TRIBOLOGICAL AND SALT WATER CORROSION BEHAVIOR OF DISSIMILAR ALLOY WELDING USING FRICTION STIR WELDING

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MASTER OF MANUFACTURING ENGINEERING
(MANUFACTURING SYSTEM ENGINEERING)

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faculty of Industrial and Manufacturing Technology and Engineering

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A master project submitted
in partial fulfillment of the requirements for the degree of
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DECLARATION

I declare that this master project entitled “Tribological And Salt Water Corrosion Behavior Of Dissimilar Alloy Welding Using Friction Stir Welding“ is the result of my own research except as cited in the references. The master project has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :..

Name : SITI HARISHAH BINTI AZMAN

Date : 21st July 2024

APPROVAL

I hereby declare that I have read this master project and in my opinion this master project is sufficient in terms of scope and quality as a partial fulfillment of Master of Manufacturing Engineering (Manufacturing System Engineering)

Signature :..

Supervisor Name : DR.Muhammad Zaimi Bin Zainal Abidin

Date :..

DEDICATION

To my beloved mother, Zabedah binti Bahar, whose unwavering love, support, and encouragement have been the guiding light throughout my life and academic journey. Your strength, wisdom, and selfless sacrifices have inspired me to pursue my dreams and reach for excellence.

To my dear husband, Shahrizwal bin Yakkop, my rock and partner in life. Your constant love, understanding, and belief in me have been my source of motivation and strength. Thank you for standing by my side through the challenges and triumphs of this master's program.

To my precious children, Harraz Shahmie bin Shahrizwal, Hifwat Shafi bin Shahrizwal, and Haura Raisha Safwa binti Shahrizwal, you are the joy and pride of my life. Your smiles, hugs, and innocent love have been my greatest comfort and inspiration. I hope this achievement will inspire you to always pursue knowledge and follow your passions.

I dedicate this master's project report to all of you, my beloved family. Your love, sacrifices, and unwavering support have been the foundation upon which I have been the bedrock upon which i have built my academic career as a master's student in manufacturing engineering (manufacturing system engineering). From an early age, you imparted in me the value of education and engendered a curiosity about technology and systems. I would not have attained my current knowledge and skills without everything you have done for me. Please accept my deepest gratitude for assisting me in arriving at this milestone and for always being my unshakable foundation. This is for you with abiding admiration and affection.

ABSTRACT

Friction stir welding (FSW) is a solid-state joining process that offers significant advantages in efficiency, cost-effectiveness, and environmental impact compared to traditional fusion welding techniques. This study focuses on the tribological and saltwater corrosion behavior of dissimilar aluminum alloy AA5052 and AA6061 welded joints produced using FSW, which are commonly used in marine applications due to their mechanical properties and corrosion resistance. The primary objective of this project was to comprehensively characterize the microstructure, mechanical properties, wear resistance, and corrosion behavior of dissimilar AA5052-AA6061 FSW joints. Various characterization techniques, including field-emission scanning electron microscopy (FESEM) and energy-dispersive X-ray spectroscopy (EDX), tensile testing, microhardness mapping, reciprocating pin-on-disk wear tests, and linear sweep voltammetry (LSV), were employed to evaluate these properties. The results revealed that the dissimilar FSW joints exhibited unique microstructural developments along the bond line, leading to higher tensile strength and ductility compared to similar alloy joints. The tensile strength of the dissimilar joints was slightly higher, but they demonstrated lower wear resistance due to the formation of intermetallic compounds, such as Al_3Mg_2, at the weld interface. Corrosion testing indicated that the dissimilar joints had a lower overall corrosion rate but were susceptible to localized galvanic corrosion at the interface. This susceptibility was attributed to changes in composition and the formation of a passive oxide film, which dissolved at approximately -0.6V. The microstructural analysis showed significant differences between the similar and dissimilar joints. The similar AA6061 joints exhibited a uniform and defect-free surface with fine grains, whereas the dissimilar AA6061-AA5052 joints displayed distinct regions corresponding to each alloy with a well-bonded interface. The EDX analysis provided insights into the elemental distribution, revealing a gradual transition in composition across the weld interface for the dissimilar joints, indicating effective material mixing during the FSW process. The mechanical testing results highlighted the superior performance of the dissimilar joints in terms of tensile strength and ductility. However, the wear testing results indicated that the dissimilar joints had lower wear resistance compared to the similar joints, which could be attributed to the formation of intermetallic compounds at the weld interface. The corrosion testing using LSV showed that while the dissimilar joints had a lower overall corrosion rate, they were more susceptible to localized galvanic corrosion due to the differences in composition and the formation of a passive oxide film. This project provides critical insights into optimizing FSW parameters to mitigate corrosion challenges and enhance the mechanical performance of dissimilar aluminum alloy joints. The findings have significant implications for the development of lightweight, corrosion-resistant marine structures, contributing to improved reliability and durability in harsh marine environments. The insights gained from this research are expected to inform future advancements in the field, addressing both performance and durability in practical applications.

TRIBOLOGI DAN SIFAT KARAT BERUNSURKAN AIR GARAM TERHADAP ALOI BERLAINAN JENIS DENGAN MENGGUNAKAN KIMPALAN KACAU GESERAN (FSW)

ABSTRAK

Kimpalan kacau geseran (FSW) ialah proses penyambungan keadaan pepejal yang menawarkan kelebihan ketara dalam kecekapan, penjimatan kos dan tidak memberi kesan alam sekitar berbanding teknik kimpalan gabungan tradisional. Kajian ini memberi tumpuan kepada sifat tribologi dan karat berunsurkan air garam bagi sambungan kimpalan aloi aluminium AA5052 dan AA6061 yang tidak serupa yang dihasilkan menggunakan FSW, yang biasanya digunakan dalam aplikasi marin kerana sifat mekanikal dan rintangan kakisannya. Objektif utama projek ini adalah untuk mencirikan secara menyeluruh struktur mikro, sifat mekanikal, rintangan haus, dan kelakuan kakisan bagi sambungan AA5052-AA6061 FSW yang berbeza. Pelbagai teknik pencirian, termasuk mikroskop elektron pengimbasan pelepasan medan (FESEM) dan spektroskopi sinar-X (EDX) penyebaran tenaga, ujian tegangan, pemetaan kekerasan mikro, ujian kehausan pin-pada-cakera salingan, dan voltammetri sapuan linear (LSV), telah digunakan untuk menilai. Keputusan menunjukkan bahawa sambungan FSW yang berbeza mempamerkan perkembangan mikrostruktur yang unik di sepanjang garis ikatan, membawa kepada kekuatan tegangan dan kemuluran yang lebih tinggi berbanding dengan sambungan aloi yang serupa. Kekuatan tegangan bagi sambungan yang berbeza adalah lebih tinggi sedikit, tetapi ia menunjukkan rintangan haus yang lebih rendah disebabkan oleh pembentukan sebatian antara logam, seperti Al3Mg2, pada antara muka kimpalan. Ujian kekaratan menunjukkan bahawa sambungan yang tidak serupa mempunyai kadar kakisan keseluruhan yang lebih rendah tetapi terdedah kepada kakisan galvanik setempat pada antara muka. Kecenderungan ini disebabkan oleh perubahan dalam komposisi dan pembentukan filem oksida pasif, yang terlarut pada kira-kira -0.6V. Analisis mikrostruktur menunjukkan perbezaan yang ketara antara sendi yang serupa dan tidak serupa. Sambungan AA6061 yang serupa mempamerkan permukaan yang seragam dan bebas kecacatan dengan butiran halus, manakala sambungan AA6061-AA5052 yang berbeza memaparkan kawasan yang berbeza sepadan dengan setiap aloi dengan antara muka yang diikat dengan baik. Analisis EDX memberikan pandangan tentang pengedaran unsur, mendedahkan peralihan beransur-ansur dalam komposisi merentas antara muka kimpalan untuk sambungan yang berbeza, menunjukkan pencampuran bahan yang berkesan semasa proses FSW. Keputusan ujian mekanikal menyerlahkan prestasi unggul sendi yang berbeza dari segi kekuatan tegangan dan kemuluran. Walau bagaimanapun, keputusan ujian haus menunjukkan bahawa sambungan yang tidak serupa mempunyai rintangan haus yang lebih rendah berbanding dengan sambungan yang serupa, yang boleh dikaitkan dengan pembentukan sebatian antara logam pada antara muka kimpalan. Ujian kakisan menggunakan LSV menunjukkan bahawa walaupun sambungan yang tidak serupa mempunyai kadar kakisan keseluruhan yang lebih rendah, mereka lebih mudah terdedah kepada kakisan galvanik setempat disebabkan oleh perbezaan dalam komposisi dan pembentukan filem oksida pasif.Projek ini memberikan pandangan kritikal untuk mengoptimumkan parameter FSW untuk mengurangkan cabaran kekaratan..

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In the Name of Allah, the Most Gracious, the Most Merciful. First and foremost, I would like to express my sincere gratitude to those who have supported me throughout my master's Report journey. I wish to express my profound appreciation to Dr. Muhammad Zaimi, whose expertise in friction stir welding transcended mere guidance and feedback. His insightful contributions shaped the very direction and execution of the Report, while his keen eye for progress never overshadowed the invaluable opportunity for independent learning and problem-solving. The delicate balance he struck between mentorship and autonomy fostered an environment conducive to intellectual growth and personal empowerment, for which I am deeply grateful.

Finally, to my family and friends, whose unwavering love, support, and encouragement served as a beacon of strength throughout my postgraduate studies, I offer my deepest gratitude. Their unwavering belief in my potential was a source of endless motivation, and their presence, a much-needed reprieve during challenging times. It is their unyielding faith in me that has carried me through, and for that, I am eternally grateful.

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LIST OF ABBREVIATIONS

AA5052	-	Aluminum alloy 5052
AA6061	-	Aluminum alloy 6061
FSW	-	Friction stir welding
GMAW	-	Gas metal arc welding
NDT	-	Non-destructive testing
UTeM	-	Universiti Teknikal Malaysia Melaka
LSV	-	Linear scanning voltammetry
UTS	-	Ultimate tensile strength
HV	-	Vickers hardness
rpm	-	Revolutions per minute
MMC	-	Metal matrix composite
HRS	-	High resistance steel
EDX	-	Energy dispersive X-ray spectroscopy
XRD	-	X-ray diffraction
EDS	-	Energy dispersive spectroscopy
SEM	-	Scanning electron microscope
OM	-	Optical microscope
W	-	Weld
HAZ	-	Heat affected zone
TMAZ	-	Thermomechanically affected zone

LIST OF SYMBOLS

ω	-	Welding speed
ω	-	Welding rotation speed
T	-	Welding Tool
φ	-	Tool pin diameter
r	-	Tool shoulder diameter
t	-	Plate thickness
η	-	Tool travel angle
θ	-	Welding pitch
HAZ	-	Heat affected zone
TMAZ	-	Thermomechanically affected zone
UTS	-	Ultimate tensile strength
YS	-	Yield strength
E	-	Young's modulus
HV	-	Vickers hardness number
ρ	-	Density
ΔH	-	Heat of fusion
I	-	Current
V	-	Voltage
R	-	Resistance
N	-	Load
K	-	Corrosion rate
Ecorr	-	Corrosion potential
icorr	-	Corrosion current density

CHAPTER 1

INTRODUCTION

1.1 Background

Friction stir welding (FSW) has gained considerable attention in recent years due to its many advantages over traditional fusion welding methods. FSW offers multiple benefits such as improved mechanical properties, lowered environmental impact, and enhanced corrosion resistance. The welding process produces joints with minimal defects and a narrow heat-affected zone, making it suitable for welding dissimilar materials as show in figure 1.1.

This study focuses on examining the tribological and saltwater corrosion behavior of dissimilar alloy welding using FSW for brass and aluminum alloys. The goal is to investigate the welding process, tribology, microstructure, mechanical properties, and corrosion resistance of brass plate and aluminum alloy plate joints created using FSW.

Aluminum and its alloys are widely used across many industries because of properties such as high strength-to-weight ratio and corrosion resistance. However, welding aluminum alloys can be challenging due to their high thermal conductivity, low melting point, and susceptibility to defects like porosity and cracking. Therefore, it is important to develop reliable welding techniques that can produce high-quality joints with minimal defects.

Welding dissimilar materials such as brass and aluminum alloys presents issues in achieving strong and corrosion-resistant joints, particularly when exposed to salty environments. FSW offers a unique solution to this problem by providing a welding process that minimizes the heat-affected zone and produces joints with improved mechanical properties.

This chapter aims to briefly introduce the importance of welding techniques for aluminum alloys and the significance of understanding welding processes for dissimilar alloys. The chapter emphasizes the need for reliable and durable joints in aluminum structures, especially in marine applications, and challenges related to welding dissimilar aluminum alloys.

