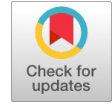


Advancing Corrosion Resistance and Micro-hardness in 6061 Aluminium Alloy through Friction Stir Surface Processing

Pankaj Sonkusare, Shri Krishna Dhakad, Pankaj Agarwal, Ravindra Singh Rana



Abstract: Friction stir surface processing (FSSP) is a promising technique for enhancing the properties of aluminium alloys. This abstract presents the findings of a study focused on the FSSP of 6061 aluminium alloy to improve its corrosion resistance and micro-hardness. The FSSP method involves the stirring of a rotating tool across the alloy's surface, inducing plastic deformation and refinement of the microstructure. The study investigates the impact of FSSP parameters such as rotational speed, traverse speed, and tool geometry on the corrosion resistance and micro-hardness of the alloy. Results show that FSSP significantly improves the corrosion resistance of the 6061 aluminium alloy, attributed to refined grain structure and reduced grain boundary corrosion susceptibility. Additionally, micro-hardness is enhanced due to the refined microstructure and dispersion strengthening effects. The findings demonstrate the potential of FSSP as a viable surface treatment technique for aluminium alloys, offering improved corrosion resistance and mechanical properties for various engineering applications.

Keywords: Friction Stir Surface Processing (FSSP), Aluminium alloy, Corrosion Resistance, Micro-Hardness, Surface Treatment, Grain Refinement, Rotational Speed, Traverse Speed, Tool geometry and Microstructure.

I. INTRODUCTION

Friction stir surface processing (FSSP) has emerged as a promising technique for enhancing the properties of aluminium alloys, offering a solid state approach to surface modification without the drawbacks associated with conventional based melting processes. Among the various aluminium alloys, 6061 aluminium alloy holds particular significance due to its widespread used in industries ranging from aerospace to automotive manufacturing. The unique properties of 6061 aluminium alloy, including its high strength excellent corrosion resistance, and good weldability, make it an attractive choice for various engineering applications.

However, there is ongoing interest in further improving its properties to meet the ever-evolving demands of modern engineering. It presents an innovative method for enhancing the surface properties of 6061 aluminium alloy, offering the potential to simultaneously improve corrosion resistance and micro-hardness. By subjecting the alloy to controlled the mechanical deformations and heat input, it includes micro-structural refinement and introduces beneficial changes at the surface.

In this topic, we provide an overview of the principles of FSSP, highlighting its advantages and applications in aluminium alloy surface modification. We have also discuss about the specific properties of 6061 aluminium alloy that make it a suitable candidate for FSSP and outline the objectives of the study. Finally, we present the roadmap for the subsequent sections, detailing the experimental approach, results, and conclusion of the research on FSSP of 6061 aluminium alloy. Through this study, we aim to contribute to the growing body of knowledge on advanced surface modification techniques for aluminium alloys, paving the way for enhanced performance and durability in engineering applications.

II. LITERATURE REVIEW

Friction stir surface processing (FSSP) has emerged as a novel technique for enhancing the properties of metallic materials, offering remarkable advancements in corrosion resistance and micro-hardness. In this study, we focus on the application of FSSP to 6061 aluminium alloy, a widely used material renowned for its excellent weldability and structural integrity. By subjecting the alloy to controlled frictional heating and mechanical stirring, we aim to induce favourable changes in its surface characteristics, thereby improving its resistance to corrosion and enhancing its micro-hardness. 6061 aluminium alloy is highly susceptible to corrosion, particularly in harsh environments or industrial applications where exposure to moisture, chemicals, or abrasive conditions is prevalent. Traditional methods of surface treatment, such as coatings or anodization, often come with limitations in terms of adhesion, durability, or cost-effectiveness. FSSP presents a promising alternative, offering a non-conventional approach that can achieve significant improvements in surface properties without compromising the bulk integrity of the material [1].

This study investigates the impact of post-weld heat treatment (PWHT) on the microstructure and mechanical properties of welded joints fabricated from 6061-T6 aluminium alloy.

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Welded joints are subjected to various thermal cycles during fabrication, leading to changes in microstructure and mechanical properties that can affect the overall performance of the welded structure. The 6061-T6 aluminium alloy is widely used in aerospace, automotive, and marine applications due to its excellent strength-to-weight ratio and corrosion resistance. Experimental procedures involve welding specimens using a suitable technique, followed by PWHT under controlled conditions. The microstructural evolution is examined using optical microscopy, scanning electron microscopy (SEM), and X-ray diffraction (XRD). Mechanical properties, including tensile strength, yield strength, and hardness, are evaluated using standard testing methods [2].

This study investigates the influence of incorporating graphite (Gr) particles and aluminium oxide (Al₂O₃) particles reinforced with silicon carbide (SiC) particles (Gr p/Al₂O₃ p with SiCp) on the wear properties of aluminium alloy 6061-T6 hybrid composites through friction stir processing (FSP). Hybrid composites offer enhanced mechanical properties compared to monolithic materials, making them attractive for various engineering applications. Friction stir processing is employed to fabricate the hybrid composites, utilizing a combination of rotational and traverse speeds to ensure uniform dispersion of reinforcing particles within the aluminium matrix. The wear behaviour of the resulting composites is evaluated using pin-on-disk wear testing under controlled conditions. Experimental results reveal that the addition of Gr p/Al₂O₃ p with SiCp significantly influences the wear resistance of the aluminium alloy 6061-T6 hybrid composites. The incorporation of reinforcing particles alters the microstructure and distribution of phases within the composite material, leading to improvements in wear resistance. Wear mechanisms are analyzed, including abrasive, adhesive, and oxidative wear, providing insights into the mechanisms governing wear behaviour in the hybrid composites [3].

