of friction surfaced deposits.

5.1.2 Visual inspection

The deposit is inspected for the physical appearance and damage. It is also inspected by using magnifying glass for visible defects such as blisters, pits, and cracks or undercut areas.

5.1.3 Visual examination of deposits

Visual examination is done to reveal the 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. The most important instrument in visual testing is the human eye. The VT is 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.

5.1.4 Visual examination of mechtrode

Like the inspection of deposits mechtrode inspection is also important to carry out after the experiment. It will show us how the mechtrode reacts to each input parameters so that next time we can minimize the loss of metal during FS. The mechtrode dimensions after FS was calculated using the digital Vernier calliper which gives the accurate measurement with an error of 0.2mm. The Vernier callipers are available with different sizes. This range of calliper is especially designed for accurate measurement and are anticorrosive in nature. The one used for this experiment measure up to 300mm x 0.02mm. The Vernier calliper has both centimetres and inches scale. Digital callipers are very easy to note the readings. Figure .1 shows the measurement of coating geometries of the obtained samples through vernier calliper.

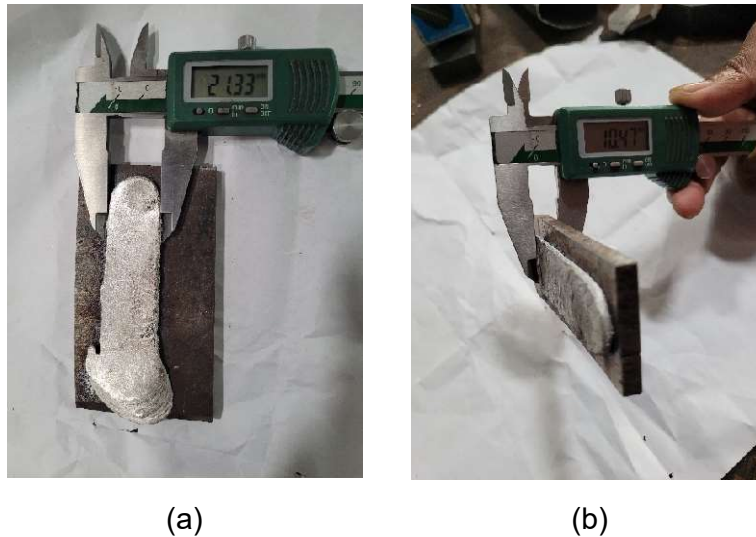


Figure 5.1: coating geometry measurement by vernier calliper (a) coating width (b) Coating thickness.

The surface of the rods is cleaned and marked for measurement. flash mass is formed in each mechtrode samples, this is due to undeposited plasticised layer flows

through the side of the rod due to heat generated during friction surfacing. The shape of the flash mass solely depends on the input parameter used for FS. The dimensions of the rods are reduced after FS. It can be seen that each mechtrode has different shapes. The thickness and diameter of the flash mass ranges from 4.26-12.4mm and 25.38-43.10 mm respectively. The observed output variables from the obtained samples are plotted in table 5.1

Table 5.1 Table 3: Observed output parameters from the experimental samples

Experiment No	Mean Coating Width(mm)	Mean Coating Thickness(mm)	Mean Interface Temp(°C)	Mean Bonding Strength (Mpa)
E1	19.34±0.26	2.23±0.27	426±11	59.6±2.6
E2	20.12±0.17	2.21±0.27	432±24	70.2±1.2
E3	19.6±0.16	1.89±0.15	456±16	68.7±1.4
E4	17.28± 0.36	1.76±0.28	452± 10	66.8±1.1
E5	19.82± 0.85	2.17±0.17	444±12	73.6±2.2
E6	19.24± 0.42	2.32±0.24	421±17	92.2±1.6
E7	18.72±1.34	1.98±0.27	427±14	66.4±1.3
E8	19.42±0.71	2.21±0.34	442±11	71.2±1.7
E9	20.32±0.15	1.78±0.32	445±13	83.6±1.2

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

Vickers micro hardness tester shown in figure 5.2, 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 millimetres.

5.2.1.1. 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 knob 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 hardness testing machine and sample set up has been shown in figure 5a and figure 5b respectively. 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. 5.3 a and fig. 5.3b 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.

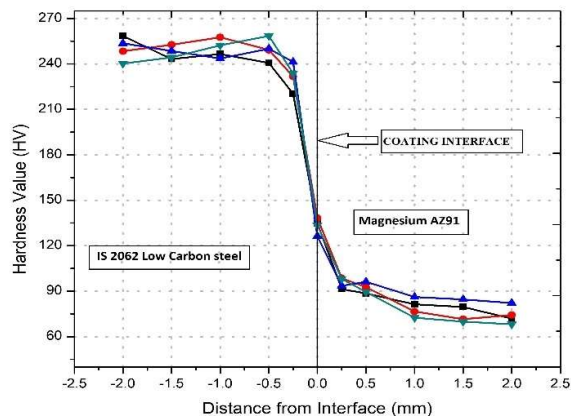


(a)

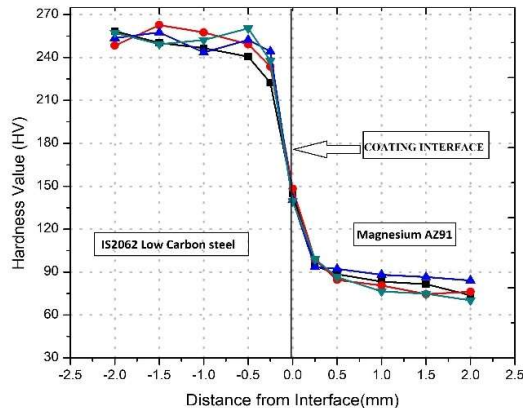


(b)

Figure 5.2: Vickers Hardness (a) testing machine (b) sample set up



(a)



(b)