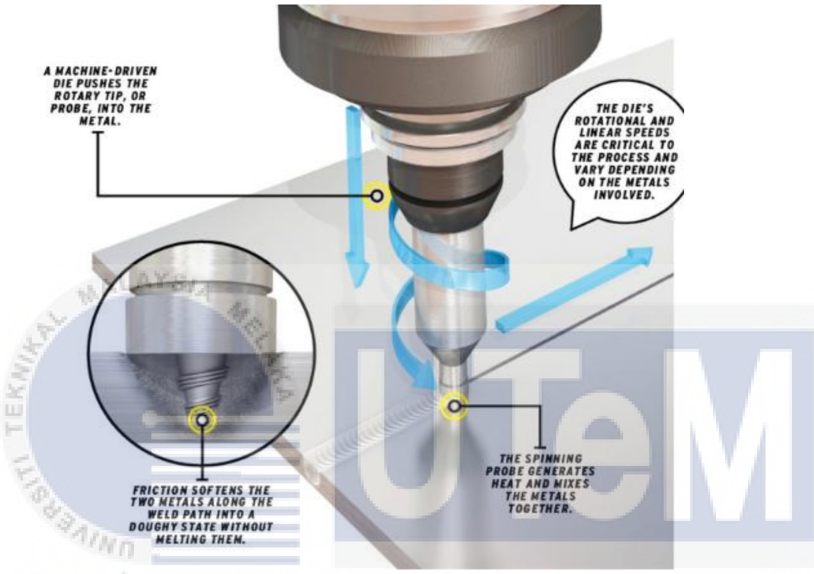


Figure 1.1: Friction stir welding (FSW) joining material process

At dissimilar alloy interface, the differences in mechanical properties lead to complex abrasive, adhesive and surface fatigue wear mechanisms. The resultant wear rate and friction depends on the effectiveness of material mixing and defect formation in the weld nugget zone (S. et al., 2023). Galvanic corrosion is another major concern for dissimilar aluminum welds in marine environments. The micro-galvanic couples formed between the alloys, intermetallic particles, and variable weld zones result in localized galvanic corrosion (Salavaravu and Dumpala, 2021).

While FSW is beneficial for aluminum welding, comprehensive understanding of the HAZ microstructural evolution, weld surface characteristics, material mixing, defect formation, wear behavior, and corrosion resistance in dissimilar aluminum FSW joints is currently lacking (Preethi and Daniel Das, 2021). This Project will address these gaps through an in-depth investigation. The outcomes will facilitate optimizing FSW parameters and advancing dissimilar aluminum welding for demanding marine structural applications.

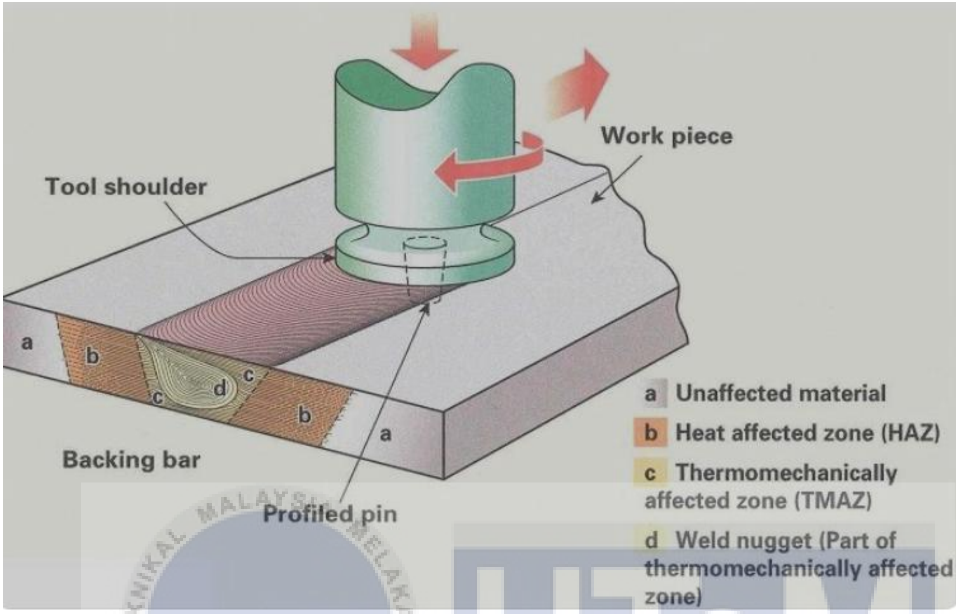


Figure 1.2: The FSW process is illustration

1.2 Background Study

Friction stir welding (FSW) is a solid-state joining process that has gained significant attention in recent years due to its numerous advantages over traditional fusion welding methods as show in figure 1.2. FSW offers several benefits, such as improved mechanical properties, reduced environmental impact, and enhanced corrosion resistance. The welding process produces joints with minimal defects and a narrow heat-affected zone, making it suitable for welding dissimilar materials. The focus of this study is on the tribological and saltwater corrosion behavior of dissimilar alloy welding using FSW for brass and aluminum alloys. The study aims to investigate the welding process, microstructure, mechanical properties, and corrosion resistance of brass plate and aluminum alloy plate joints produced using FSW.

Aluminum and its alloys are widely used in various industries due to their favorable properties, such as high strength-to-weight ratio and corrosion resistance. However, welding of aluminum alloys can be challenging due to their high thermal conductivity, low melting point, and susceptibility to defects such as porosity and cracking. Therefore, it is essential to develop reliable welding techniques that can produce high-quality joints with minimal defects.

The welding of dissimilar materials, such as brass and aluminum alloys, presents challenges in terms of achieving strong and corrosion-resistant joints, particularly when exposed to saltwater environments. FSW offers a unique solution to this problem by providing a welding process that minimizes the heat-affected zone and produces joints with improved mechanical properties. This chapter provides a brief overview of the importance of welding techniques for aluminum alloys and the significance of understanding the welding processes for dissimilar alloys and its tribiology behaviour in saltwater.

1.3 Problem Statement

The provided problem statement is comprehensive and well-articulated. It addresses the challenges and significance of friction stir welding (FSW) of dissimilar aluminum alloys, particularly the AA5052 and AA6061 alloys, and highlights the need to understand the tribological behavior, corrosion resistance, and joint integrity of the welded joints, especially under saline operating conditions. The statement also emphasizes the importance of investigating the microstructure, mechanical properties, sliding wear behavior, electrochemical corrosion kinetics, and resultant surface damage morphology of the dissimilar weld as show in figure 1.3.

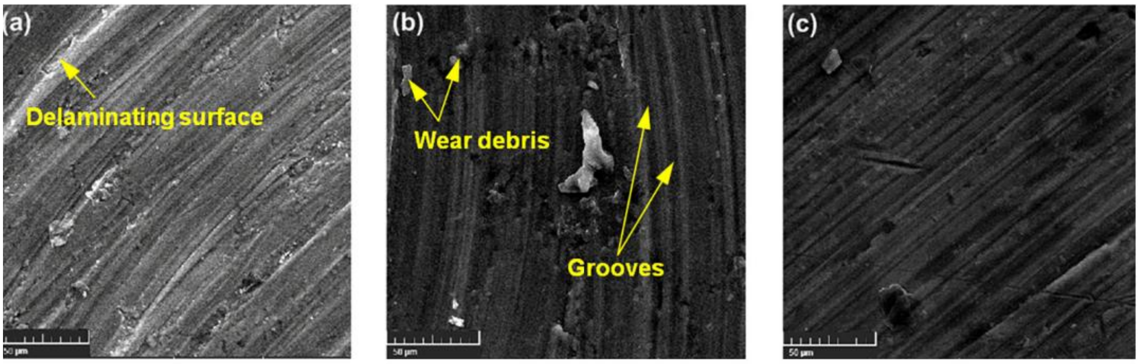


Figure 1.3: Scanning electron microscope images of worn-out surfaces(M et al.,2021).

Furthermore, it outlines the specific experimental techniques and tests to be conducted, such as pin-on-disk sliding wear tests, scanning electron microscopy, electrochemical corrosion experiments, salt spray exposure, and immersion testing. The statement also underlines the Project's objective to reveal optimal process parameters through structure-property-performance relations, aiming to facilitate the greater adoption of AA5052-AA6061 dissimilar aluminum FSW joints in lightweight engineering applications requiring excellent wear and corrosion resistance.

The problem statement is well-supported by relevant Project, such as the optimization of friction stir welding of dissimilar grades of aluminum alloy.(Rajesh et al., 2022), the corrosion and tribological behavior of friction stir processed aluminum alloys (Hari et al., 2022), and the effects of friction stir processing on the tribological, corrosion, and erosion properties of steel (Ralls et al., 2021). These sources provide valuable insights into the tribological, and corrosion properties of materials processed using friction stir welding, supporting the need for a comprehensive investigation into the dissimilar alloy welding process (Namboodiri et al., 2018).

Overall, the tribological properties of the dissimilar friction stir welding of AA5052-AA6061 is less know. Thus, in this study of the tribiological properties of friction stir welding are analyze using FESEM-EDX, tensile test, hardness and dry friction pin-on-disk test.

1.4 Report Question

"How do friction stir welding (FSW) parameters affect the microstructural evolution, mechanical properties, tribological behavior, and corrosion resistance of dissimilar AA5052-AA6061 aluminum alloy welds, especially under marine operating conditions?"

Key Aspects:

1. What are the dominant wear mechanisms under dry sliding conditions and how is the tribological behavior of the dissimilar AA5052-AA6061 welds affected by the FSW process parameters?
2. How do the FSW joints perform under electrochemical corrosion tests and prolonged immersion in saline solution in terms of degradation kinetics and surface damage?
3. How do FSW parameters influence the microstructure, mechanical properties and fracture morphology of dissimilar AA5052-AA6061 aluminum alloy welds?
4. What correlations exist between FSW parameters, microstructural evolution, mechanical attributes, tribological response, and corrosion resistance for the dissimilar aluminum welds?

The report will provide a comprehensive understanding of microstructural evolution, mechanical properties, wear mechanisms, corrosion susceptibility, and their interrelationships for dissimilar AA5052-AA6061 friction stir welds.

1.5 Report Objective

The increasing use of dissimilar aluminum alloys joined by friction stir welding (FSW) in marine applications has highlighted knowledge gaps regarding their long-term durability in ocean environments. The key objectives of this report are:

1. To investigate the tribological behavior of dissimilar aluminum alloy welded joints produced using friction stir welding (FSW) when exposed to marine environments.
2. To study the saltwater corrosion behavior of dissimilar aluminum alloy welded joints fabricated by FSW.
3. To analyze the mechanical properties like hardness, tensile strength, and fracture morphology of the dissimilar alloy welded joints produced using FSW.
4. To establish comprehensive structure-property-performance correlations between the FSW parameters, microstructure, mechanical properties, tribological response and corrosion resistance.

The report will address significant gaps in holistically understanding the microstructural evolution, mechanics, wear and corrosion behavior of dissimilar aluminum FSW joints in marine environments. The insights provided will facilitate optimal use of these lightweight dissimilar welds offshore.

1.6 Scope of Report

The project scope encompasses a comprehensive investigation of the tribological and saltwater corrosion behavior of dissimilar alloy welding using friction stir welding (FSW). This includes welding brass plate with aluminum alloy plate of similar 4 mm thickness using FSW, with specific attention to the weld microstructure, observation of any defects and porosity, and corrosion tests in artificial saltwater to observe the corrosion behavior between the welded area and the base metal. The scope also involves an in-depth evaluation of the microstructure, mechanical performance, sliding wear behavior, electrochemical corrosion test, saline corrosion response, and resulting surface damage morphology of the dissimilar weld. Various experimental techniques and tests, such as pin-on-disk sliding wear tests, scanning electron microscopy, electrochemical corrosion experiments will be used to provide critical insights into the tribocorrosion behavior. The ultimate goal is to reveal optimal process parameters through structure-property-performance relationships, facilitating greater adoption of dissimilar aluminum FSW joints in lightweight engineering applications requiring excellent wear and corrosion resistance.

1.7 Significance of the Study

This study aims to provide novel understandings of the tribological and corrosion behavior of dissimilar AA5052-AA6061 aluminum friction stir welds. The Project will address major gaps in knowledge regarding the interrelationships between FSW parameters, microstructural development, galvanic effects, wear mechanisms, and the resulting mechanical and electrochemical properties.

The comprehensive experimental analysis will facilitate scientifically-guided selection of optimal FSW process parameters to obtain high-quality dissimilar aluminum welds. Enhanced service performance and reliability can enable greater adoption of mixed aluminum alloys for lightweight, sustainable, and cost-effective designs in marine applications.

Fundamental advances in understanding microstructure-property correlations from this work can be extended to other heat treatable aluminum alloys and high-strength dissimilar material FSW joints. Opportunities exist for further Project to model and predict dissimilar aluminum weld zone characteristics.

Overall, this Project will make significant contributions towards advancing dissimilar aluminum FSW technology and expanding the application of mixed aluminum alloys for critical marine structural components. The economic and environmental benefits of optimizing aluminum welding and enabling sustainable alloy substitutions are far-reaching for the marine sector.