This study investigates the microstructure, mechanical properties, and corrosion resistance of aluminium alloy 6061 (Al6061) surface composite reinforced with boron nitride (BN) particles, prepared using friction stir processing (FSP). Surface composites offer enhanced properties compared to bulk materials, making them attractive for various industrial applications. Friction stir processing is employed to fabricate the Al6061/BN surface composite, with varying processing parameters to optimize the distribution and dispersion of BN particles within the aluminium matrix. Micro-structural analysis is conducted using scanning electron microscopy (SEM) and X-ray diffraction (XRD), while mechanical properties are evaluated through hardness testing and tensile testing. Corrosion resistance is assessed using electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) [4].

This study investigates the synergistic effect of combining equal-channel angular pressing (ECAP) with heat treatment to enhance the corrosion resistance of 6061 aluminium alloy. ECAP is utilized to refine the microstructure, while heat treatment is employed to optimize the alloy's corrosion resistance. The combined approach shows promise in significantly improving the corrosion resistance of 6061

aluminium alloy, presenting opportunities for various industrial applications [5].

Multi-channel spiral twist extrusion (MCSTE) is introduced as an innovative severe plastic deformation technique aimed at grain refinement in metallic materials. This novel method involves the simultaneous rotation and translation of a workpiece through multiple channels with a spiral twist geometry, inducing significant plastic deformation. The unique processing conditions of MCSTE lead to refined grain structures and enhanced mechanical properties in various metallic alloys. This paper discusses the principles and advantages of MCSTE, as well as its potential applications in metallurgical engineering [6].

This study evaluates the corrosion properties of aluminium (Al) nanocomposite sheets reinforced with nanosilica particles, produced via the accumulative roll bonding (ARB) process. The incorporation of nanosilica particles aims to enhance the corrosion resistance of the Al matrix. The ARB process is utilized to achieve uniform dispersion of nanosilica within the Al matrix and to refine the grain structure, thereby improving mechanical properties. Corrosion properties are assessed through electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), supplemented by micro-structural analysis using scanning electron microscopy (SEM) and X-ray diffraction (XRD). The influence of nanosilica content and processing parameters on corrosion behaviour is investigated [7].

This study investigates the effect of grain refinement on the mechanical and electrochemical properties of ultra-fine-grained (UFG) AA1050 aluminium alloy fabricated via the accumulative roll bonding (ARB) process. The ARB process is utilized to achieve significant grain refinement in the alloy, leading to enhanced mechanical properties. Mechanical properties, including tensile strength, yield strength, and hardness, are evaluated through standard testing methods. Electrochemical properties are assessed using techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), to understand the corrosion behaviour of the UFG AA1050 alloy. Results demonstrate that grain refinement via the ARB process leads to notable improvements in mechanical properties, attributed to the reduction in grain size and the development of a refined microstructure. Moreover, the electrochemical properties of the UFG AA1050 alloy exhibit enhanced corrosion resistance compared to coarse-grained counterparts, owing to the refined grain structure [8][40].

Friction stir processing (FSP) technology has gained significant attention in recent years due to its capability to modify the microstructure and properties of metallic materials without melting. This review provides a comprehensive overview of FSP technology, covering its principles, process parameters, applications, and recent advancements. The fundamental principles of FSP, including the thermo-mechanical effects induced by the rotating tool and the plastic deformation mechanisms occurring within the material, are discussed.

Process parameters such as rotational speed, traverse speed, and tool geometry are explored in relation to their influence on micro-structural evolution and property enhancement. Various applications of FSP across different metallic alloys, including aluminium, magnesium, titanium, and steels, are highlighted. These applications range from grain refinement and texture modification to the production of surface composites, leading to improvements in mechanical, corrosion, and wear properties. Recent advancements in FSP technology, such as hybrid processes combining FSP with other techniques, advancements in tool materials and designs, and numerical modelling for process optimization, are also reviewed. These advancements contribute to the continued evolution and adoption of FSP in industrial applications [9].

This study investigates the chloride-induced pitting corrosion behaviour of ultra-fine-grained (UFG) 5052 aluminium alloy produced via the accumulative roll bonding (ARB) process. UFG materials are known to exhibit unique corrosion characteristics due to their refined microstructure, which influences the initiation and propagation of corrosion defects. The corrosion behaviour of UFG 5052 aluminium alloy is evaluated through immersion tests in chloride-containing environments, complemented by electrochemical measurements such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). Micro-structural analysis using scanning electron microscopy (SEM) and X-ray diffraction (XRD) is performed to correlate the corrosion behaviour with the grain structure and phases present in the material. Results reveal that UFG 5052 aluminium alloy exhibits increased susceptibility to chloride-induced pitting corrosion compared to coarse-grained counterparts. The refined grain structure promotes localized corrosion initiation sites, leading to accelerated pit propagation under chloride exposure. Factors influencing the corrosion behaviour, including grain boundary characteristics and precipitate distribution, are discussed. This study provides insights into the chloride-induced pitting corrosion behaviour of UFG 5052 aluminium alloy produced by the ARB process, contributing to a better understanding of the corrosion performance of UFG materials and guiding the development of corrosion-resistant aluminium alloys for marine and other chloride-rich environments [10][38][39].