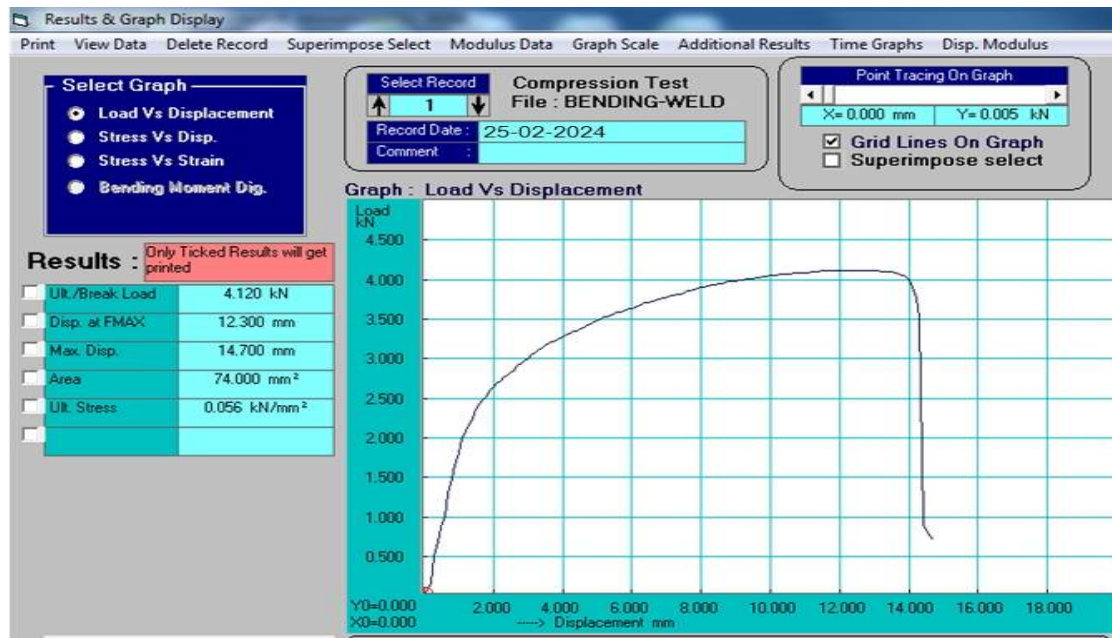
Figure 5.3 : Hardness values of the samples at (a) longitudinal direction (b) Transverse direction.

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. 5.4(a) and 5.4 (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 3 tons, 3.5 tons and 4 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 3 tons, 3.5 tons and 4 tons required to bend the specimen at 30°, 60° and 120° 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 magnesium over low carbon steel by friction surfacing process can be deformed to required shape. The bend test results are shown in figure 5.4.



(a)



(b)

Figure 5.4 Bend test results obtained from samples of (a) face bend (b) root bend.

5.3 MICROSTRUCTURE ANALYSIS

Microstructure is the very small-scale structure of a material, defined as the structure of a prepared surface of material as revealed by a microscope above 25x magnification. The microstructure of a material can strongly influence the physical properties such as strength, toughness, ductility, hardness, corrosion resistance, high/low temperature behaviour or wear resistance. These properties in turn govern the application of these materials in industrial practice. Microstructure at scales smaller than can be viewed with optical microscopes is often called nanostructure, while the structure in which individual atoms are arranged is known as crystal structure.

5.3.1 Field Emission Scanning Electron Microscope (FE-SEM)

A Field Emission Scanning Electron Microscope (FE-SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. The electrons interact with the atoms in the sample, producing various signals that contain information about the surface topology and composition of the sample. The electron beam is scanned in a raster scan pattern, and the position of the beam is combined with the intensity of the detected signal to produce an image. In the most common SEM mode, secondary electrons emitted by atoms excited by the electron beam are detected using an Everhart-Thornley detector. The number of secondary electrons that can be detected, and thus the signal intensity, depends, among other things, on specimen topography. SEM can achieve resolution better than 1 nanometre. In this investigation the SEM images here are taken at the coating interface of magnesium and carbon steel. It is done to ensure the bonding between the two different metals and the minimum existence of oxidation, pores and cracks. The materials taken for the testing are sectioned with 5mm length and 5mm width and polished at the surfaces. Due to the formation of heat during friction surfacing the specimens get mixed with each other and the active recrystallization occurred and leads to the mixture of chemical composition like magnesium, silicon, phosphorous, sulphur 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.

The Fig 5.5 represents the interface between the magnesium and low carbon steel deposit material. The parameters used in the selected sample were axial load of

5 kN, rotation speed of 1000 rpm, 1500 rpm and 2000 rpm with transverse speed 60 mm/min and 90 mm/min. The compositional profile across the interface shows good level of mixing of species on the either side of the interface. It is clearly visible that the interface is in good condition which shows proper bonding was occurred during friction surfacing.