1.8 Report Outline

The report will be structured into five main chapters. Chapter 1, the Introduction, will provide background information on friction stir welding of dissimilar aluminum alloys and brass, discussing the importance and challenges associated with joining these materials. It will clearly define the problem statement and project gaps, state the main research question and objectives, and outline the scope and significance of the study.

Chapter 2, the Literature Review, will cover existing knowledge related to the project, including an overview of welding techniques for aluminum alloys, the corrosion behavior of aluminum alloys in salt water environments, an in-depth review of friction stir welding technology and processes, and previous studies on dissimilar alloy welding. This chapter will also identify relevant gaps in the current literature.

Chapter 3, Methodology, will describe the project methodology in detail, explaining materials and sample preparation, defining friction stir welding parameters and processes, and outlining various experimental techniques for data collection and analysis. These techniques include microstructural characterization, mechanical testing, wear testing, and corrosion testing. The chapter will also list equipment and facilities used and acknowledge limitations of the proposed methodology.

Chapter 4, Results and Discussion, will present and analyze the results obtained from the various tests, interpreting them in relation to the project objectives and existing literature. The relationships between welding parameters, microstructure, and properties will be examined. Finally,

Chapter 5, Conclusion and Recommendations, will summarize the key findings, draw conclusions, discuss the implications of the project, acknowledge limitations, and provide recommendations for future work. This comprehensive structure ensures a logical flow of information and addresses all aspects of the study on friction stir welding of dissimilar aluminum alloys and brass.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Friction stir welding (FSW) has emerged as a revolutionary solid-state joining process, offering a compelling alternative to traditional fusion welding methods. One of its most significant advantages lies in its ability to mitigate the challenges associated with the heat-affected zone (HAZ) in dissimilar alloy welding (Preethi and Daniel Das, 2021). This innovative technique has garnered substantial attention due to its capacity to produce high-quality welds without the detrimental effects of a HAZ, making it particularly well-suited for joining dissimilar materials (Newishy et al., 2023) as show in figure 2.1. In the context of this literature review, the focus is on the application of FSW to join a 4 mm thick brass plate with an aluminum alloy plate.

The welding process involves the use of a friction stir welding machine at fixed parameters and load to create a joint between the brass and aluminum alloy plates. Subsequently, the microstructure of the weld is meticulously examined using field-emission scanning electron microscopy with energy-dispersive X-ray spectroscopy (FESEM-EDX) after mirror-like polishing to eliminate any surface irregularities (S. et al., 2023). Additionally, ultrasonic thickness measurements are conducted using an Olympus Epoch 650 ultrasonic flaw detector to identify and characterize any potential defects or porosity within the weld.

Furthermore, the corrosion behavior of the welded joint is comprehensively evaluated through corrosion testing in an artificial salt environment (Salavaravu and

Dumpala, 2021). This testing aims to assess the corrosion resistance of the weld between the brass and aluminum alloy, as well as its interaction with the base metals.

This literature review aims to provide a detailed and comprehensive analysis of the existing scholarly literature on the tribological and saltwater corrosion behavior of dissimilar alloy welding using FSW for brass and aluminum alloys (Anandan and Manikandan, 2023). The review will delve into the specific aspects of FSW, tribological behavior, corrosion resistance, and the mechanical properties of the welded joints, providing a critical analysis of the gaps in the current literature and the implications for the field.

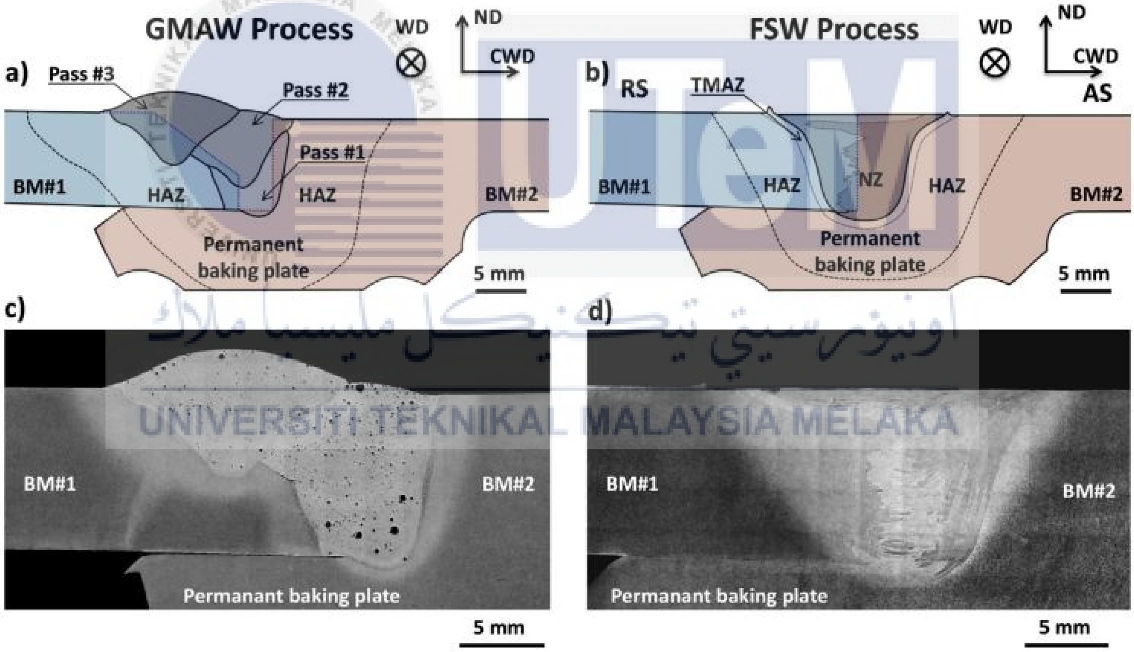


Figure 2.1: Comparison HAZ of welding between GMAW and FSW welding.

2.2 Classification of Aluminum Alloys

Once choosing materials for a variety of purposes, including additive manufacturing, the categorization of aluminium alloys is an important consideration.

Traditionally, aluminium alloys are divided into wrought alloys and cast alloys according to the conditions in which they are manufactured (Rajesh et al., 2022). The primary alloying elements are used to further subclassify each of these classes. Based on the concentration of the main alloying elements, wrought alloys are categorised into various series, while cast alloys have additional subclasses of their own. In order to help with material specification and selection for certain use cases as show in fugure 2.2, the aluminium alloy designation system offers an organised method of identifying and classifying distinct alloy types (Sun et al.,2023).

Figure 2.2: Aluminum alloy overview

The classification of aluminum alloys is particularly relevant to the selection of suitable.materials for the additive manufacturing process. The project may involve the use of specific aluminum alloy models, such as 2024, 5183, and others, which are commonly employed in additive manufacturing and other industrial applications. Understanding the classification system and the unique properties of each alloy type is essential for making informed decisions regarding material utilization and process optimization. Additionally, the classification of aluminum alloys plays a significant role in the development of predictive models for material behaviour, including corrosion characteristics and mechanical properties (Gnanaraj and Appadurai, 2022), which are essential for ensuring the quality and reliability of additively manufactured components.

1. Understanding the classification system for aluminum alloys is crucial for appreciating the challenges and possibilities presented by joining AA5052 and AA6061:
2. Major alloying elements:AA5052 belongs to the 5XXX series (aluminum-magnesium), known for good weldability and formability but moderate strength. AA6061 falls under the 6XXX series (aluminum-magnesium-silicon), offering higher strength and hardness but slightly lower weldability.
3. Heat treatment:Both alloys are heat-treatable, enabling further customization of their mechanical properties. Understanding the temper designations of the specific AA5052 and AA6061 used for interpreting their behaviour.
4. Microstructure:FSW significantly alters the microstructure of the base materials in the weld zone. The resulting grain size, precipitate distribution, and intermetallic phases can influence both tribological and corrosion performance.

2.3 Welding Techniques for Aluminum Alloys

The overview of welding techniques for aluminum alloys encompasses a range of methods used to join aluminum and its alloys. Welding is the primary joining method for aluminum alloys, and the selection of the appropriate welding technique is crucial to ensure the integrity and quality of the welded joints. The following provides a summary of the various welding methods and their application to aluminum alloys (S. et al., 2023).

Welding Methods:Aluminum alloys can be welded using several methods, including fusion welding techniques such as tungsten inert gas (TIG) welding, metal inert gas (MIG) welding as show in figure 2.3 and figure 2.4, and laser welding. Additionally, solid-state welding processes like friction stir welding (FSW) are increasingly being utilized for joining aluminum alloys (Verma and Kumar Lila, 2021).

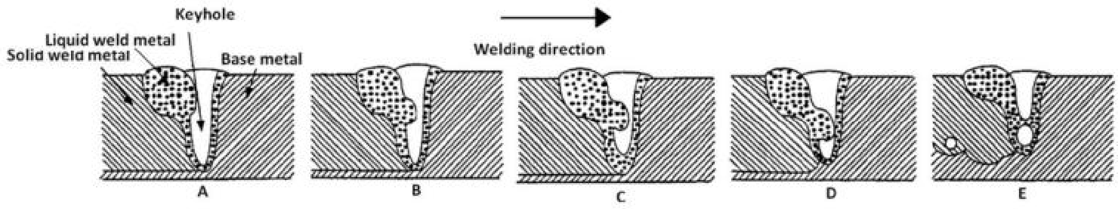


Figure 2.3: Schematic diagram showing formation of porosity at the welding root.

2. Welding Parameters:The welding of aluminum alloys requires careful consideration of parameters such as heat input, travel speed, and shielding gas to ensure the formation of sound welds with minimal defects. Fig. 4 illustrates the important welding parameters generally used for welding aluminum alloys (Verma and Lila, 2021)
3. Challenges and Advantages:Each welding method has its own application and adaptability to various aluminum alloys. For instance, FSW offers advantages such as low welding temperature, minimal deformation, and good mechanical properties, making it suitable for joining aluminum alloys (Anandan and Manikandan, 2023).
4. Corrosion and Weld Quality:The weld quality in aluminum alloys is a critical consideration, as these materials are sensitive to heat from welding and can experience issues such as deformation and cracking. Understanding the metallurgical principles involved in welding and its effects on the strength and

corrosion resistance of aluminum alloys is essential for ensuring the long-term performance of welded structures (Chekalil et al., 2024).

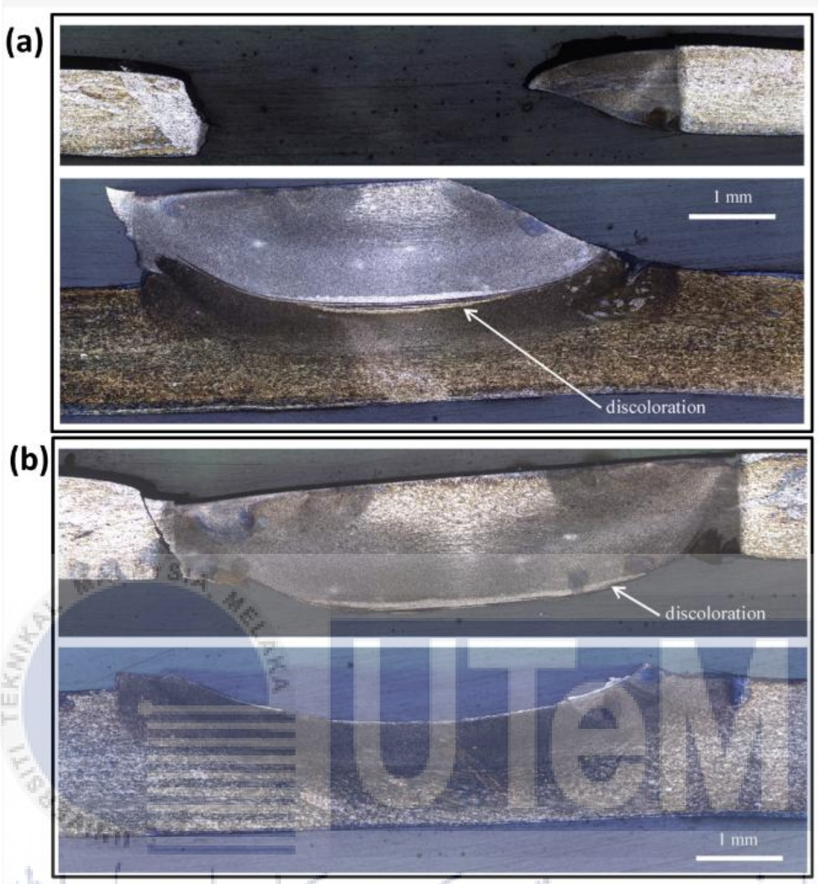


Figure 2.4: Failure mode of the FSW. (a) Cross-Section of nugget pullout failure:top sheet cross-section (top) and bottom sheet cross-section (bottom). (b) Cross-Section of interfacial failure:top sheet cross-section (top) and bottom

The overview of welding techniques for aluminum alloys highlights the diverse range of methods available for joining aluminum and its alloys, emphasizing the importance of selecting the most suitable welding technique to achieve high-quality, durable welds with minimal defects and optimal corrosion resistance (Bagheri et al., 2021).

