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

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***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 stirring a rotating tool across the alloy's surface, inducing plastic deformation and refining the microstructure. The study examines the influence of FSSP parameters, including rotational speed, traverse speed, and tool geometry, on the corrosion resistance and microhardness 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 melting processes. Among the various aluminium alloys, 6061 aluminium alloy holds particular significance due to its widespread use 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.

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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 improve corrosion resistance and micro-hardness simultaneously. By subjecting the alloy to controlled mechanical deformation and heat input, it undergoes microstructural refinement, introducing beneficial changes at the surface.

In this topic, we provide an overview of the principles of FSSP, highlighting its advantages and applications in modifying the surface of aluminium alloys. We have also discussed the specific properties of 6061 aluminium alloy that make it a suitable candidate for FSSP and outlined 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 the 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 examines the effect of post-weld heat treatment (PWHT) on the microstructure and mechanical properties of welded joints produced from 6061-T6 aluminium alloy.

Welded joints are subjected to various thermal cycles during fabrication, resulting in changes to their microstructure and mechanical properties that can impact 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/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 a desirable choice 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 phase distribution within the composite material, resulting in enhanced 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 polarisation and electrochemical impedance spectroscopy (EIS), supplemented by microstructural 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 utilised to achieve significant grain refinement in the alloy, resulting in 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].

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 tenets 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, including rotational speed, traverse speed, and tool geometry, are examined for their impact on microstructural 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, including hybrid processes that combine FSP with other techniques, improvements in tool materials and designs, and numerical modelling for process optimisation, 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 localised corrosion initiation sites, resulting in 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].

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 recognised for its ability to refine the microstructure and enhance 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 polarisation and electrochemical impedance spectroscopy (EIS), along with surface characterisation 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 that lead to improved corrosion resistance are identified, considering factors such as grain refinement, microstructural homogeneity, and the 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][12].

This study presents a comprehensive investigation into the microstructural characterisation 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 examines the simultaneous enhancement of mechanical strength, ductility, and corrosion resistance in stir-cast Al7075-2% SiC micro- and nanocomposites via friction stir processing (FSP). Al7075 alloy is renowned for its high strength, but it has limited ductility and corrosion resistance. The addition of SiC nanoparticles offers potential for improving these properties. 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, including potentiodynamic polarisation 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 examines the impact of reduced surface grain structure and enhanced 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 using electrochemical techniques, such as potentiodynamic polarisation and electrochemical impedance spectroscopy (EIS), supplemented by microstructural analysis via 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 offers insights into the electrochemical response of a partially recrystallised Al-Mg-Si alloy and its correlation with corrosion events. Partial recrystallisation is induced in the alloy to investigate its influence on corrosion behaviour, considering the complex microstructural evolution associated with recrystallisation processes. Electrochemical techniques, such as potentiodynamic polarisation and electrochemical impedance spectroscopy (EIS), are employed to evaluate the corrosion behaviour of the partially recrystallised 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 recrystallised Al-Mg-Si alloy is influenced by the extent of recrystallisation, grain size distribution, and the presence of precipitates. A correlation between electrochemical parameters and corrosion events, such as localised corrosion initiation and propagation, is established, shedding light on the underlying mechanisms governing corrosion behaviour in partially recrystallised alloys. This study enhances our understanding of the electrochemical response of partially recrystallized Al-Mg-Si alloys and their 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 used to refine the microstructure of the alloy, while cryogenic treatment is applied to enhance its mechanical and corrosion properties further. The corrosion behaviour of ECAP-processed AA6012 alloy is evaluated through electrochemical techniques, including potentiodynamic polarisation and electrochemical impedance spectroscopy (EIS), supplemented by microstructural 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.