This study investigates the effect of processing parameters on the corrosion behaviour of friction stir processed (FSP) AA 2219 aluminium alloy. FSP is a solid-state processing technique known for its ability to refine microstructure and improve mechanical properties without melting. Understanding the influence of FSP parameters on corrosion behaviour is crucial for optimizing the performance of FSP-treated alloys in corrosive environments. Various processing parameters, including tool rotation speed, traverse speed, and tool geometry, are systematically varied to study their impact on the corrosion resistance of FSP-treated AA 2219 alloy. Corrosion behaviour is evaluated using electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), along with surface characterization using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). Results demonstrate that processing parameters significantly influence the corrosion behaviour of

FSP-treated AA 2219 alloy. Optimal processing conditions leading to improved corrosion resistance are identified, considering factors such as grain refinement, micro-structural homogeneity, and distribution of second-phase particles. This study provides valuable insights into the relationship between processing parameters and corrosion behaviour in FSP-treated AA 2219 aluminium alloy, aiding in the development of corrosion-resistant materials for aerospace and other demanding applications [11].

This study presents a comprehensive investigation into the micro-structural characterization and corrosion behaviour of multipass friction stir processed (FSP) AA2219 aluminium alloy. FSP is a solid-state processing technique known for its ability to refine microstructure and enhance mechanical properties without inducing melting, making it suitable for improving the corrosion resistance of aluminium alloys. Micro-structural characterization of multipass FSP-treated AA2219 alloy is conducted using scanning electron microscopy (SEM) and X-ray diffraction (XRD) to assess the grain structure, texture, and distribution of second-phase particles. Corrosion behaviour is evaluated through electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), along with immersion testing in corrosive environments. Results reveal significant microstructural modifications induced by multipass FSP, including grain refinement, reduction in second-phase particle size, and homogenization of microstructure. These microstructural changes contribute to enhanced corrosion resistance of the AA2219 alloy. The study provides insights into the relationship between microstructure and corrosion behaviour in multipass FSP-treated AA2219 aluminium alloy, offering valuable information for optimizing FSP parameters and developing corrosion-resistant materials for aerospace and other critical applications [11].

This study investigates the effects of friction stir processing (FSP) and friction stir vibration processing (FSVP) on the mechanical, wear, and corrosion characteristics of Al6061/SiO₂ surface composite. FSP and FSVP are advanced solid-state processing techniques used to fabricate surface composites by incorporating reinforcing particles into a metal matrix. Al6061/SiO₂ surface composite specimens are subjected to FSP and FSVP under varying processing parameters to explore their influence on mechanical properties, wear resistance, and corrosion behaviour. Mechanical properties are assessed through tensile testing, hardness measurements, and impact testing. Wear resistance is evaluated using pin-on-disk wear testing, while corrosion behaviour is studied through electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). Results reveal that both FSP and FSVP lead to significant improvements in mechanical properties and wear resistance of the Al6061/SiO₂ surface composite compared to the base material. Additionally, the corrosion resistance of the composite is enhanced, attributed to the refined microstructure and improved particle distribution achieved through FSP and FSVP.

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This study provides valuable insights into the effects of FSP and FSVP on the mechanical, wear, and corrosion characteristics of Al6061/SiO₂ surface composite, offering potential for the development of advanced materials with superior performance for aerospace, automotive, and other engineering applications [13].

This study explores the simultaneous enhancement of mechanical strength, ductility, and corrosion resistance in stir cast Al7075-2% SiC micro- and nanocomposites through friction stir processing (FSP). Al7075 alloy is renowned for its high strength but limited ductility and corrosion resistance, while the addition of SiC nanoparticles offers potential for property improvement. FSP is employed to refine the microstructure and disperse SiC nanoparticles uniformly within the Al7075 matrix. The effects of processing parameters on mechanical properties, ductility, and corrosion resistance are systematically investigated using tensile testing, hardness measurements, and electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). Results demonstrate a significant improvement in mechanical strength and ductility of the Al7075-2% SiC micro- and nanocomposites after FSP, attributed to grain refinement and dispersion strengthening effects. Moreover, the corrosion resistance of the composites is enhanced due to the formation of a protective oxide layer on the surface. This study provides valuable insights into the simultaneous improvement of mechanical properties, ductility, and corrosion resistance in stir cast Al7075-2% SiC micro- and nanocomposites by FSP, offering potential for the development of advanced materials for aerospace, automotive, and other high-performance applications [14].

This study investigates the effects of reduced surface grain structure and improved particle distribution on the pitting corrosion resistance of AA6063 aluminium alloy. Surface grain structure refinement and particle distribution improvement are achieved through advanced solid-state processing techniques such as friction stir processing (FSP) and friction stir vibration processing (FSVP). AA6063 aluminium alloy specimens are subjected to FSP and FSVP under varying processing parameters to optimize grain refinement and particle distribution. Pitting corrosion resistance is evaluated through electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), supplemented by micro-structural analysis using scanning electron microscopy (SEM) and X-ray diffraction (XRD). Results demonstrate that FSP and FSVP lead to significant improvements in pitting corrosion resistance of AA6063 aluminium alloy due to the refined surface grain structure and more uniform particle distribution. The correlation between micro-structural modifications and corrosion behaviour is elucidated, providing insights into the mechanisms governing pitting corrosion in aluminium alloys. This study contributes to a better understanding of the relationship between surface grain structure, particle distribution, and pitting corrosion resistance in AA6063 aluminium alloy, offering potential for the development of corrosion-resistant materials for various engineering applications, including automotive, marine, and construction industries [15].