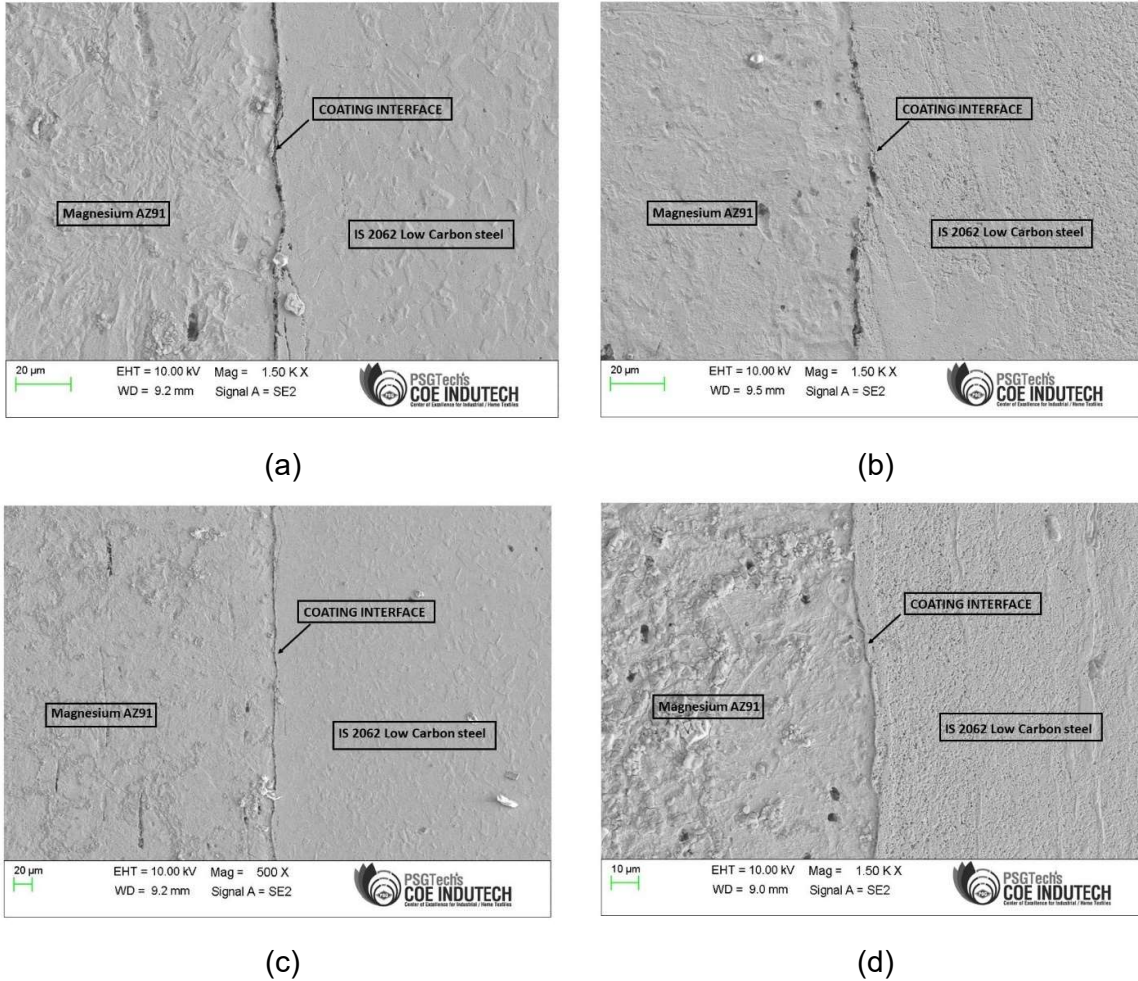
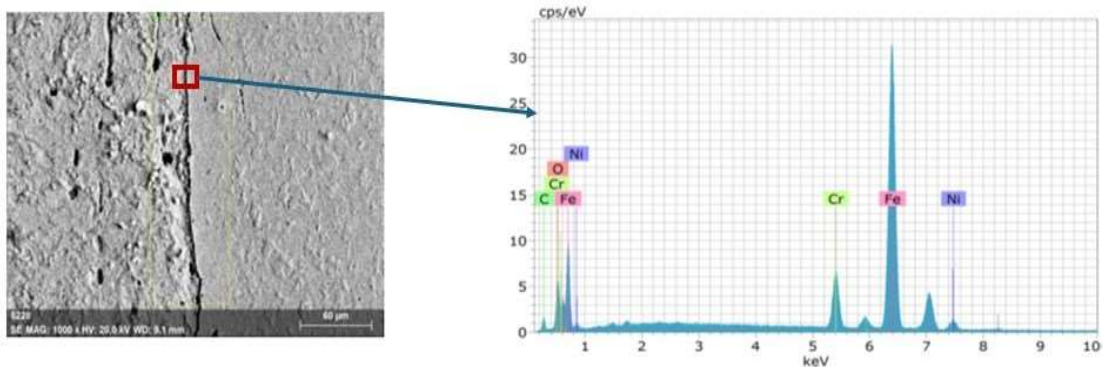


Fig 5.5: SEM image obtained at the interface of Mg AZ91 over IS2062 carbon steel(a)5kN, 1000 rpm,60 mm/min (b) 5kN, 1500 rpm, 90 mm/min (c) 5kN, 2000 rpm, 90 mm/min (d) 5kN, 1500 rpm, 120 mm/min

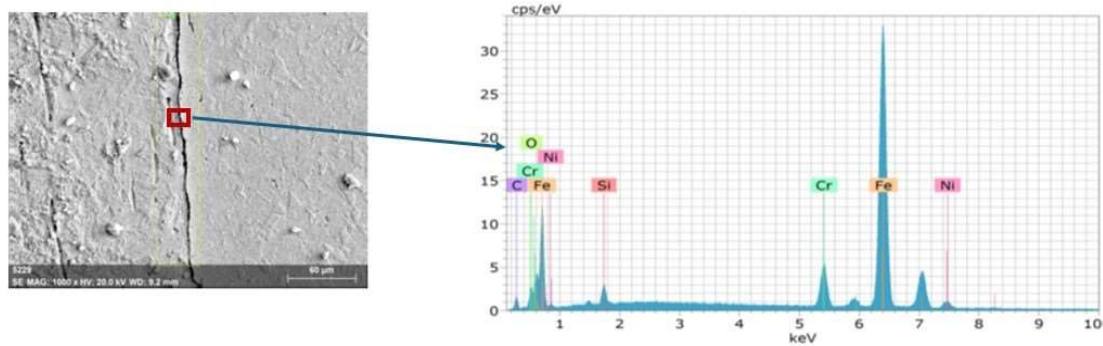
5.3.2. EDAX Spectroscopy (Energy Dispersive X-ray Analysis)

The EDAX test was conducted to fine the chemical composition of the sample at the interfacial region of the deposition. The chemical compositions of Magnesium and low

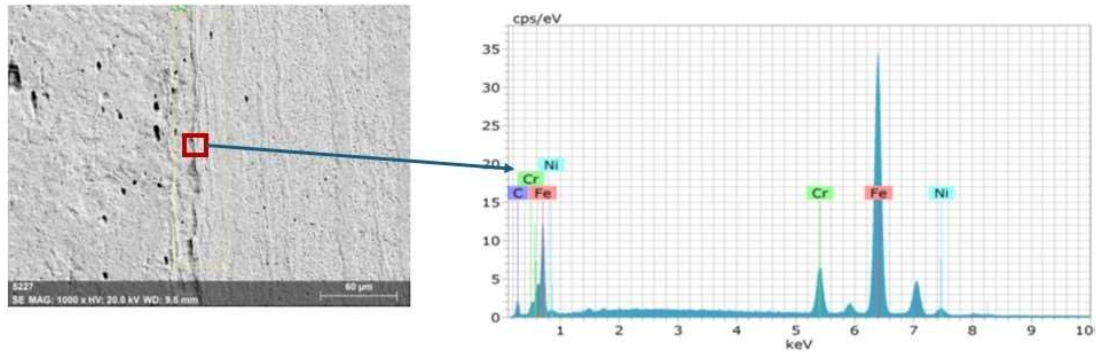
carbon steel are well known before the experimental work. whereas during the friction surfacing process due to the dynamic recrystallization the composition of at the deposition interface changes considerably. It is noted that the aluminium percentage of magnesium is less than 09% but after the surfacing the aluminium percentage increases to 14.07% which obviously leads to the increase in the resistance against corrosion. The weight of aluminium 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.