2.4 Corrosion Behaviour of Aluminum Alloys in Salt Water

The corrosion behaviour of aluminum alloys in saltwater environments is a critical consideration for the selection of appropriate materials and welding techniques for marine applications. Saltwater environments can cause severe corrosion damage to aluminum alloys, leading to reduced mechanical properties and structural integrity (Salavaravu and Dumpala, 2021). Therefore, understanding the corrosion mechanisms and behaviour of aluminum alloys in saltwater environments is essential for ensuring the long-term performance and reliability of welded structures (Sun et al., 2023).

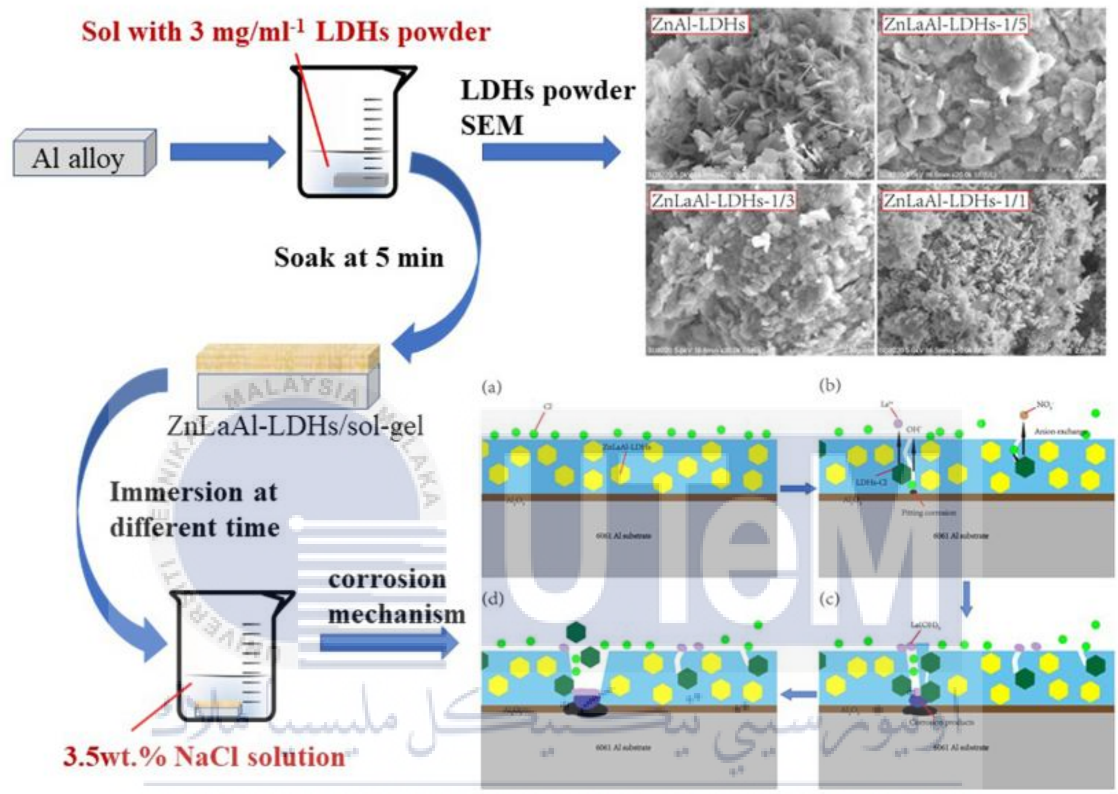


Figure 2.5: Corrosion mechanism for alloy with 3.5wt.% NaCL solution.

Several studies have investigated the corrosion behaviour of aluminum alloys in saltwater environments, including seawater and waste salt refining and recycling equipment as show in figure 2.5. The studies have examined the impact of heavy metal ions, temperature, and microstructural changes on the corrosion behaviour of aluminum alloys (Wang et al., 2022). The corrosion behaviour of AA5052 aluminum alloy in the presence of heavy metal ions has been studied, and the results showed that pitting corrosion caused by heavy metal ions remains a challenge for the application of aluminum alloy materials in low-temperature and medium-temperature seawater (Zhang et al., 2024).

The corrosion behaviour of cold-formed AA5754 alloy sheets has also been studied, and the results showed that the corrosion potentials of the deformed areas had slightly lower values than the corrosion potentials of the undeformed areas(Dobkowska et al., 2021). The study on the corrosion behaviour of Al-Cu-Li alloy in NaCl solution simulated the seawater environment, and the results showed that the corrosion resistance of Al-Cu-Li alloy was better than that of Al-Zn-Mg-Cu alloy (Wang et al., 2022).

Previous studies have found that selective laser melted (SLM) aluminum alloys exhibit better corrosion resistance compared to cast and wrought aluminum alloys (Chen et al., 2020). However, further studies are needed to investigate the corrosion behaviours of SLMed aluminum alloys in corrosive atmospheres and to gain more insights into the corrosion mechanism.

The provided search results contain information on the corrosion behavior of welded joints, including resistance spot-welded joints of zinc-coated interstitial free steel, carbon steel weldments, and friction stir welded (FSW) aluminum alloys. The studies investigate the corrosion characteristics of the welded joints and their susceptibility to localized corrosion, galvanic corrosion, and wear. The Project emphasizes the importance of understanding the corrosion behavior of welded joints to assess their suitability for specific applications and to develop effective corrosion inhibition strategies.

The study of the corrosion behavior of resistance spot-welded joints of zinc-coated interstitial free steel, as well as carbon steel weldments, highlights the likelihood of corrosion around the weld metal area and its adjacent heat-affected zone. The Project identifies intensive galvanic currents and non-uniform corrosion as significant factors affecting the welded joints (Yang et al., 2021).

In the context of FSW, the literature review on the wear and corrosion behavior of FSW aluminum alloys provides an overview of the available literature concerning the development in tribological and corrosion behavior of friction stir welds. The review emphasizes the importance of understanding the wear and corrosion characteristics of FSW joints, particularly in dissimilar alloy combinations, to assess their suitability for specific applications (Olatunji and Akinlabi, 2019).

The corrosion behaviour of aluminum alloys in saltwater environments is a complex phenomenon that is influenced by several factors, including heavy metal ions, temperature, micro-structural changes, and the welding process. Understanding the corrosion mechanisms and behaviour of aluminum alloys in saltwater environments is essential for ensuring the long-term performance and reliability of welded structures in marine applications.

2.5 Friction Stir Welding (FSW)

Friction stir welding (fsw) is a solid-state joining process that has gained significant attention for its effectiveness in producing quality welds and resolving solidification issues aluminum alloys found in fusion welding processes as per figure 2.6.

Figure 2.6: The stages of FSW steel alloy using the WC tool. (a) Initial stage of a tool plunging at the abutting edge of the two tightly clamped plates on the table of the FSW machine, (b) after plunging and traversing, and (c) at the end of the FSW and just before extracting the tool.

FSW is a solid-state joining process that offers several advantages over traditional fusion welding methods, particularly for joining aluminium alloys. Its energy efficiency, lower heat input, and ability to produce high-quality welds make it a promising alternative to fusion welding processes like GMAW(Anandan and Manikandan, 2023), especially for dissimilar alloy welding as show in figure 2.7.

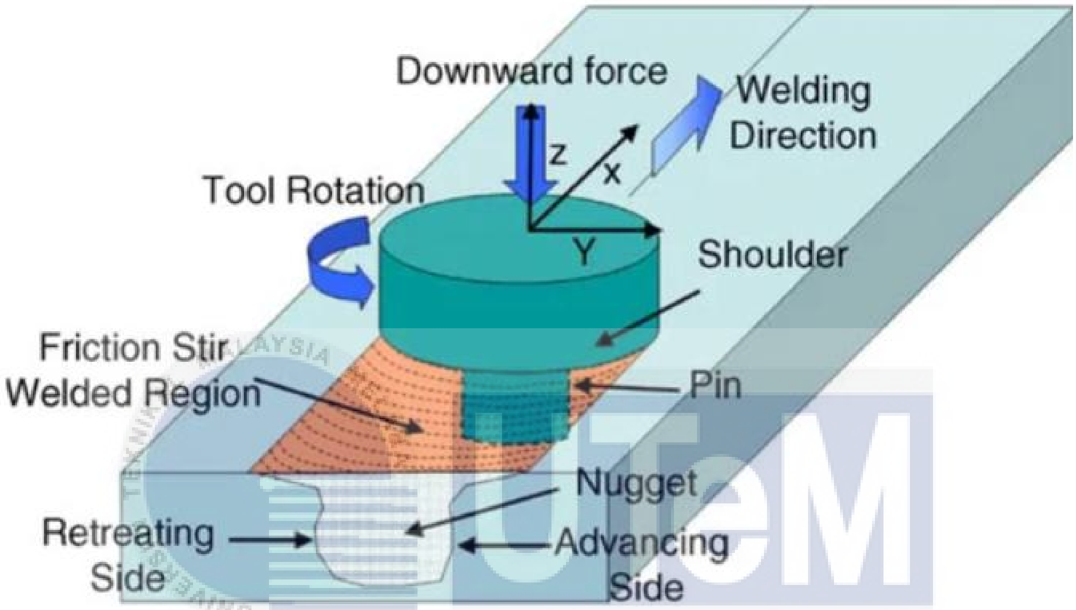


Figure 2.7: Simulation of FSW welding.

FSW is regarded as one of the energy-efficient and eco-friendly manufacturing processes, as it operates below the melting point of the materials, without the participation of the liquid phase, resulting in lower heat input and better joint properties. (Majeed et al., 2021). The process involves the intense plastic deformation of the material, leading to the formation of fine grains in the weld core, which is a significant advantage of FSW over other methods.

This technology is considered one of the greatest achievements in welding technology, and it is commonly used in industries such as automotive and shipbuilding. The limited weldability of certain aluminium alloys, resulting from their tendency to hot cracking and low fatigue strength, has driven the search for more effective joining methods, making FSW a promising alternative (Noga et al., 2023).

Gas metal arc welding (GMAW) is a fusion welding process that uses an electric arc established between a consumable wire electrode and the workpiece, generating the heat needed to melt and fuse the base metals. While GMAW is a widely used and versatile process, it can lead to issues such as porosity and solidification cracking in aluminium alloys, particularly when joining dissimilar alloys. (Anandan and Manikandan, 2023). In contrast, FSW offers advantages such as lower heat input, reduced distortion, and improved mechanical properties, making it an attractive option for joining aluminium alloys, especially dissimilar ones (Noga et al., 2023).

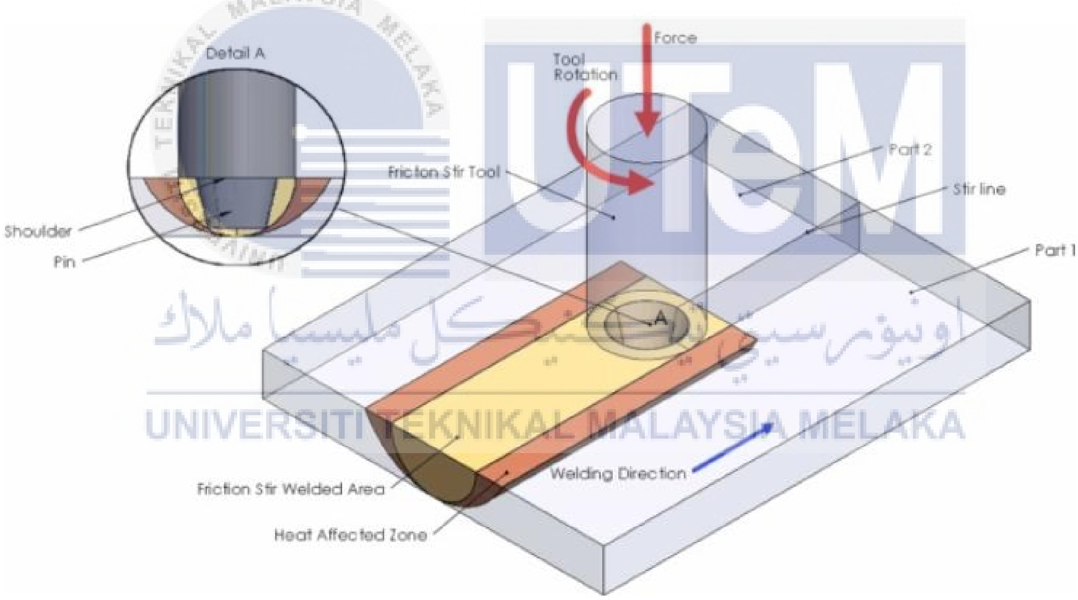


Figure 2.8: Schematic representation of FSW welding.