This study provides insights into the electrochemical response of a partially recrystallized Al-Mg-Si alloy and its relationship to corrosion events. Partial recrystallization is induced in the alloy to investigate its influence on corrosion behaviour, considering the complex micro-structural evolution associated with recrystallization processes. Electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) are employed to evaluate the corrosion behaviour of the partially recrystallized Al-Mg-Si alloy under various conditions. Micro-structural characterization using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) complements the electrochemical analysis, providing insights into the relationship between microstructure and corrosion resistance. Results reveal that the electrochemical response of the partially recrystallized Al-Mg-Si alloy is influenced by the extent of recrystallization, grain size distribution, and the presence of precipitates. Correlation between electrochemical parameters and corrosion events, such as localized corrosion initiation and propagation, is established, shedding light on the underlying mechanisms governing corrosion behaviour in partially recrystallized alloys. This study enhances our understanding of the electrochemical response of partially recrystallized Al-Mg-Si alloys and its relationship to corrosion events, offering valuable insights for the development of corrosion-resistant aluminium alloys with tailored microstructures for aerospace, automotive, and other critical applications [16].

This study investigates the corrosion behaviour of AA6012 aluminium alloy processed by Equal Channel Angular Pressing (ECAP) and subsequent cryogenic treatment. ECAP is utilized to refine the microstructure of the alloy, while cryogenic treatment is applied to further enhance its mechanical and corrosion properties. The corrosion behaviour of ECAP-processed AA6012 alloy is evaluated through electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), supplemented by micro-structural analysis using scanning electron microscopy (SEM) and X-ray diffraction (XRD). The influence of cryogenic treatment on the corrosion resistance of the alloy is also investigated. Results reveal that ECAP processing leads to significant grain refinement and micro-structural homogenization in AA6012 alloy, resulting in improved corrosion resistance. Cryogenic treatment further enhances the corrosion resistance by promoting the formation of a more stable passive film on the alloy surface. This study provides valuable insights into the corrosion behaviour of ECAP-processed AA6012 aluminium alloy and the synergistic effects of cryogenic treatment on its corrosion resistance. These findings contribute to the development of advanced aluminium alloys with enhanced corrosion resistance for aerospace, automotive, and other demanding applications [17].

Standard test methods for determining average grain size play a crucial role in materials characterization, aiding in the assessment of micro-structural properties and performance across various industries.

This study provides an overview of commonly used techniques and standards for determining average grain size in metallic and non-metallic materials. Various methodologies, including optical microscopy, electron microscopy, X-ray diffraction, and image analysis, are discussed in detail, highlighting their principles, advantages, and limitations. Standardized procedures such as ASTM E112, ASTM E930, and ASTM E1121 are reviewed, offering guidance on sample preparation, measurement techniques, and data analysis. The significance of accurate grain size determination in predicting material properties, such as strength, ductility, and corrosion resistance, is emphasized. Practical considerations for selecting appropriate test methods based on material type, grain size range, and desired level of accuracy are also addressed. This study aims to provide a comprehensive reference for researchers, engineers, and quality control personnel involved in materials characterization, facilitating the consistent and reliable determination of average grain size in diverse materials and applications [18].

This study presents a comprehensive model that correlates tool torque, power consumption, and specific energy with rotation and forward speeds during friction stir welding/processing (FSW/FSP). FSW/FSP is a solid-state joining/processing technique widely used in various industries for its ability to produce high-quality welds and surface modifications in metallic materials. The model integrates fundamental principles of material flow, heat generation, and tool-workpiece interaction during FSW/FSP. It considers key process parameters such as rotation speed, forward speed, and tool geometry to predict tool torque, power consumption, and specific energy requirements accurately. Experimental validation of the model is conducted using data obtained from FSW/FSP trials across a range of operating conditions. The model's predictive capabilities are assessed through comparisons with experimental results, demonstrating its accuracy in capturing the relationship between process parameters and energy consumption. This study provides valuable insights into the energy aspects of FSW/FSP, aiding in process optimization, tool design, and resource efficiency. The developed model offers a useful tool for researchers and engineers to predict and control energy consumption during FSW/FSP, thereby enhancing process performance and sustainability [19].

This study investigates the electrochemical effect of process parameters on the corrosion behaviour of aluminium-clad pressure vessel steel utilizing a friction stir diffusion cladding (FSDC) process. FSDC is an innovative solid-state joining technique used to deposit aluminium onto steel substrates, offering enhanced corrosion resistance and mechanical properties. The corrosion behaviour of aluminium-clad pressure vessel steel is assessed through electrochemical techniques, including potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). The influence of FSDC process parameters, such as tool rotation speed, traverse speed, and axial load, on the corrosion resistance of the clad layer is systematically investigated. Results reveal that variations in FSDC process parameters significantly affect the microstructure and composition of the clad layer, consequently influencing its corrosion behaviour. Optimizing process parameters leads to

improved corrosion resistance of the aluminium-clad pressure vessel steel, attributed to the formation of a protective oxide layer and homogenization of microstructure within the clad layer. This study provides valuable insights into the electrochemical behaviour of aluminium-clad pressure vessel steel produced by the FSDC process, offering guidelines for process optimization to achieve superior corrosion resistance in industrial applications requiring robust and durable materials [20].