(a)



(b)

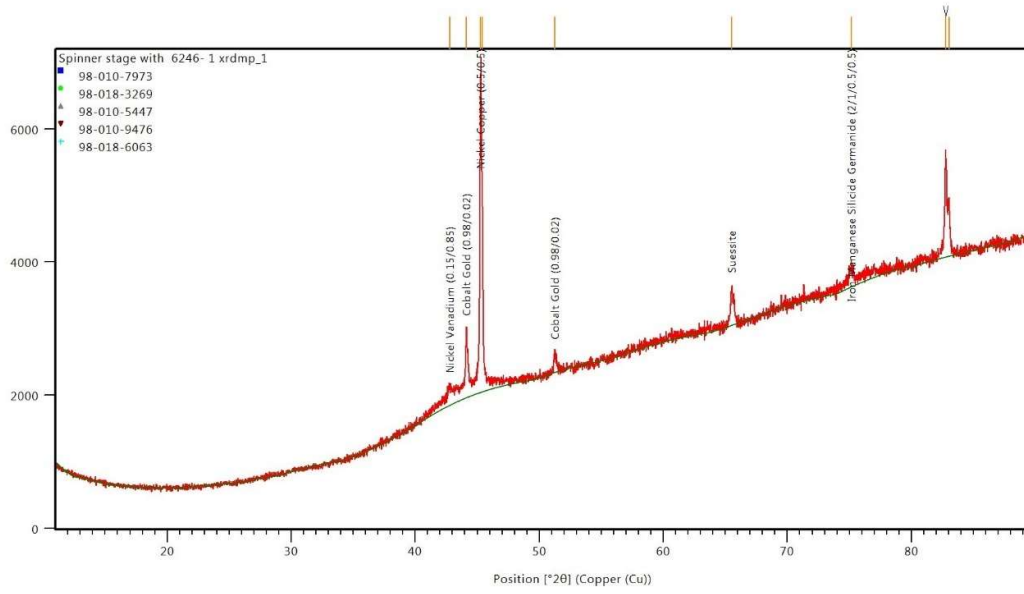


(c)

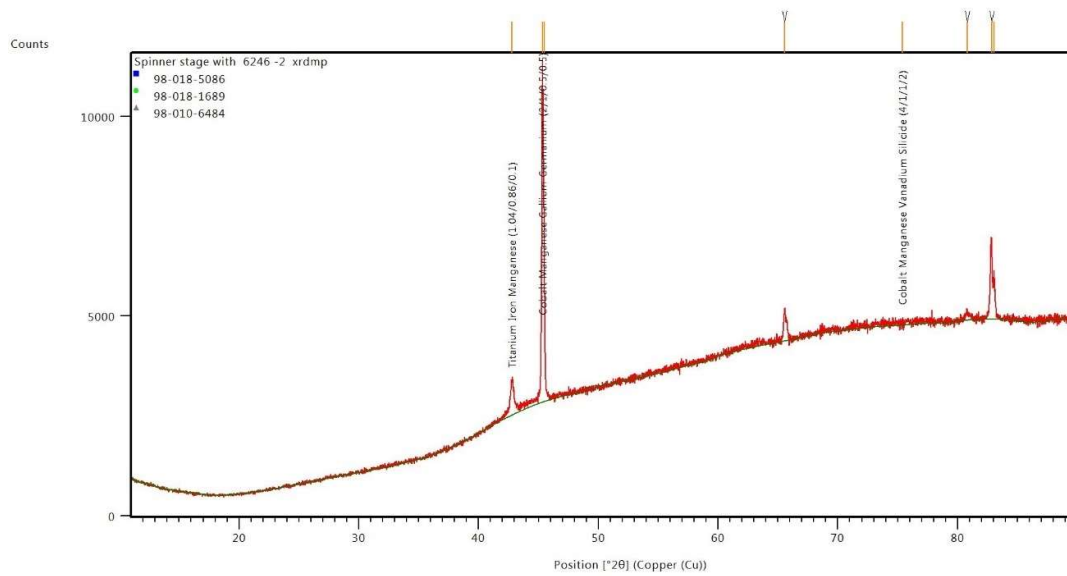
Figure 5.6: EDAX obtained at the interface of Mg AZ91 over IS2062 carbon steel samples at (a) 5kN, 1000 rpm, 60 mm/min (b) 5kN, 1500 rpm, 90 mm/min (c) 5kN, 2000 rpm, 90 mm/min

5.3.3 X-Ray Diffractometer Analysis:

X-Ray Diffractometer Analysis or XRD is used to study the crystal structure, which is used to identify the crystalline phases present in a material and thereby revealing the chemical composition. X-Ray Diffraction (XRD) can be defined as a fast-systematic method that is mostly used for phase detection of a crystalline material and can give all the features on unit cell geometry. The average bulk composition is determined by making the analysed material finely ground and homogenized. XRD investigation process was done to note the existence of intermetallic and elemental dispersion towards the coated interface. The peak intensity in XRD shows the extent of the crystallinity of the particular plane. The Graph 5.7 (a, b) represents the XRD image of magnesium over low carbon steel. The most intense peak was observed at 2θ values at 42.778° , 44.124° , 45.2878° , 51.226° , 65.523° , 75.181° , 82.75° and 75.18° which is in correct order compared to standard pattern. Some peaks of α -Fe content were noticed at 2θ values from 60° to 85° which shows the better bonding of magnesium on low carbon steel.