The process offers several advantages over conventional fusion welding, including: -

1. No melting required:FSW joins materials without melting them, resulting in fewer defects and improved mechanical properties.
2. Lower heat input:FSW generates less heat than fusion welding, reducing the risk of heat-sensitive material decomposition or oxidation.

3. Faster than fusion welding:FSW is typically faster than fusion welding due to its ability to join materials at a deeper level without the need for preheating.

4. Cost-effective:FSW requires less energy and produces less waste than fusion welding, making it a more cost-effective option(Kılıc et al., 2023).

In the context of aluminum alloys AA5052 and AA6061, FSW has been shown to produce high-quality joints with good mechanical properties when optimized for the specific material combination. Report has identified crucial factors influencing joint quality, such as the rotational speed of the tool, welding speed, shoulder form, and tool profile as show in figure 2.8. Furthermore, Project indicates that sounder joints can result from positioning the harder alloy (AA6061) on the advancing side. It has also been investigated how pin eccentricity affects microstructure and mechanical characteristics, highlighting the advantages of tailoring tool design for a particular material. combinations.

Friction Stir Welding (FSW) has revolutionized the joining of aluminum alloys, particularly dissimilar pairings like AA5052 and AA6061. Unlike conventional fusion welding, which struggles with melting point discrepancies and thermal expansion differences, FSW excels due to its solid-state nature. Several studies have investigated the FSW of dissimilar aluminum alloy combinations, including AA5052 and AA6061, and identified crucial factors influencing joint quality: -

1. Welding Parameters:Report by (Kılıc et al., 2023) identified several crucial factors influencing joint quality, including tool profile, shoulder shape, welding speed, and tool rotational speed as show in figure 2.9 and figure 2.10.
2. The Impact of Tool Tilt Angle and Alloy Positioning:(Newishy et al., 2023) discovered that by positioning the harder alloy (AA6061) on the advancing side, greater heat dissipation and a decreased susceptibility to cracking can result in sounder junctions.

3. Influence of Pin Eccentricity on Microstructure and Mechanical Properties:(Wang et al.,2019) demonstrated the benefits of optimizing tool design for specific material combinations, showing that specific eccentricities can promote grain refinement and enhance joint strength through optimized material mixing as show in figure 2.11.
4. Tribological Behaviour:A study by (Sivaselvan et al., 2023) investigated the influence of FSW parameters on the tribological behaviour of dissimilar aluminum alloy joints, highlighting the importance of understanding the wear performance of such joints at different tool parameters.
5. Mechanical Properties:(Ahmed et al.,2023) investigated the combined effect of tool rotation speed, welding speed, and travel speed on the mechanical properties of AA5052-AA6061 joints, identifying optimal parameter ranges for maximizing tensile strength and joint efficiency.

FSW has several advantages for joining aluminum alloys, and ongoing Report continues to explore the influence of various parameters on the quality, mechanical properties, and tribological behaviour of FSW joints between dissimilar aluminum alloys.

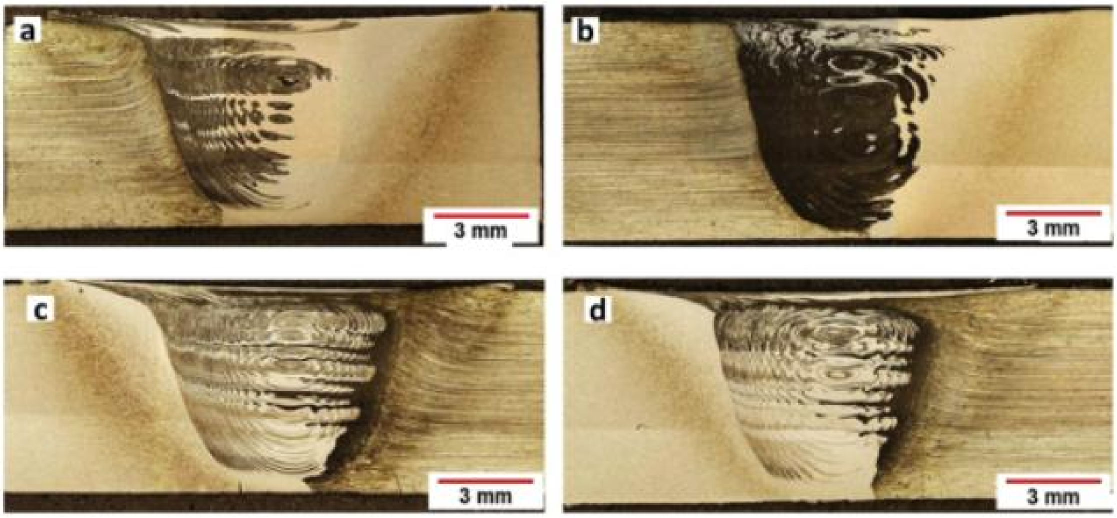


Figure 2.9: Macro-graphs showing the weld cross-sections of the dissimilar AA6061/AA7075 joints produced at 1200 rpm and under different conditions:(a) AA6061 alloy is on the trailing side and the welding speed is 3 mm/s, (b) AA6061 alloy is on the trailing side and the welding speed is 5mm/s.

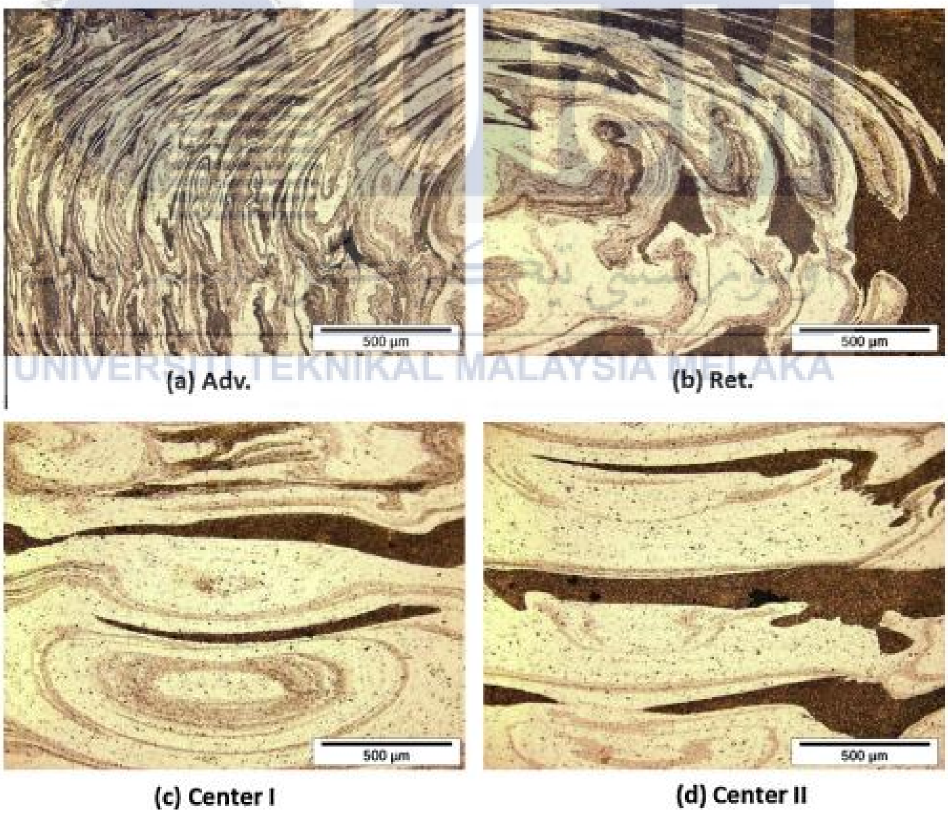


Figure 2.10: The complex materials flow patterns (onion rings) on the top advancing and retreating sides:(a and b), and the multiple vortexes in the nugget center:(c and d).

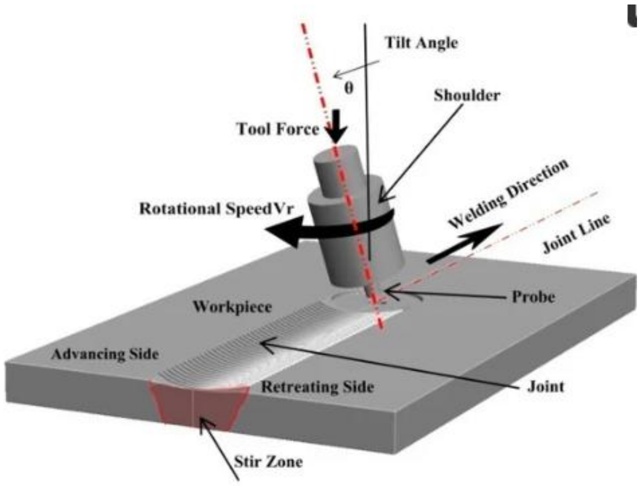


Figure 2.11: A schematic of the FSW process, indicates the process's main characteristic features. The FSW tool is shown with the exit hole just below the tool after extraction.

2.7 Tribological Behavior of FSW Welds

Tribology is the science of friction, wear, and lubrication of interacting surfaces in relative motion. In the context of Friction Stir Welding (FSW), tribological behavior refers to the wear characteristics of the FSW joints. The tribological behavior of FSW welds has been investigated in several studies, including those listed in the search results.

The study (Deleanu et al., 2021) provided an overview of the wear behavior of friction stir welded aluminum alloys. The study highlighted the importance of understanding the wear characteristics of FSW joints, particularly in dissimilar alloy combinations, to assess their suitability for specific applications. The study by (Ahmed et al. 2023) assessed the corrosion behavior of friction stir welded dissimilar aluminum alloys. The findings emphasized the need to evaluate the corrosion resistance of FSW joints in saltwater environments.

The study by (Kumar et al. 2021) investigated the tribological behavior of friction stir welded aluminum alloys. The study found that the wear rate and coefficient of friction of the FSW joints were influenced by the welding parameters, such as welding speed and tool rotational speed. The study by (Silva et al. 2023) proposed tool design guidelines for FSW of aluminum alloys. The Project focused on providing practical equations for the design process of FSW tools for different aluminum series. The findings offered valuable insights into optimizing the FSW process for dissimilar aluminum alloy combinations.

In summary, tribological behavior of FSW welds refers to the wear characteristics of the FSW joints. The tribological behavior of FSW welds has been investigated in several studies, highlighting the importance of understanding the wear and corrosion characteristics of FSW joints, particularly in dissimilar alloy combinations.

2.8 Corrosion Behaviour of FSW Welds

The search results provide valuable insights into the corrosion behavior of various welded joints, including friction stir welded (FSW) joints of aluminum and magnesium alloys. The studies highlight the significance of understanding the corrosion characteristics of welded joints and the need for effective corrosion inhibition strategies to ensure their reliability and durability in practical applications.

The corrosion behavior of FSW joints has been investigated in the context of different materials, such as AA3003 aluminum alloy (Chekalil et al., 2024), dissimilar aluminum alloys (AA6061 and AA8011) (Alfattani et al., 2021), and magnesium alloys(Kumar et al., 2023). These studies have revealed that the corrosion resistance in the weld zone can differ from that of the base materials, with factors such as microstructural alterations in the heat-affected zones influencing the corrosion attacks (Alfattani et al., 2021). The presence of intergranular corrosion, deep corrosion, localized pit dissolution, and corrosion pits has been observed in the weld regions, particularly in acidic solutions (Alfattani et al., 2021). Additionally, the effects of FSW on the mechanical and corrosion properties of welded joints have been investigated, emphasizing the importance of understanding the relationship between the welding process and the resulting corrosion behaviour (Salavaravu and Dumpala, 2021).

Furthermore, the studies suggest the potential for galvanic corrosion in FSW joints, especially under harsh alkaline and acidic conditions, highlighting the importance of considering corrosion protection measures such as conversion layer coatings (Alfattani et al., 2021). The review of the corrosion behavior of FSW joints in magnesium alloys also underscores the need for a comprehensive understanding of the factors influencing the corrosion resistance of such welds (Kumar et al., 2023).

In summary, the search results emphasize the complex nature of the corrosion behavior of FSW joints and the importance of considering various factors, including microstructural changes, environmental conditions, and material combinations, in the development of effective corrosion mitigation strategies for welded joints.

2.9 Research Gaps

In this literature review, the gaps in the existing Project on the tribological and saltwater corrosion behavior of dissimilar alloy welding using FSW for brass and aluminum alloys will be identified. The review will critically analyze the existing literature, evaluate the strengths and limitations of previous studies, and identify the gaps in the current literature. The review will also suggest future Project directions to address the identified gaps and limitations.Some of the gaps identified in the literature include:

1. Limited Project on the tribological behavior of dissimilar alloy welded joints using FSW.
2. Insufficient Project on the influence of FSW parameters on the wear performance of dissimilar aluminum alloy welded joints.

3. Limited Project on the corrosion resistance of dissimilar alloy welded joints using FSW in saltwater environments.
4. Lack of Project on the microstructure and mechanical properties of dissimilar aluminum alloy welded joints using FSW
5. Limited Project on the comparison of FSW with other fusion welding methods for dissimilar alloy welding

By addressing these gaps, future Project can contribute to a better understanding of the tribological and saltwater corrosion behavior of dissimilar alloy welding using FSW for brass and aluminum alloys.