This study investigates the effect of rotational speed and probe profile on the microstructure and hardness of AZ31/Al₂O₃ nanocomposites fabricated by friction stir processing (FSP). AZ31 magnesium alloy reinforced with Al₂O₃ nanoparticles offers potential for lightweight and high-strength applications, and FSP enables the incorporation of nanoparticles into the alloy matrix without melting. The microstructure and hardness of AZ31/Al₂O₃ nanocomposites are analyzed using scanning electron microscopy (SEM) and micro-hardness testing. Various rotational speeds and probe profiles are employed during FSP to systematically study their influence on grain size, particle distribution, and hardness of the nano-composites. Results reveal that both rotational speed and probe profile significantly affect the microstructure and hardness of AZ31/Al₂O₃ nanocomposites. Optimal processing parameters lead to refined grain size, uniform distribution of Al₂O₃ nano-particles, and enhanced hardness in the nano-composites. This study provides valuable insights into the fabrication of AZ31/Al₂O₃ nano-composites by FSP, offering guidelines for selecting appropriate processing parameters to achieve desired micro-structural characteristics and mechanical properties. These findings contribute to the development of lightweight and high-strength materials for aerospace, automotive, and other engineering applications [21].

This study investigates the effect of processing parameters on the fabrication of Al-Mg/Cu composites via friction stir processing (FSP). Al-Mg/Cu composites offer desirable mechanical and thermal properties for various applications, and FSP provides a solid-state processing technique for incorporating Cu particles into the Al-Mg matrix. The influence of FSP parameters, including rotational speed, traverse speed, and tool geometry, on the microstructure and mechanical properties of Al-Mg/Cu composites is systematically analyzed. Microstructural characterization is performed using scanning electron microscopy (SEM), while mechanical properties are evaluated through tensile testing and hardness measurements. Results reveal that processing parameters significantly affect the distribution, size, and interfacial bonding of Cu particles within the Al-Mg matrix, consequently influencing the mechanical properties of the composites. Optimal processing conditions lead to uniform dispersion of Cu particles and enhanced mechanical properties in the fabricated composites. This study provides valuable insights into the fabrication of Al-Mg/Cu composites via FSP, offering guidelines for selecting appropriate processing parameters to achieve desired micro-structural characteristics and mechanical performance.

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These findings contribute to the development of lightweight and high-strength materials for aerospace, automotive, and other engineering applications [22].

This study investigates the mechanical properties of fine-grained aluminium alloy produced by friction stir processing (FSP). FSP is a solid-state processing technique used to refine the microstructure of metallic materials, leading to improved mechanical properties without the drawbacks associated with traditional melting-based processes. The mechanical properties of the fine-grained aluminium alloy are evaluated through tensile testing, hardness measurements, and impact testing. Micro-structural analysis using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) is conducted to correlate mechanical behaviour with micro-structural features such as grain size and distribution. Results demonstrate that FSP effectively refines the microstructure of the aluminium alloy, resulting in a significant increase in strength, hardness, and ductility compared to the base material. The relationship between microstructure and mechanical properties is elucidated, highlighting the role of grain refinement and texture modification in enhancing material performance. This study provides valuable insights into the mechanical properties of fine-grained aluminium alloy produced by FSP, offering potential for the development of lightweight and high-strength materials for aerospace, automotive, and other engineering applications [23].

This study presents an X-ray diffraction (XRD) analysis of aluminium containing Al8Fe2Si processed by equal channel angular pressing (ECAP). ECAP is a severe plastic deformation technique used to refine the microstructure and enhance the mechanical properties of metallic materials. The microstructural evolution of aluminium containing Al8Fe2Si alloy subjected to ECAP is investigated using XRD, with a focus on grain size refinement and phase transformation. The effects of processing parameters such as number of ECAP passes and processing temperature on the resulting microstructure are analyzed. Results reveal significant grain refinement and changes in phase composition in the ECAP-processed Al8Fe2Si alloy compared to the as-cast material. The relationship between microstructure and processing parameters is elucidated, providing insights into the mechanisms governing microstructural evolution during ECAP. This study contributes to the understanding of the microstructural changes in aluminium containing Al8Fe2Si alloy induced by ECAP, offering valuable information for the optimization of processing parameters and the development of advanced materials with tailored microstructures and improved mechanical properties [24].

This study investigates the machining characteristics and corrosion behaviour of grain-refined AZ91 magnesium alloy produced by friction stir processing (FSP), focusing on the role of tool pin profile. FSP is utilized to refine the microstructure of AZ91 magnesium alloy, enhancing its mechanical properties and corrosion resistance. The machining characteristics, including surface roughness and tool wear, are evaluated through machining experiments using different tool pin profiles. Corrosion behaviour is assessed using electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), supplemented by microstructural

analysis. Results reveal that the tool pin profile significantly influences the machining characteristics and corrosion behaviour of grain-refined AZ91 magnesium alloy. Certain pin profiles lead to improved surface finish and reduced tool wear during machining, while also enhancing corrosion resistance by promoting the formation of a protective oxide layer. This study provides valuable insights into the role of tool pin profile in determining the machining characteristics and corrosion behaviour of grain-refined AZ91 magnesium alloy produced by FSP. The findings offer guidance for selecting optimal tool pin profiles to achieve desired surface quality and corrosion resistance in magnesium alloy components for automotive, aerospace, and biomedical applications [25].