(a)



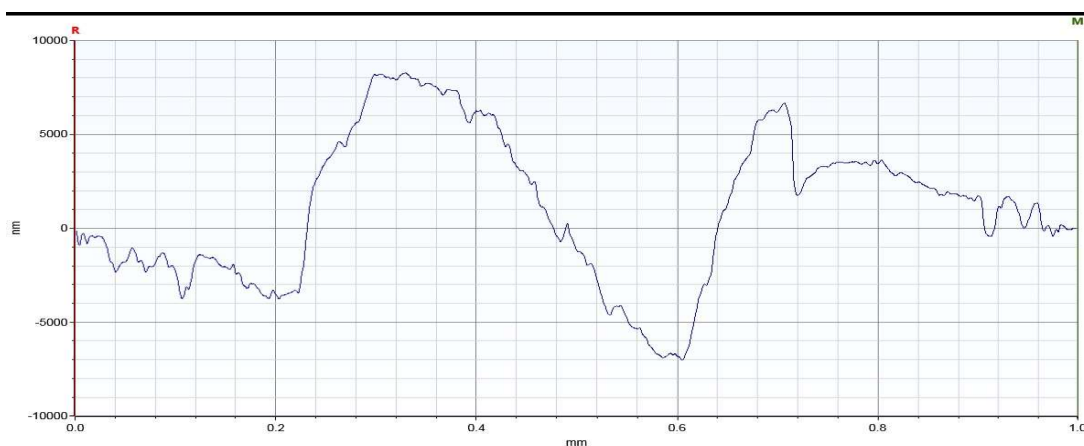
(b)

Figure 5.7: XRD analysis of Magnesium over Low carbon steel at (a) (a)5kN, 1000 rpm,60 mm/min (b) 5kN, 1500 rpm, 90 mm/min

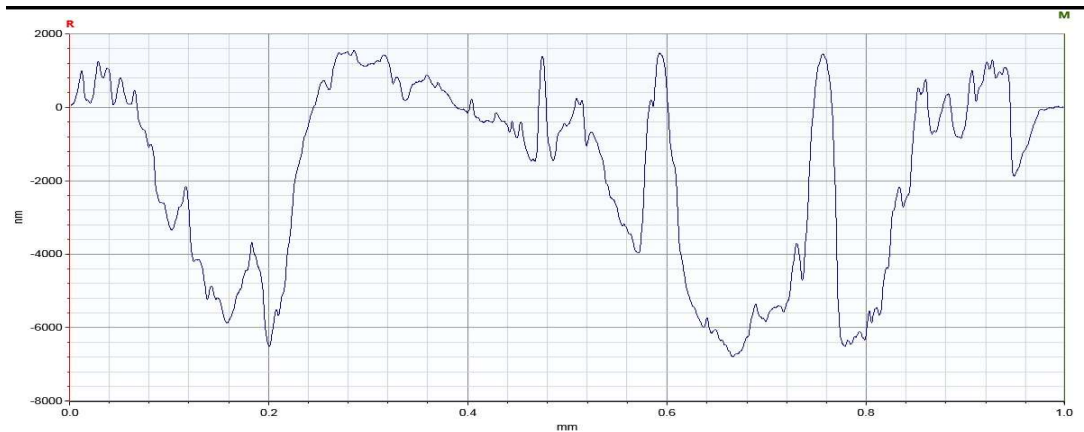
5.3.4 Interference Roughness

Surface roughness is the component of surface texture. Surface texture is the repetitive or random deviation from the nominal surface that forms the three-dimensional topography of the surface. It includes roughness, waviness, lay and flaws. Surface is defined as the deviations in the direction of normal vector of real surface

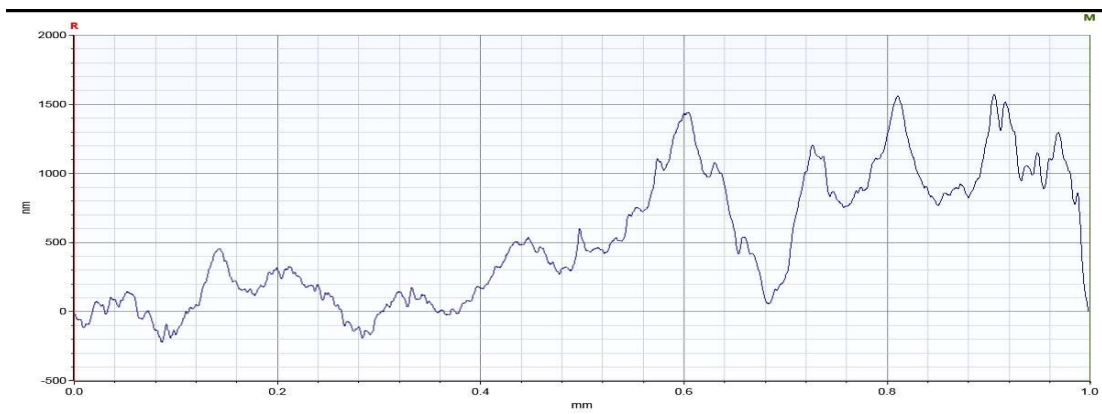
from its ideal form. If these deviations are large then the surface is rough, if the deviations are small roughness is smooth. Roughness plays an important role in determining how a real object interacts in an environment. Roughness analysis determines the roughness parameters of a surface. Roughness parameters are statistical parameters that measure the vertical characteristics of the surface. A roughness value can either be calculated on a profile (line) or on a surface (area). The cross section of the specimen revealed that the bonding between coating and substrate interface was a certain degree of mechanical interlocking. During initial investigation, it was noticed that the quality of the bonding has influence on the geometry of intermixing at interface; which in sequence could be presented by height and distance of the peak noticeable at the interface. The obtained profile could then be benchmarked with a roughness profile originated from a surface topography. The interfacial roughness profile of the specimen coating-substrate was extracted by using Roughness tester PCE-RT 11-ICA. Graph 5.4-5.6 displays the roughness profile of magnesium over low carbon steel. It can be seen that at central region of the coating substrate interface the roughness is more uniform. From the figures we can see the roughness profile in nanoscale.