2.10 Analysis Techniques

The analysis techniques for the study on the tribological and saltwater corrosion behaviour of dissimilar alloy welding using friction stir welding (FSW) and gas metal arc welding (GMAW) processes may include the following:

1. Surface Morphology Analysis:Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) can be used to examine the microstructure, grain size, and the presence of any defects such as porosity or cracks in the welded joints. This analysis technique can be used to observe the microstructure of the welded joints using FESEM-EDX after mirror-like polishing to remove burr. (Chen et al., 2019).
2. Tensile Testing:Tensile tests will be conducted to determine the mechanical properties of the welded joints, including tensile strength, ductility, and fracture behaviour (Gnanaraj and Appadurai, 2022).

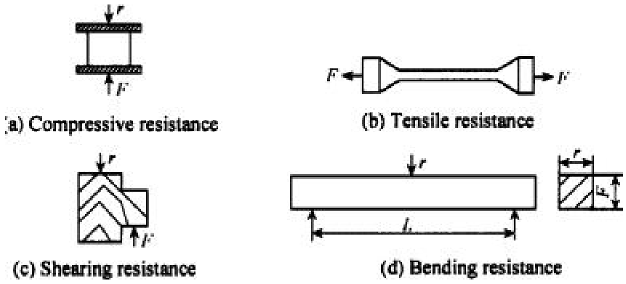


Figure 2.12: Mechanical Strength Properties.

3. Hardness Testing:Vickers hardness testing will be employed to evaluate the hardness of the welded joints, which is an important parameter for assessing the wear resistance and fatigue life of the components (Paik, 2009).

4. Electrochemical Testing:The electrochemical behaviour of the welded joints in saltwater settings will be investigated using Linear Scanning Voltammetry (LSV). LSV will make it possible to ascertain the alloys' passive zone, corrosion potential, and corrosion current density (Zhang et al., 2022).

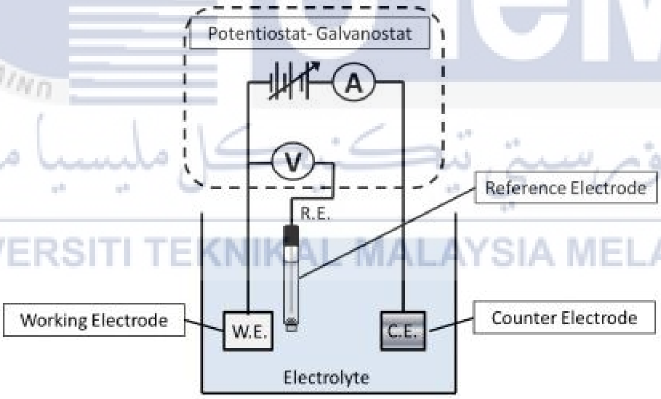


Figure 2.13: Arrangement in electrochemical measurement analysis

5. Wear Testing:Wear testing involves subjecting the FSW joints to controlled wear conditions to evaluate their wear resistance. Wear testing can be performed using pin-on-disk, ball-on-disk, or reciprocating sliding tests (Malyshev, 2014).

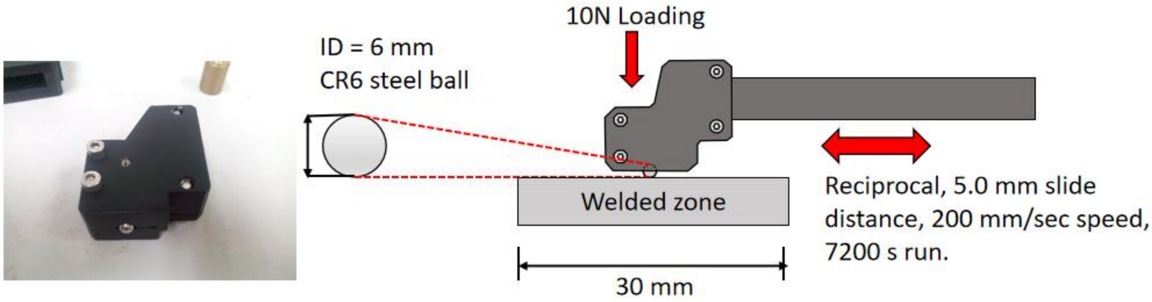


Figure 2.14: Simulation of pin-on-disk.

By employing a combination of experimental and computational analysis techniques, this study aims to provide a comprehensive understanding of the tribological and saltwater corrosion behaviour of dissimilar alloy welds, as well as the influence of different welding processes on the performance of these welded joints.

2.11 Summary of Literature Review

The literature review conducted for this report encompasses recent studies from 2019 to 2024 on the tribological and saltwater corrosion behavior of dissimilar alloy welding using Friction Stir Welding (FSW). A visual summary has been created to highlight the key areas of research and their interconnections.

The literature review focuses on six main areas:Friction Stir Welding (FSW), Aluminum Alloys, Tribological Behavior, Salt Water Corrosion, Mechanical Properties, and Analysis Techniques. In the field of Friction Stir Welding, recent studies from 2023 have focused on process parameters (Kılıç et al.), tool design (Silva et al.), and advantages over traditional welding (Noga et al.). Microstructural changes during FSW were examined by Chen et al. in 2019.

Regarding Aluminum Alloys, the classification was studied by Rajesh et al. in 2022, while properties and weldability were investigated in 2023 by Sun et al. and Nunes et al., respectively. Tribological Behavior has been a key area of research, with studies on wear resistance by Deleanu in 2021, friction characteristics by Ayvaz in 2022, and the influence of FSW parameters on tribological behavior by Sivaselvan in 2023.

Salt Water Corrosion has been extensively studied, with recent work examining corrosion mechanisms (Zhang, 2024), the influence of microstructure on corrosion (Alfattani, 2021), galvanic corrosion (Kumar, 2023), and comparisons of corrosion resistance (Chen, 2020). In terms of Mechanical Properties, recent research has focused on tensile strength (Ahmed et al., 2023), hardness (Preethi and Daniel Das, 2021), and ductility (Heramo and Workneh, 2023). Various Analysis Techniques have been employed in these studies, including surface morphology analysis (S., 2023), mechanical testing (Ahmed, 2023), electrochemical testing (Chekalil, 2024), and wear testing (Hari, 2022).

This research (Harishah, 2024) aims to integrate these various aspects, particularly focusing on the relationships between tribological behavior, saltwater corrosion, and mechanical properties in the context of FSW of dissimilar aluminum alloys.

The majority of the reviewed studies are from 2021-2024, demonstrating the currency and relevance of this research. The literature review has identified several gaps or areas for future research, such as the need for more detailed analysis of the interaction between tribological and corrosion behaviors in dissimilar welds.

Finally, a concept map or visual summary is introduced to illustrate the key areas of the literature review and their interconnections. This visual aid helps readers quickly grasp the scope and focus of the research. By structuring the literature review summary in this way, a comprehensive overview of the current state of research in the field is provided, demonstrating the relevance and timeliness of the study, and showing how the work fits into and builds upon existing knowledge as show in figure 2.15.

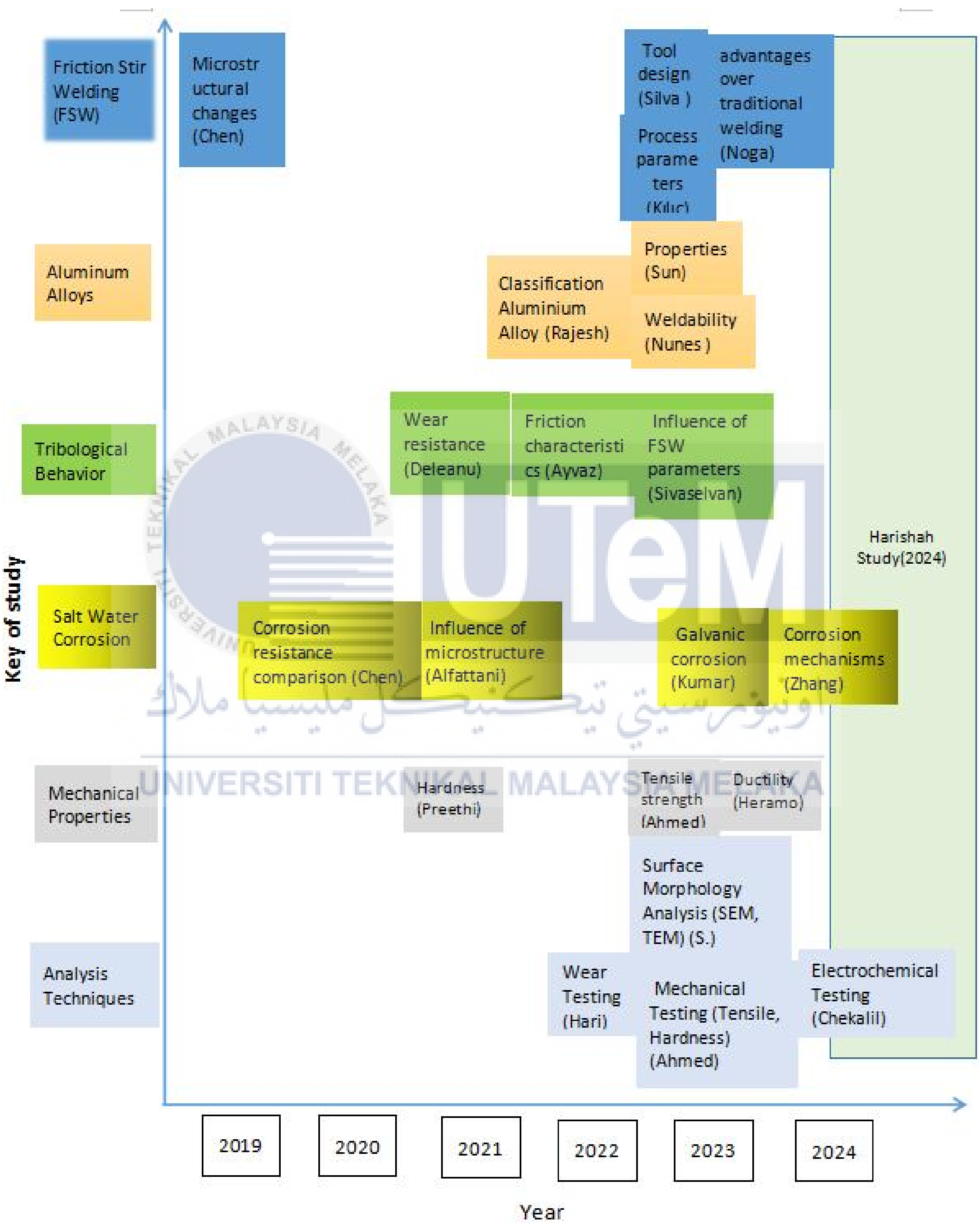


Figure 2.15:The summary of literature review.