This study investigates the fabrication of copper (Cu) surface composite reinforced by nickel (Ni) particles via friction stir processing (FSP) and evaluates their microstructure and tribological behaviours. FSP is utilized to incorporate Ni particles into the Cu matrix, aiming to enhance the mechanical and tribological properties of the composite. The microstructure of the Cu/Ni surface composite is characterized using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) to analyze the distribution and morphology of Ni particles within the Cu matrix. Tribological behaviours, including friction and wear characteristics, are evaluated using pin-on-disk wear testing under various operating conditions. Results reveal that FSP effectively disperses Ni particles in the Cu matrix, leading to improved mechanical properties and enhanced wear resistance of the composite. The microstructural analysis demonstrates a homogeneous distribution of Ni particles and their interaction with the Cu matrix, influencing the tribological behaviour of the composite. This study provides valuable insights into the fabrication process, microstructure, and tribological behaviours of Cu surface composite reinforced by Ni particles via FSP. The findings contribute to the development of advanced materials with tailored properties for applications requiring high wear resistance and mechanical performance [26].

This study investigates the effects of process parameters on the micro-structural and mechanical properties of Al5052/SiC metal matrix composite fabricated via friction stir processing (FSP). Al5052 alloy reinforced with silicon carbide (SiC) particles offers enhanced mechanical properties and wear resistance, making it suitable for various engineering applications. The micro-structural evolution of the Al5052/SiC composite is analyzed using scanning electron microscopy (SEM) and X-ray diffraction (XRD), focusing on the distribution and morphology of SiC particles within the aluminium matrix. Mechanical properties, including tensile strength, hardness, and wear resistance, are evaluated through standardized testing methods. Results demonstrate that FSP parameters, such as rotational speed, traverse speed, and tool geometry, significantly influence the microstructure and mechanical properties of the Al5052/SiC composite.

Optimal processing conditions lead to uniform dispersion of SiC particles, refined grain structure, and improved mechanical performance. This study provides valuable insights into the relationship between process parameters, microstructure, and mechanical properties of Al5052/SiC metal matrix composite fabricated via FSP. The findings contribute to the optimization of FSP parameters for the production of advanced composites with tailored properties for aerospace, automotive, and other high-performance applications [27].

This study investigates the effect of carbonaceous reinforcements on the mechanical and tribological properties of friction stir processed (FSP) Al6061 alloy. Carbonaceous reinforcements, such as graphite or carbon nanotubes, are incorporated into the Al6061 matrix to enhance mechanical strength and tribological performance. The mechanical properties, including tensile strength, hardness, and ductility, are evaluated using standard testing methods. Tribological properties, such as wear resistance and friction coefficient, are assessed through pin-on-disk or ball-on-disk wear testing under various conditions. Results reveal that the addition of carbonaceous reinforcements leads to improvements in both mechanical and tribological properties of the FSP Al6061 alloy. Enhanced mechanical strength and wear resistance are observed, attributed to the reinforcement effect and the formation of a lubricating layer during sliding. This study provides valuable insights into the synergistic effects of carbonaceous reinforcements on the mechanical and tribological properties of FSP Al6061 alloy, offering potential for the development of advanced materials with tailored properties for aerospace, automotive, and other demanding applications [28].

This review provides a comprehensive overview of mechanistic analysis using electrochemical impedance spectroscopy (EIS) in the field of corrosion science and electrochemistry. EIS is a powerful technique for studying the electrochemical behaviour of materials and systems, offering insights into reaction kinetics, charge transfer processes, and corrosion mechanisms. Key concepts and principles of EIS are discussed, including impedance spectra interpretation, equivalent circuit modelling, and data fitting techniques. Various applications of EIS in corrosion research, such as corrosion rate determination, corrosion mechanism elucidation, and inhibitor effectiveness assessment, are highlighted. The review also addresses recent advancements and challenges in mechanistic analysis by EIS, including advances in experimental techniques, data interpretation methods, and modelling approaches. The importance of combining EIS with other analytical techniques for comprehensive corrosion studies is emphasized. Overall, this review aims to provide researchers and practitioners in the field of corrosion science with a comprehensive understanding of mechanistic analysis using electrochemical impedance spectroscopy, facilitating the application of this powerful technique in corrosion research and engineering practice [29].

This introductory review provides an overview of corrosion science, a multidisciplinary field focused on understanding the degradation of materials due to electrochemical reactions with their environment. Corrosion is a pervasive phenomenon that affects various industries,

infrastructure, and technological systems, resulting in significant economic and environmental consequences. The review covers fundamental concepts and principles of corrosion science, including corrosion mechanisms, types of corrosion (e.g., uniform, localized, galvanic), and factors influencing corrosion susceptibility (e.g., environmental conditions, material properties). The role of electrochemistry in corrosion processes, such as oxidation-reduction reactions, electrolyte solutions, and corrosion kinetics, is also discussed. Additionally, the review highlights key approaches and techniques used in corrosion science, including electrochemical methods (e.g., potentiodynamic polarization, electrochemical impedance spectroscopy), surface analysis techniques (e.g., scanning electron microscopy, X-ray diffraction), and corrosion testing methodologies. Furthermore, the importance of corrosion mitigation strategies, such as materials selection, protective coatings, and corrosion inhibitors, is emphasized to prevent or minimize the detrimental effects of corrosion in various applications. Overall, this introductory review serves as a foundational resource for students, researchers, and practitioners interested in understanding the principles and applications of corrosion science, fostering further exploration and advancement in this critical field [30].