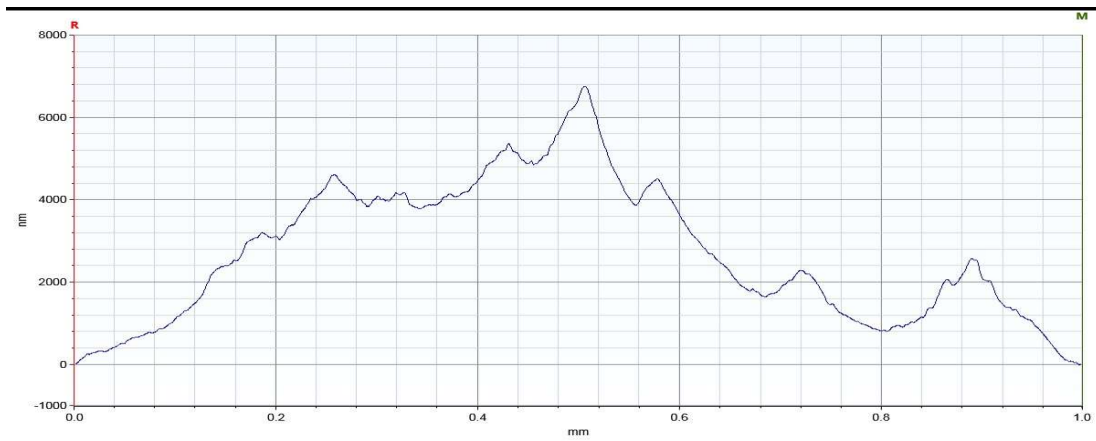
(a)



(b)



(c)



(d)

Figure 5.8: Interface roughness between magnesium and low carbon steel at (a) 5kN, 1000 rpm, 60 mm/min (b) 5kN, 1500 rpm, 90 mm/min (c) 5kN, 2000 rpm, 90 mm/min (d) 5kN, 1500 rpm, 120 mm/min

5.4 CORROSION ANALYSIS

5.4.1. Salt Spray Test

In friction surfacing process, the magnesium is heated near to its melting point, due to friction, bonding is taken place on the low carbon steel substrate. When the magnesium is cooled to room temperature, depending its cooling rate, the magnesium deposit may be subjected to corrosion attack. Hence it is important to test corrosion resistance of deposit.

Salt spray test was carried out on sections of 5mm×5mm×5mm without diagonal illuminators. Salts pray tests were used for simulating the sea faring atmosphere where low carbon steel was evident according to ASTM B 117-3. 5% NaCl solution was prepared and played the role of salt spray solution with a pH of 6.9, air pressure of 15psi. Temperature in the salt spray chamber was kept under control in the range 33.8-35.1°C. The duration of the experiment (test) was 250 hours, continuously and without any intermission. Cleaning of the specimen was done before loading and after completion as per the following procedure. a) A gentle cleaning was done before applying a load. b) The specimen was washed gently with clean, running water for removal of salt deposited on the surface and then the moisture was removed by drying. The panels were carefully observed for spots affected by the formation of rust on their surfaces.

5.4.1.1 Intergranular Corrosion.

At temperatures above approximately 535°C, chromium carbides are completely dissolved in low carbon steels. However, when these steels are slowly cooled from these high temperatures or reheated into the range of 425 to 515°C magnesium carbides are precipitated at the grain boundaries. These carbides contain more magnesium than the matrix does. The precipitation of the carbides depletes the matrix of magnesium adjacent to the grain boundary. The diffusion rate of magnesium in magnesium alloy is slow at the precipitation temperatures, therefore, the depleted zone persists, and the alloy is sensitized to intergranular corrosion. This sensitization occurs because the depleted zones have higher corrosion rates than the matrix in many environments. The wide differences in the corrosion rate are the result of the differences in the magnesium content. With the lower- magnesium -bearing alloy, the passive film is more soluble in the acid, and therefore, more metal must dissolve to

repair the film. If the low carbon steels are cooled rapidly to below approximately 425°C, the carbides do not precipitate, and the steels are immune to intergranular corrosion. Welding is the common cause of the sensitization of carbon steels to intergranular corrosion. Although the cooling rates in the weld itself and the base metal immediately adjacent to it are sufficiently high to avoid carbide precipitation, the weld thermal cycle brings part of the heat-affected zone (HAZ) into the precipitation temperature range. Carbides can precipitate, and a zone somewhat removed from the weld becomes susceptible to intergranular corrosion.

5.4.2 Potentiodynamic Polarization Studies

Diagram displays characteristic potentiodynamic polarization curves for magnesium AZ91, Mg (AZ91) - Low Carbon Steel (IS2062) and low carbon steel material substrate in 3.5% NaCl. It was obvious that the polarization curves for mechtrode demonstrate extraordinary potential shifts to noble values match up to the substrate absorbed in 3.5% NaCl.

The corrosion current and the corrosion potential (ie E_{cor} and I_{corr}) values was obtained from potentiodynamic polarization test. The sample with higher I_{corr} and lower E_{cor} showed a tendency to corrode greater. Table 5.2 clearly shows low carbon steel having greater corrosion current and least potential values and hence it was understood that it has lower corrosion resistance. magnesium AZ91, Mg (AZ91) - Low Carbon Steel (IS2062) have lesser corrosion current and higher potential than low Carbon Steel and hence this section as having exhibits higher corrosion resistance. A greater the Tafel slope value indicates the substrate as having poor response on resistance to corrosion. However, the coating and the mechtrode have a smaller slope, shows better resistance.

The potential for mechtrode and the coatings has a higher positive feature compared to substrate while the corrosion current density is much lower compared to the substrate. The observation, therefore, was that the coatings applied on mechtrode magnesium AZ91 place restrictions on the relations amongst the material and the electrolyte to a great magnitude.