CHAPTER 3

METHODOLOGY

3.1 Flow Chart of Process

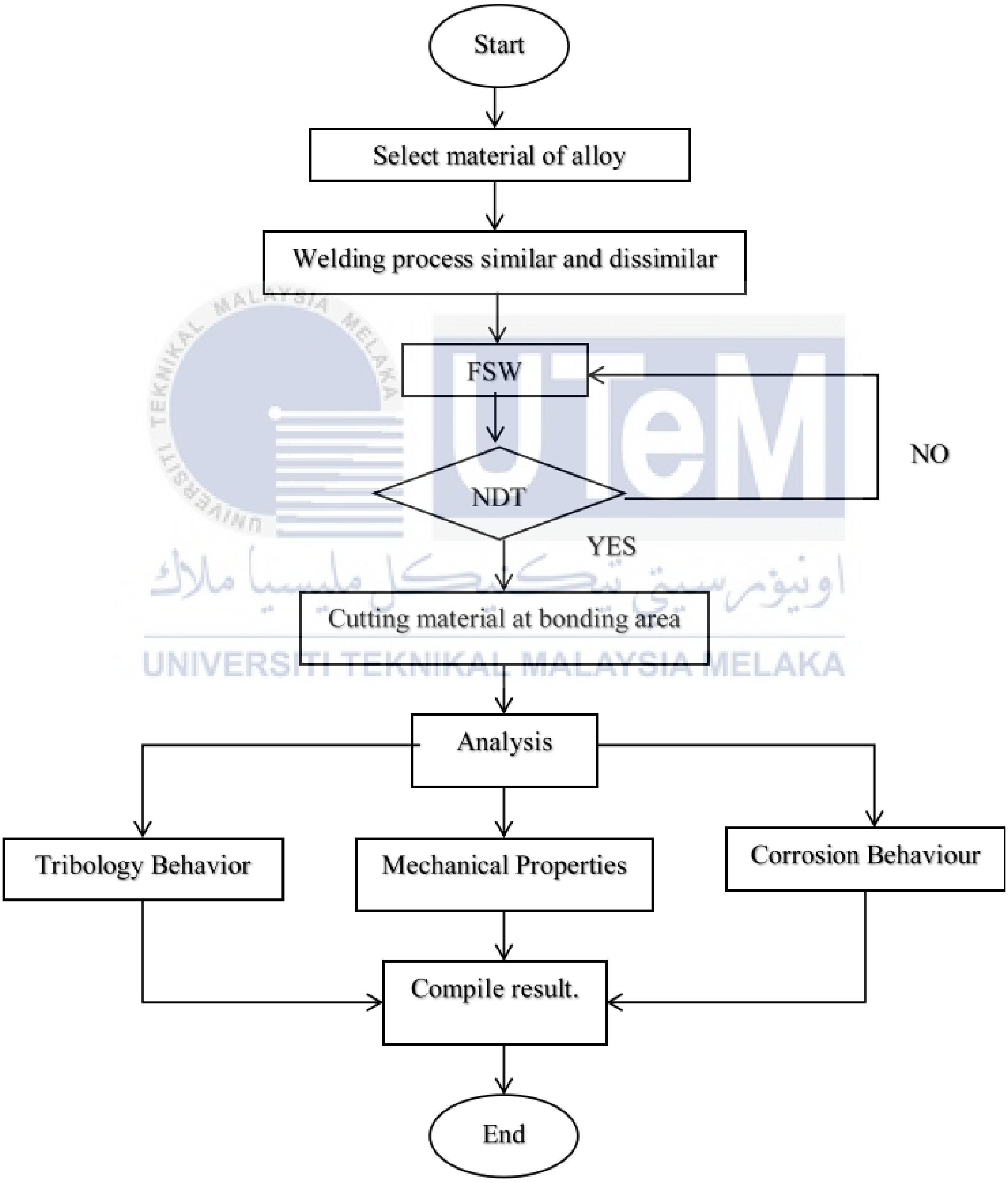


Figure 3.1: Project Flow Chart.

This study leverages a systematic approach to connect microstructure observations to quantitative performance data for friction stir welded dissimilar joints between aluminum alloys AA5052 and AA6061. Non-destructive testing as well as metallographic preparations for macro and microscopic weld profiling are performed. Relating this diverse dataset provides evidence to develop improved structure-performance-lifetime relationships valuable for qualifying welding processes across various applications through the following analyses:

1. Surface Morphology Evaluation:For the testing and analysis of the tribological and saltwater corrosion behavior of dissimilar alloy welds using FSW for brass and aluminum alloys, the following surface morphology analysis techniques can be employed:

    i. Scanning Electron Microscopy (SEM):SEM can be used to look at the grain size, microstructure, and if there are any flaws in the welded seams, including porosity or cracks. The surface morphology of the welded joint may be seen in high-resolution photos thanks to this analytical method.

    ii. Energy Dispersive X-ray Spectroscopy (EDX):This technique can be used to examine the welded joint's elemental structure. This study method can reveal details regarding the elemental distribution inside the welded joint.By employing a combination of surface morphology analysis techniques and experimental analysis techniques, this study aims to provide a comprehensive understanding of the tribological and saltwater corrosion behavior of dissimilar alloy welds using FSW for brass and aluminum alloys. The surface morphology analysis techniques can help evaluate the microstructure and defects in the welded joint, while the experimental analysis techniques can provide valuable insights into the integrity of the weld.Tensile Testing:Tensile strength, yield point and elongation at break quantify mechanical properties and ductility meeting industrial testing standards for aluminum weld integrity.

iii. Wear Testing:Wear testing involves subjecting the FSW joints to controlled wear conditions to evaluate their wear resistance. Wear testing can be performed using pin-on-disk testing. The pin-on-disk test involves a rotating disk in contact with a fixed pin with a spherical top. The test material is moved on a circular path over the specimen with a defined standard force (approx. 5 N) during the test, and the friction force or the coefficient of friction is measured continuously. The wear is subsequently determined by measuring the wear track and the abrasion of the test.

2. Mechanical properties:The mechanical properties of friction stir welded (FSW) joints are primarily evaluated through tensile and hardness testing.

I. Hardness Testing:Using Vickers hardness machine determines hardness gradients resulting from structural and compositional variations within the distinct heat-affected and thermal-mechanically affected sub-regions of the welds.

II. Tensile testing:Universal testing machine (UTM) use to tensile testing assesses the strength and ductility of the welded joints, measuring key properties such as ultimate tensile strength (UTS), yield strength, and elongation. For FSW joints, the UTS often increases with different heat treatments, while the elongation indicates the joint's ductility. The fracture location during tensile testing provides insights into the weakest region of the welded joint, typically occurring in the heat-affected zone (HAZ) or thermomechanically affected zone (TMAZ).

3. Corrosion behavior Testing:Linear Sweep Voltammetry (LSV) is an electrochemical technique used to determine the potential at which the cathodic and anodic currents of a process cancel out, providing information about the corrosion rate, mechanisms, and susceptibility of materials to corrosion in various environments. It involves sweeping the potential of the working electrode and measuring the current response, making it a valuable method for studying the corrosion behavior of materials

3.2 Materials and Sample Preparation

This study investigates the joining characteristics of two commonly used aluminum alloys, AA 5052 and AA 6061, using Friction Stir Welding (FSW) technique. AA 5052 - Offers excellent corrosion resistance, good weldability, and is readily available and affordable. AA6061 - Possesses higher strength than AA 5052 but is less weldable due to its higher magnesium content. The chemical compositions of the base materials are listed in Table 3.1. Sheets of 4 mm thickness were used for welding. The edges of the sheets were milled to achieve regular joint faces and ensure proper root penetration during welding.

After welding, the specimens were cut from the welded sheets using a band saw for different characterization purposes. The joint cross-sections were prepared following standard metallographic procedures including grinding and polishing, and then etched using Keller's reagent as show figure 3.2. for microstructural analysis.

Figure 3.3: Keller's reagent.

Table 3.1: Chemical compositions (in wt%) of AA5052 and AA6061 aluminum alloys.

Alloy	**Mg**	**Si**	**Fe**	**Cu**	**Mn**	**Cr**	**Zn**	**Ti**	**Al**
AA5052	2.2-2.8	0.25	0.4	0.1	0.5	-	0.25	0.15	Balance
AA6061	0.8-1.2	0.4-0.8	0.7	0.15-0.4	0.15	0.04-0.35	Max.	0.15	Balance

3.2.1 Sample Configurations:

Two sample configurations were prepared: -

1. **Sample A:**Two pieces of AA 5052 joined together (AA 5052 - AA 5052). This configuration serves as a baseline for comparison with the dissimilar joint.

2. **Sample B:**AA 5052 and AA 6061 joined together (AA 5052 - AA 6061). This configuration investigates the feasibility and challenges of joining dissimilar materials.

3.2.2 Welding Techniques:

FSW is the solid-state joining process generates frictional heat and stirring to plasticize the materials and create a bond without melting them as show in figure 3.3. Specific FSW parameters like tool rotation speed, travel speed, and plunge depth were controlled and documented for each sample.

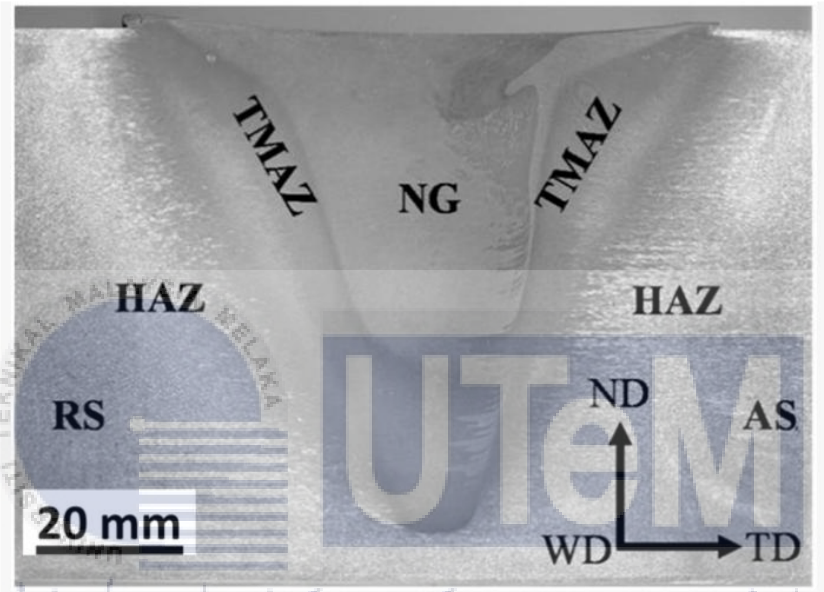


Figure 3.4: Transverse cross-section optical macrograph of friction-stir-welded 75 mm-thick AA6082 on which the different zones are labelled. TD, WD, and ND stand for transverse direction, welding direction, and normal direction, respectively (Ahmed et al., 2023).

3.2.3 Data Collection and Analysis:

Following welding, the samples were evaluated for various aspects: -

1. Joint strength:Tensile testing will be conducted to determine the mechanical strength of the joined region.
2. Microstructure:Optical microscopy will be used to examine the microstructure of the weld zone and assess the integrity of the bond.

3. Visual inspection:The weld appearance will be visually inspected for potential defects like cracks, porosity, or incomplete penetration.

The collected data will be analysed to compare the performance of FSW on both similar and dissimilar material combinations. The findings will contribute to understanding the optimal joining approaches for different aluminum alloy configurations in various applications.

3.3 Method

3.3.1 Friction Stir Welding

By using Fiction Stir welding machine as per figure 3.4 to joining the materials, the plates to be fused were mechanically and chemically cleaned with acetone to remove surface contamination. Table 3.2 shows the tool dimensions and Figure 3.5 depicts the tool. H13 tool steel was used to fabricate the cylindrical pin tool. H13 is a chromium-molybdenum alloy commonly used for tooling due its durability and thermal stability, qualities which led to its selection here. The shoulder angle is an important parameter as it helps reduce flash generation during welding. The welding was performed using an FSW machine. A double-sided butt joint configuration was used to join the materials. Table 3.3 lists the welding process parameters. Figures 3.6 and 3.7depict the welding process setup.

Figure 3.5: Friction stir welding machine.

Table 3.2: Tool dimensions.

Measurement	Dimension
Tool holder	25 mm
Tool holder diameter	12 mm
Shoulder diameter	25 mm
Shoulder gap	5.8 mm
Pin diameter	9 mm
Thickness of upper shoulder	18 mm
Thickness of lower shoulder	8 mm
Angle of convex shoulder	5o

Figure 3.6: Pin tool for FSW.

Table 3.3: FSW parameter

Tool thickness	Pin 2mm
Tool tilt angle	2.5º from vertical axis
Pressure	400 kg
Tool rotation speed	800 rpm

Figure 3.7: Machine coding setup.

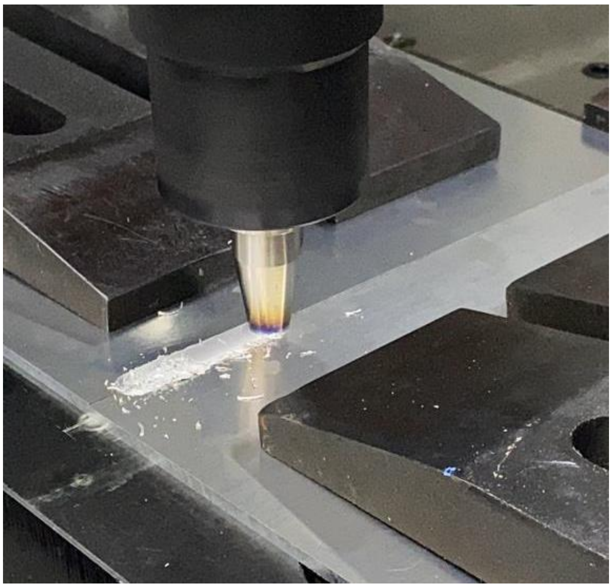


Figure 3.8: Plates welded using FSW.

3.3.3 Non-destructive Test

Non-destructive testing (NDT) techniques are used to evaluate the quality of welded joints without damaging the material. In this study, A-scan ultrasonic testing using the Olympus Epoch 650 ultrasonic flaw detector was employed to assess the welded joints. A-scan ultrasonic testing is based on the principle of using high-frequency sound waves to detect indications in the material. The Olympus Epoch 650 ultrasonic flaw detector was used to perform A-scan measurements, providing a high level of inspection performance for evaluating the quality of the welded joints.