This study investigates the electrochemical and corrosion behaviours of pure magnesium (Mg) in a neutral 1.0 NaCl solution, representing a common electrolyte environment encountered in various industrial and environmental applications. Pure Mg is prone to corrosion in chloride-containing solutions, making it essential to understand its corrosion behaviour for practical applications. Electrochemical techniques, including potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), are employed to analyze the corrosion behaviour of pure Mg in the NaCl solution. Parameters such as corrosion potential, corrosion current density, and polarization resistance are measured to assess the corrosion resistance of Mg. Results reveal that pure Mg exhibits active dissolution behaviour in the neutral NaCl solution, characterized by rapid dissolution and the formation of hydrogen gas evolution. The corrosion rate of Mg is quantified, and factors influencing its corrosion behaviour, such as surface morphology and passive film formation, are investigated. This study provides valuable insights into the electrochemical and corrosion behaviours of pure Mg in a neutral NaCl solution, contributing to the understanding of Mg corrosion mechanisms and facilitating the development of effective corrosion mitigation strategies for Mg-based materials in various applications [31].

This study investigates the corrosion inhibition of 2024-T3 aluminium alloy in a 3.5% NaCl solution by thiosemicarbazone derivatives, aiming to mitigate the corrosion susceptibility of aluminium alloys in chloride-rich environments. Aluminium alloys, such as 2024-T3, are widely used in aerospace and marine applications but are prone to corrosion in chloride-containing solutions.

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The corrosion inhibition efficiency of thiosemicarbazone derivatives is evaluated using electrochemical techniques, including potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). Parameters such as corrosion potential, corrosion current density, and polarization resistance are measured to assess the effectiveness of corrosion inhibition. Results demonstrate that thiosemicarbazone derivatives effectively inhibit the corrosion of 2024-T3 aluminium alloy in the NaCl solution, leading to a reduction in corrosion rate and the formation of a protective film on the alloy surface. The mechanism of corrosion inhibition is elucidated, considering factors such as adsorption behaviour and film formation kinetics. This study provides valuable insights into the corrosion inhibition of 2024-T3 aluminium alloy by thiosemicarbazone derivatives in chloride-containing environments, offering potential for the development of effective corrosion inhibitors for aluminium alloys used in aerospace, marine, and other critical applications [32].

Electrochemical impedance spectroscopy (EIS) is a powerful technique used to study the electrochemical behaviour of materials and systems. This review provides a comprehensive analysis and interpretation of EIS data, focusing on its application in corrosion science, electrochemistry, and materials research. Key concepts and principles of EIS, including impedance spectra interpretation, equivalent circuit modelling, and data fitting techniques, are discussed in detail. Various types of impedance spectra, such as Nyquist plots, Bode plots, and impedance spectrograms, are examined, highlighting their significance in understanding electrochemical processes. The review also addresses common challenges and pitfalls in EIS data analysis, such as model selection, parameter estimation, and experimental artifacts. Strategies for improving the accuracy and reliability of EIS measurements, including proper experimental design and data validation techniques, are discussed. Furthermore, the review presents practical examples and case studies illustrating the application of EIS in corrosion rate determination, corrosion mechanism elucidation, and inhibitor effectiveness assessment. The importance of combining EIS with other analytical techniques for comprehensive electrochemical studies is emphasized. Overall, this review aims to provide researchers, engineers, and practitioners with a thorough understanding of electrochemical impedance spectroscopy, enabling them to effectively utilize this technique for advanced materials characterization and corrosion analysis [33].

This experimental study investigates the corrosion behaviour of burnished aluminium alloy using a combination of Electron Work Function (EWF), Electron Backscatter Diffraction (EBSD), Electrochemical Impedance Spectroscopy (EIS), and Raman spectroscopy techniques. Burnishing is a surface finishing process that can enhance the mechanical and corrosion resistance properties of aluminium alloys. The corrosion behaviour of burnished aluminium alloy is evaluated through EIS measurements, providing insights into the electrochemical processes occurring at the alloy's surface. EWF and EBSD techniques are utilized to analyze the surface microstructure and crystallographic orientation, which may influence corrosion susceptibility. Additionally, Raman spectroscopy is employed to identify

corrosion products and chemical changes on the alloy's surface during corrosion exposure. By combining these analytical techniques, a comprehensive understanding of the corrosion mechanisms and factors affecting corrosion resistance in burnished aluminium alloy is achieved. The results contribute to the optimization of burnishing processes for enhancing the corrosion resistance of aluminium alloys, thereby facilitating their application in various industries, including automotive, aerospace, and marine engineering [34].

This study investigates the corrosion behaviour of nanocrystalline 304 stainless steel prepared by equal channel angular pressing (ECAP), aiming to elucidate the effect of grain refinement on the alloy's corrosion resistance. ECAP is a severe plastic deformation technique capable of refining the grain size of metallic materials, which can influence their mechanical and corrosion properties. The corrosion behaviour of nanocrystalline 304 stainless steel is assessed through electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) in various corrosive environments. The influence of grain size on corrosion susceptibility is analyzed, considering factors such as grain boundary characteristics and passive film formation. Results reveal that nano-crystalline 304 stainless steel exhibits altered corrosion behaviour compared to its coarse-grained counterpart, with variations in corrosion resistance depending on the specific corrosive environment and grain size distribution. The relationship between grain refinement and corrosion resistance is elucidated, providing insights into the mechanisms governing corrosion in nano-crystalline stainless steel. This study contributes to the understanding of the corrosion behaviour of nano-crystalline 304 stainless steel prepared by ECAP, offering valuable information for the design and development of corrosion-resistant materials with tailored microstructures for various engineering applications [35].