Table 5.2 Corrosion parameters in potentio-dynamic polarization test

Sample	I_{corr} Corrosion current in amps/cm ²	E_{corr} Corrosion Potential in V	Area of sample in cm ²	log (I_{corr}/A)	Tafel Slope
Mg-AZ81	8.10×10^{-6}	-0.5276	1	-4.086	-1.98×10^{-4}
IS 2062 -Mg- AZ81	3.21×10^{-5}	-0.3475	1	-3.179	-1.47×10^{-3}
IS 2062 LCS	1.31×10^{-2}	-0.7295	1	-3.719	-7.43×10^{-3}

Such a limitation to the access of corrosive sorts was higher with such mechtrode (Mg AZ91) and for the substrate. Such a behavior exhibited by AISI316-Medium Carbon Steel could be due to a decrease in the active exterior resulting from the occurrence of oxide elements. Details of the sequence of corrosion resistance of the material were given below:

Magnesium AZ91 > Mg-AZ91-Low Carbon Steel > Low Carbon Steel

5.4.3 *Electrochemical Impedance Spectroscopy (EIS)*

The mechtrode bonded material and substrate were inspected thoroughly with Electrochemical Impedance Spectroscopy (EIS) for further assimilation of corrosion behavior. Measurements were taken for corrosion potential at sinusoidal voltage excitation with deviation in amplitude of 10 mV in a frequency range from 100 kHz to 0.01 Hz. A record was made of all the impedance values and they were displayed as Nyquist Figure 5.9 displays the Nyquist plots of the substrate, mechtrode Mg AZ91 and the bonded material.

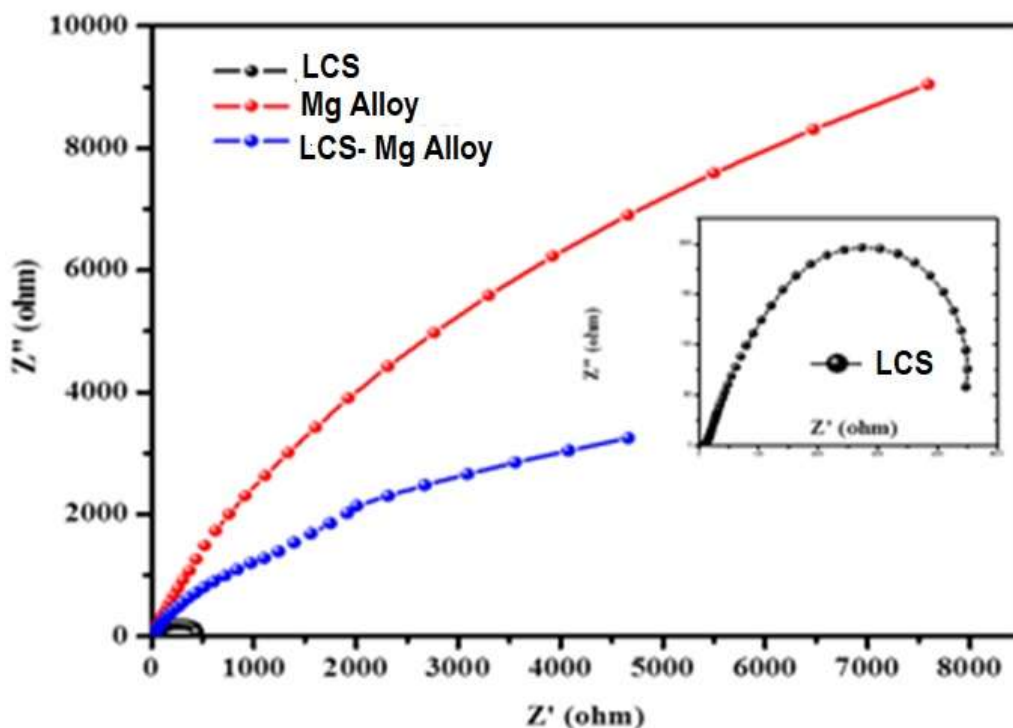


Figure 5.9 Nyquist plot of Magnesium AZ91, Mg-AZ91-Low Carbon Steel and Low Carbon Steel in 3.5% NaCl

These Nyquist give the appearance of being vis-a-vis their loops but the shapes produced by the curve with respect to the diameter were not the same. In other words, the adjacent shape geometry could be used for calculating the impedance response, enters larger loop diameter indicating higher resistance to corrosion. Therefore, it predicted extremely good corrosion existence for the bonded material and the mechtrode depending on the result if ECS whereas the substrate showed poor resistance to corrosion. So the measurements from EIS indicate fair and accurate corrosion resistance with polarization.

The Bode plots mechtrode, bonded material and substrate are illustrated in Figure 5.10. EIS Studies were conducted for mechtrode, bonded material and the substrate in 3.5%NaCl. This good corrosion resistance accessible by the coating method Mg-AZ91-Low Carbon Steel may be the result of the presence of light coat of chromium oxide, which provided a faultless coating of low absorbency, great crosslinking density having upgraded bonding reliability.