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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. Standardised procedures, such as ASTM E112, ASTM E930, and ASTM E1121, are reviewed to guide sample preparation, measurement techniques, and data analysis. The significance of accurately determining grain size in predicting material properties, such as strength, ductility, and corrosion resistance, is emphasised. Practical considerations for selecting appropriate test methods, based on material type, grain size range, and the 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 and processing (FSW/FSP). FSW/FSP is a solid-state joining and 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 accurately predict tool torque, power consumption, and specific energy requirements. 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 offers valuable insights into the energy aspects of FSW/FSP, facilitating process optimisation, tool design, and resource efficiency. The developed model provides a valuable 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-cladded 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-cladded 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. Optimising 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 the microstructure within the clad layer. This study provides valuable insights into the electrochemical behaviour of aluminium-cladded 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 influence of rotational speed and probe profile on the microstructure and hardness of AZ31/Al2O3 nanocomposites produced via 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 nano-composites. Optimal processing parameters yield a refined grain size, a uniform distribution of Al2O3 nanoparticles, and an enhanced hardness in the nanocomposites. This study offers valuable insights into the fabrication of AZ31/Al2O3 nanocomposites via FSP, providing guidelines for selecting suitable processing parameters to achieve the desired microstructural 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 examines the impact of processing parameters on the fabrication of Al-Mg/Cu composites through 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 yield the uniform dispersion of Cu particles and enhance the mechanical properties of 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. Microstructural analysis using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) is conducted to correlate mechanical behaviour with microstructural 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 an aluminium alloy containing Al8Fe2Si, subjected to ECAP, is investigated using XRD, with a focus on grain size refinement and phase transformation. The effects of processing parameters, such as the number of ECAP passes and processing temperature, on the resulting microstructure are analysed. 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 the 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 has a significant influence on the machining characteristics and corrosion behaviour of grain-refined AZ91 magnesium alloy. Specific pin profiles result in an 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 the 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 a copper (Cu) surface composite reinforced by nickel (Ni) particles via friction stir processing (FSP) and evaluates its microstructure and tribological behaviour. 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 characterised using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) to analyse 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 reveals a homogeneous distribution of Ni particles and their interaction with the Cu matrix, which influences 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 influence of process parameters on the microstructural and mechanical properties of Al5052/SiC metal matrix composites produced 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 microstructural evolution of the Al5052/SiC composite is analysed using scanning electron microscopy (SEM) and X-ray diffraction (XRD), with a focus 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.


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Optimal processing conditions yield a uniform dispersion of SiC particles, a 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 aluminium 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 the sliding process. 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 the interpretation of impedance spectra, equivalent circuit modelling, and data fitting techniques. Various applications of EIS in corrosion research, including the determination of corrosion rates, elucidation of corrosion mechanisms, and assessment of inhibitor effectiveness, 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 thorough 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 encompasses fundamental concepts and principles of corrosion science, including corrosion mechanisms, various types of corrosion (e.g., uniform, localised, and galvanic), and factors that influence corrosion susceptibility (e.g., environmental conditions and 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 material selection, protective coatings, and corrosion inhibitors, is emphasised to prevent or minimise 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 familiar 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 polarisation and electrochemical impedance spectroscopy (EIS), are employed to analyse the corrosion behaviour of pure Mg in a NaCl solution. Parameters such as corrosion potential, corrosion current density, and polarisation resistance are measured to evaluate the corrosion resistance of magnesium (Mg). Results reveal that pure Mg exhibits active dissolution behaviour in neutral NaCl solution, characterised by rapid dissolution and the evolution of hydrogen gas. 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.

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 offers a comprehensive analysis and interpretation of EIS data, with a focus on its applications 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, including model selection, parameter estimation, and experimental artefacts. 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 that illustrate the application of EIS in determining corrosion rates, elucidating corrosion mechanisms, and assessing the effectiveness of inhibitors. 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 employed to analyse the surface microstructure and crystallographic orientation, which can influence corrosion susceptibility. Additionally, Raman spectroscopy is used to identify corrosion products and chemical changes on the alloy's surface during exposure to corrosion. 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 that can refine the grain size of metallic materials, thereby influencing their mechanical and corrosion properties. The corrosion behaviour of nanocrystalline 304 stainless steel is assessed through electrochemical techniques, including potentiodynamic polarisation and electrochemical impedance spectroscopy (EIS), in various corrosive environments. The influence of grain size on corrosion susceptibility is analysed, considering factors such as grain boundary characteristics and the formation of passive films. 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 a 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 localised corrosion is evaluated and compared with that of 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 everyday. The corrosion behaviour of Al-bearing TRIP steels is evaluated using electrochemical techniques, including potentiodynamic polarisation and electrochemical impedance spectroscopy (EIS), in chloride solutions with varying concentrations. Parameters, including corrosion potential, corrosion current density, and polarisation resistance, are analysed 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. **Optimisation of FSSP Parameters: The study examines the impact of FSSP parameters, including rotational speed, traverse speed, and tool geometry, on the corrosion resistance and microhardness** 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. 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. **Optimisation of Processing Parameters:** The study identifies optimal FSSP parameters, including rotational speed, traverse speed, and tool geometry, to achieve the desired improvements in corrosion resistance and microhardness. 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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