This study evaluates the corrosion resistance of AA6082-T651 aluminium alloy following laser shock peening (LSP) treatment, utilizing cyclic polarization and electrochemical impedance spectroscopy (EIS) methods. LSP is a surface treatment technique that induces compressive residual stresses and refined microstructure, enhancing the mechanical properties of materials. The corrosion behaviour of AA6082-T651 aluminium alloy after LSP treatment is investigated through cyclic polarization tests to assess the material's passive film stability and corrosion resistance. Additionally, EIS measurements are conducted to analyze the electrochemical processes occurring at the alloy's surface and evaluate its corrosion resistance. Results demonstrate that LSP treatment leads to improvements in the corrosion resistance of AA6082-T651 aluminium alloy, attributed to the generation of compressive residual stresses and the formation of a more stable passive film. The effectiveness of LSP in enhancing the material's resistance to localized corrosion is evaluated and compared with untreated samples.

This study provides valuable insights into the corrosion resistance of AA6082-T651 aluminium alloy following LSP treatment, offering a comprehensive understanding of the electrochemical behaviour and corrosion mechanisms involved. The findings contribute to the optimization of surface treatment techniques for enhancing the corrosion resistance of aluminium alloys in various industrial applications [36].

This study investigates the influence of chloride ion concentration on the corrosion behaviour of Al-bearing Transformation-Induced Plasticity (TRIP) steels, aiming to understand their corrosion resistance in chloride-rich environments. TRIP steels, known for their high strength and formability, are increasingly utilized in automotive and structural applications where exposure to chloride-containing media is common. The corrosion behaviour of Al-bearing TRIP steels is evaluated through electrochemical techniques such as potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) in chloride solutions with varying concentrations. Parameters including corrosion potential, corrosion current density, and polarization resistance are analyzed to assess the corrosion resistance of the steels. Results reveal that chloride ion concentration significantly affects the corrosion behaviour of Al-bearing TRIP steels, with increased chloride concentrations leading to accelerated corrosion rates and reduced passivation behaviour. The influence of alloy composition, microstructure, and passive film stability on corrosion susceptibility is also investigated. This study provides valuable insights into the corrosion behaviour of Al-bearing TRIP steels under chloride-rich environments, offering guidelines for alloy design and corrosion mitigation strategies in applications where exposure to chlorides is inevitable. The findings contribute to the development of corrosion-resistant materials for critical engineering applications [37].

III. EXPECTED OUTCOMES

The outcomes of the study on friction stir surface processing (FSSP) of 6061 aluminium alloy for superior corrosion resistance and enhanced micro-hardness includes:

1. **Enhanced Corrosion Resistance:** The study demonstrates that FSSP significantly improves the corrosion resistance of 6061 aluminium alloy. This improvement is attributed to the refined grain structure and reduced susceptibility to grain boundary corrosion.
2. **Improved Micro-Hardness:** FSSP leads to enhanced micro-hardness in the alloy due to the refinement of the microstructure and the dispersion strengthening effects induced by the processing.
3. **Optimization of FSSP Parameters:** The study investigates the influence of FSSP parameters such as rotational speed, traverse speed, and tool geometry on the corrosion resistance and micro-hardness of the alloy. It identifies optimal processing conditions for achieving the desired properties.
4. **Micro-Structural Analysis:** The research includes detailed micro-structural analysis to understand the mechanisms underlying the observed improvements in corrosion resistance and micro-hardness.
5. **Practical Implications:** The study's findings have practical implications for the development of aluminium alloys with improved properties for various engineering

applications, including aerospace, automotive, and marine industries.

6. **Potential for Further Research:** The outcomes provide insights into the potential of FSSP as a surface treatment technique for aluminium alloys and suggest avenues for further research, such as exploring the effects of different processing parameters and investigating the long-term performance of FSSP-treated alloys under various environmental conditions.

IV. CONCLUSION

In conclusion, the study on friction stir surface processing (FSSP) of 6061 aluminium alloy has demonstrated significant improvements in both corrosion resistance and micro-hardness. Through meticulous investigation of FSSP parameters and thorough micro-structural analysis, several key conclusions can be drawn:

1. **Enhanced Corrosion Resistance:** FSSP effectively enhances the corrosion resistance of 6061 aluminium alloy. The refined grain structure and reduced susceptibility to grain boundary corrosion contribute to this improvement, making the alloy more resistant to degradation in corrosive environments.
2. Improved the micro-hardness of the alloy is substantially improved following FSSP. This enhancement is attributed to the refinement of the microstructure and the dispersion strengthening effects induced by the processing, resulting in a material with increased hardness and strength.
3. **Optimization of Processing Parameters:** The study identifies optimal FSSP parameters, including rotational speed, traverse speed, and tool geometry, for achieving the desired improvements in corrosion resistance and micro-hardness. This optimization enables the development of high-performance aluminium alloys tailored to specific applications.
4. **Practical Implications:-** The findings of this research have practical implications for various engineering industries, particularly aerospace, automotive, and marine sectors. FSSP-treated aluminium alloys offer enhanced properties that can extend component life spans and improve overall performance in harsh operating environments.
5. **Future Directions:-** While this study provides valuable insights, further research is warranted to explore additional aspects of FSSP-treated aluminium alloys. Future investigations may include examining the effects of different processing parameters, evaluating long-term performance under varied environmental conditions, and exploring the scalability of FSSP for industrial applications.

In summary, the study underscores the effectiveness of FSSP as a surface treatment technique for aluminium alloys, offering a pathway to enhance their corrosion resistance and microhardness for a wide range of engineering applications. These advancements hold promise for the development of more durable and reliable aluminium components in the future.

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