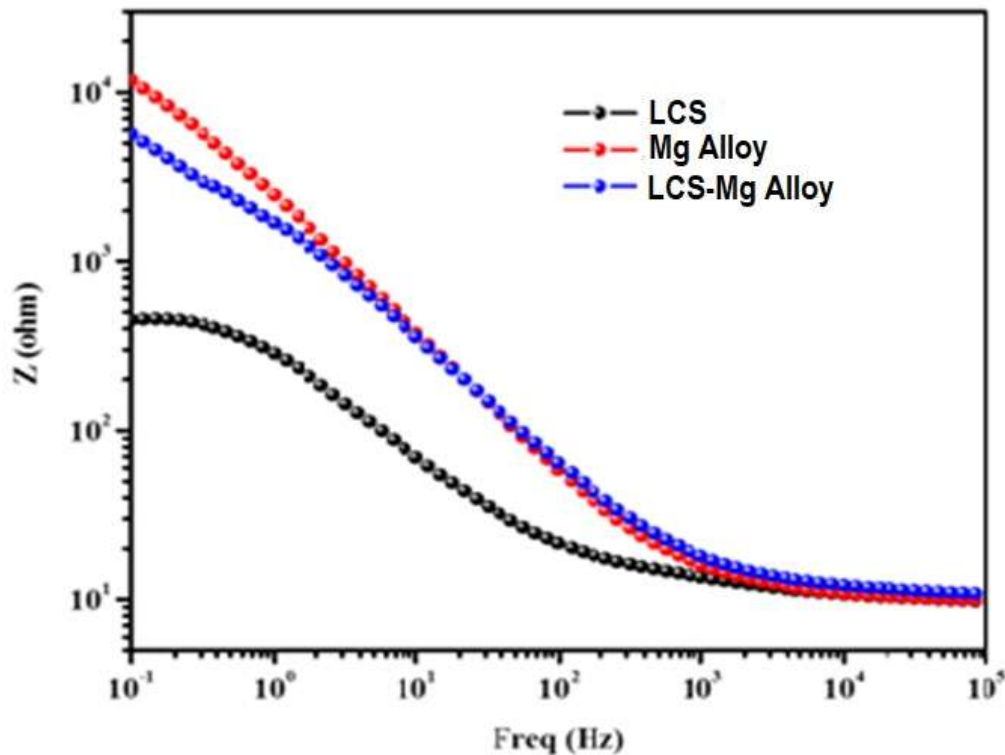


Figure 5.10 Bode plot of Magnesium AZ91, Mg-AZ91-Low Carbon Steel and Low Carbon Steel in 3.5% NaCl

The Performance of the coatings pertaining to the protection rendered against corrosion, has been evaluated with the help of the useful parameter, phase angle at high frequencies. The dielectric pathways are preferred by the flowing current, when the coating substance provides very high resistance. From Figure 5.11 it is evident that the frequencies between 10 kHz and 100 kHz are experienced at higher phase angles which provide the voltage and current. The lower phase angles are seen in the coatings that offer very low resistance to the passing current, through the conductive pathways. Measurement of changes in angle between potential difference and current at 10 kHz of immersion of the specimens was done by EIS. The phase angle plots of mechtrode (Mg AZ91), bonded material (Mg AZ91- low Carbon Steel) and substrate (low Carbon Steel) of present study. Figure 5.11 is a graphical representation of the results, when the coated sample submerged in the 3.5% salt solution. The phase angle variation for different materials used for coating, upon exposing them to the solution of electrolytic in nature are clearly shown in graphical form in Figure 5.11. A point of interest to note is that the phase angle values of Mg

AZ91of concentration in electrolyte solution were 70°, representing a capacitive performance.

Magnesium AZ91 >Mg-AZ91-Low Carbon Steel > Low Carbon Steel

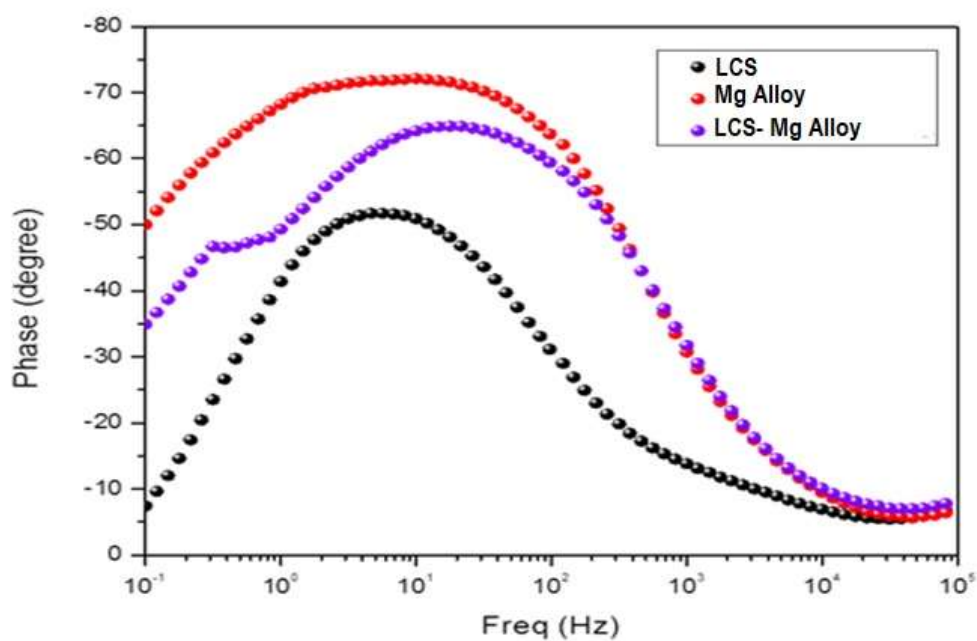


Figure 5.11 Phase angle plot of AISI316, AISI316-Medium Carbon Steel and Medium Carbon Steel in 3.5% NaCl.

CHAPTER 6

CONCLUSION

In the present work friction surfacing was done on magnesium AZ91 over low carbon steel with various parametric combinations and it concludes with following findings,

1. A total of 9 samples has been coated successfully with magnesium over low carbon steel as substrates.
2. No crack was observed in the coating, and no melting was occurred during friction surfacing.
3. The parametric combinations like Axial load of 4, 5, and 6 kN, Rotation speed of 1000, 1500 and 2000 rpm and Transverse speed of 60, 90 and 120 mm/min are more suitable for friction surfacing.
4. The SEM analysis is done to find the microstructural structure at the interface of the coating. It has been observed that intermolecular bonding was achieved without any gaps or pores. Since magnesium was used as the mechtrode, during friction surfacing the dynamic recrystallization occurred and iron particles have got mixed with aluminium.
5. The EDAX analysis was performed at the interface of the coating to find material composition. It is noted that the majority of material composition at the interface contains Iron, Aluminium, Silicon, Manganese and Chromium. High content of magnesium also shows that the mechtrode was perfectly deposited in the substrate.
6. Interference roughness was tested at the coating interface and the roughness was seen to be uniform in all conditions.
7. Finally, an assessment of power and material consumption was performed revealing that Friction Surfacing is quite competitive but at the same time it can be useful than other surface coating technologies.
8. The coated metal has two peaks with α -Fe content were observed at 2θ values from 40° to 80° with the average crystal size of 5.76 nano meters.
9. No corrosion was found on the mechtrode Mg AZ91 during the 250-hour test.
10. Electrochemical behavior was studied at 3.5% NaCl When compare to the substrate, stable passivation occurred in Mg-AZ91-LCS and this corrosion

resistance was due to elements of chromium and nickel present in the coated material which having a possibility of formation of film on the surface.

11. From the above results, it is concluded that the coating between Magnesium AZ91 over IS2062 Low carbon steel is successful and can be used for further appliances.

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