Prior to testing, an ultrasonic couplant was applied to the surface of the welded samples. The couplant ensures good acoustic contact between the transducer and the test piece, allowing for efficient transmission of ultrasonic energy into the material.The A-scan technique provides a time-based display of the amplitude of the received ultrasonic signals. This allows for the detection and characterization of internal defects, such as porosity, lack of fusion, or cracks within the welded joint. Additionally, the A-scan can be used to measure material thickness and assess the overall integrity of the weld. By employing A-scan ultrasonic testing with proper couplant application, this study aims to provide a comprehensive non-destructive evaluation of the friction stir welded joints between dissimilar aluminum alloys. This NDT technique helps assess the quality of the welded joint without damaging the material, complementing the other experimental analysis techniques used in this project as show in figure 3.8.

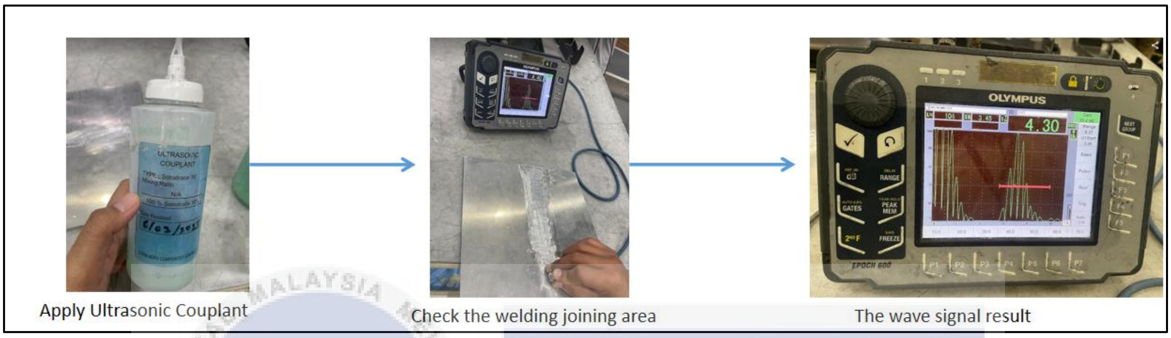


Figure 3.9: A-scan process.

3.3.4 Testing and analysis

3.3.4.1 Surface morphology analysis

The samples were cut using bandsaw Bomar stg230gb at FKP machining lab with the dimensions 20 mm x 10 mm x 4 mm. After that, the samples were ground using sandpaper with grits of 200, 400, 600, 800 and 1200 sequentially to remove any scratches from the cutting process. Mouting sample by using resin and mould and left at temperature room for one day as per figure 3.9.

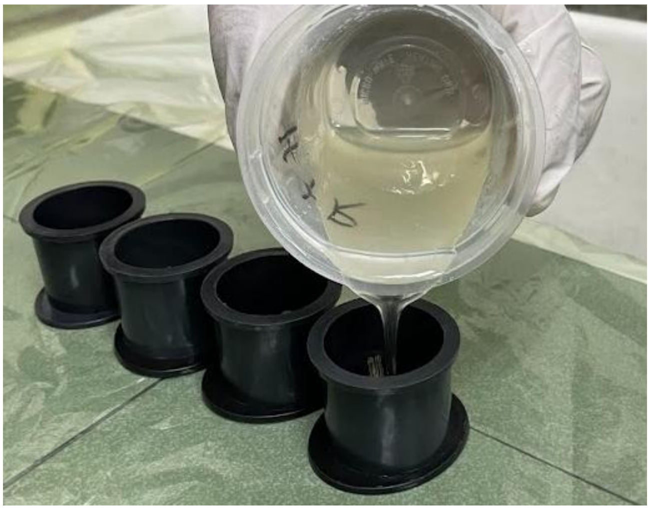


Figure 3.10: Mounting process for similar and dissimilar FSW sample.

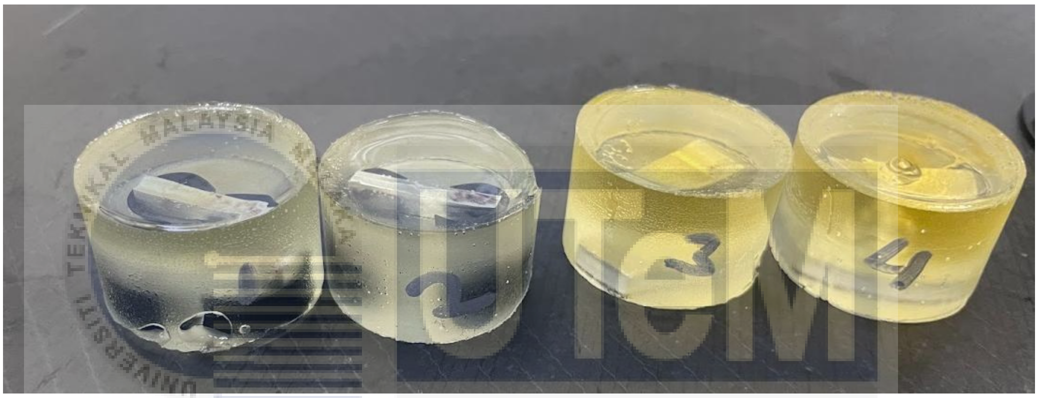


Figure 3.11: Sample after demould process

Sample had cure process then demould sample as showed at figure 3.10. A Buehler grinder-polisher was used, as shown in Figure 3.11, to conduct the grinding.

Figure 3.12: Buehler grinder-polisher.

Following the grinding process, the samples were polished using a 1 μm diamond suspension until achieving a mirror-like finish, as depicted in 3.13. A Metkon Grinder-

Polisher, as shown in Figure 3.12, was employed to conduct the polishing process. Prior to polishing, the pad was made moderately wet with diamond lubricant to prevent scratching of the sample surfaces during the process.

Figure 3.13: Metkon Grind.

Figure 3.14: Appearance sample with mirror.

The polished samples as show in figure 3.16 were then observed under an optical microscope to ensure freedom from scratches. Next, the samples were sent to the SEM lab for surface morphology analysis using scanning electron microscopy (SEM).

Figure 3.15: FESEM-EDX Machine.

SEM observation was performed using a microscope equipped with FESEM-EDX capabilities for mapping, point, and line analyses. As depicted in Figure 3.15, areas of interest were demarcated on the samples with fine lines prior to SEM examination.

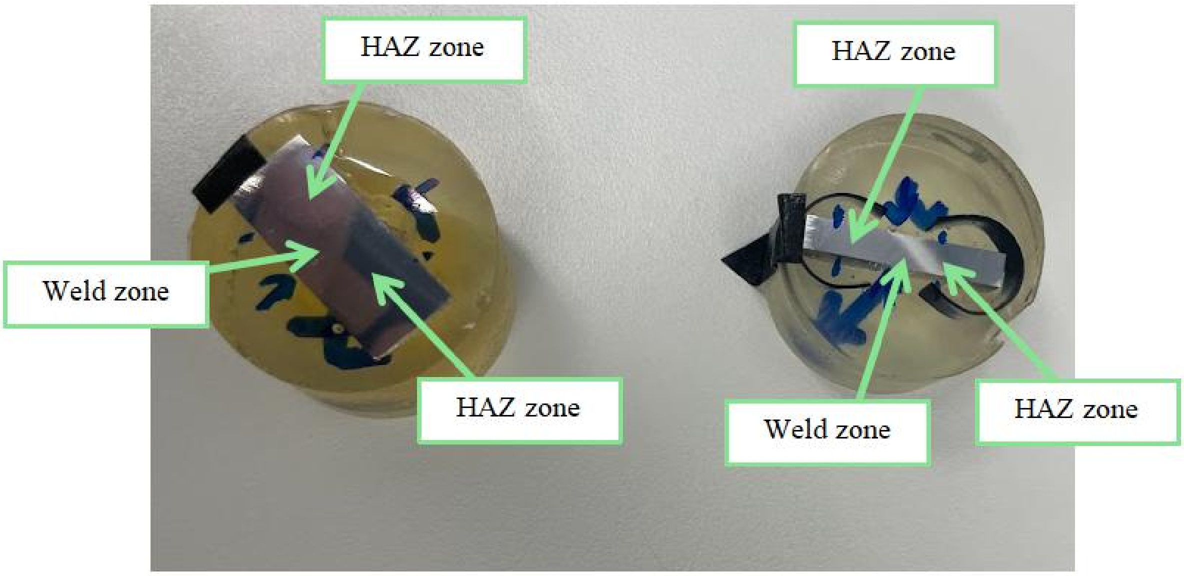


Figure 3.16: Points that will be observed for surface morphology test FSW dissimilar and FSW similar

3.3.4.2 Tensile test

Tensile testing of the samples was performed at room temperature using a 20kN capacity Shimadzu Universal Tensile Machine (UTM), as depicted in Figure 3.18, in accordance with ASTM E8 standard procedures. A gripping length of 40mm and crosshead speed of 10 mm/min were employed. Prior to testing, sample preparation was conducted. Sharp edges from the cutting process were removed using a square file. The samples were cut into rectangular prisms measuring 300 mm x 8 mm x 4 mm as shown in 3.17. Figure 3.19 depicts the tensile testing process.

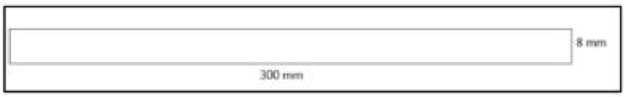


Figure 3.17: The dimension of sample FSW for Tensile Test.

Figure 3.18: Shimadzu Universal Tensile Machine (UTM) 20kN.

Figure 3.19: Tensile test.

3.3.4.3 Hardness test

Hardness testing was performed using a Vickers hardness tester, as depicted in 3.21, with a conical diamond indenter. Sample hardness was determined by measuring the depth of indenter penetration under an applied test force of 60 kgf. Prior to testing, the samples were cut into rectangular prisms measuring 200 mm x 10 mm x 4 mm, as shown in Figure 3.20, along which the indented imprints were made within the cross-sectional area. Testing sites included the weld zone, heat-affected zone (HAZ), and base material. Measurements at each site were taken three times and averaged.

Figure 3.20: The dimension of sample FSW for Hardness Test.

Figure 3.21: Vickers Hardness tester

3.3.4.4 Corrosion testing

Corrosion test perform by using methode Linear sweep voltammetry (LSV). LSV is a simple electrochemical analysis technique. Similar to cyclic voltammetry, LSV involves a single linear potential sweep from the lower to upper potential limit, rather than cycling potential bidirectionally. Table 3.4 lists the equipment used to perform the LSV tests and outlines the test parameters.

Table 3.4: List of equipment for LSV

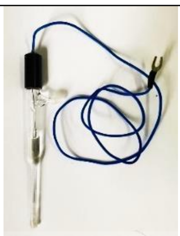
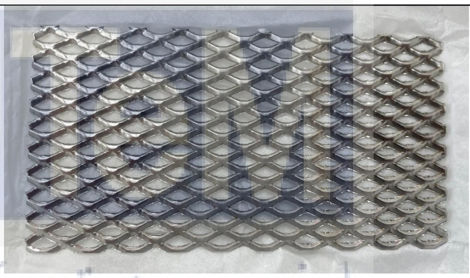
Equipment	Figure
Autolab PGSTAT 101	
Reference electrode:silver/silver chloride (Ag/AgCl) electrode saturated in potassium chloride (KCl)	
Counter electrode:Platinum mesh (Pt)	
Working electrode: FSW; 5052-5052, 5052-6061 BM; 5052,6061	
Electrolyte:0.35 NaCl	

Table 3.5: Parameter for LSV

No.	Specification	Condition
1	Test Solution	3.5wt. % NaCI solution
2	Scanning range	Range -1.5V to 1V
3	Scanning	Rate 1 mV/s
4	Sample Area	100 mm^2
5	Measurement Method	Linear Voltammetry Measurement

The procedures to complete the test has been listed as below:

1. Samples Preparation

i. The samples were cut into rectangular prisms measuring 200mm x 10 mm x 4 mm using a Bomar STG230GB bandsaw in the FKP machining lab, as depicted in Figure 3.22. After that, all the samples were covered with Araldite paste resin and left with only welded surface as in figure 3.23. It is to make sure other surfaces will not be affected during electrochemical process.

ii. Next, the top surface of each sample was soldered using a Pulsivo soldering kit, as shown in Figure 3.24. A tin solder wire was used. After that, all the samples were covered with Araldite paste resin and left with only welded surface as in figure 3.23. It is to make sure other surfaces will not be affected during electrochemical process.

iii. Electrolyte Preparation (NaCl Solution):First, 14.61g of NaCl powder was weighed to prepare 0.5M NaCl solution. The powder was then dissolved in 500 ml of distilled water.

Figure 3.22: Bandsaw Bomar stg230gb

Figure 3.23: Sample for LSV

Figure 3.24: Pulsivo soldering kit

v. Experiment Setup:The electrochemical test using LSV was set up as depicted in Figure 3.25. Cable connections were properly made according to electrode type and labeled to avoid erroneous connections. A PGSTAT 101 potentiostat was connected to a computer to observe oxidation graphs of the samples using NOVA 1.10 software. Upon starting the experiment, a linear graph appeared showing reactions between the electrodes and electrolyte. The y-axis was changed to log scale for improved visibility given the small linear current values.

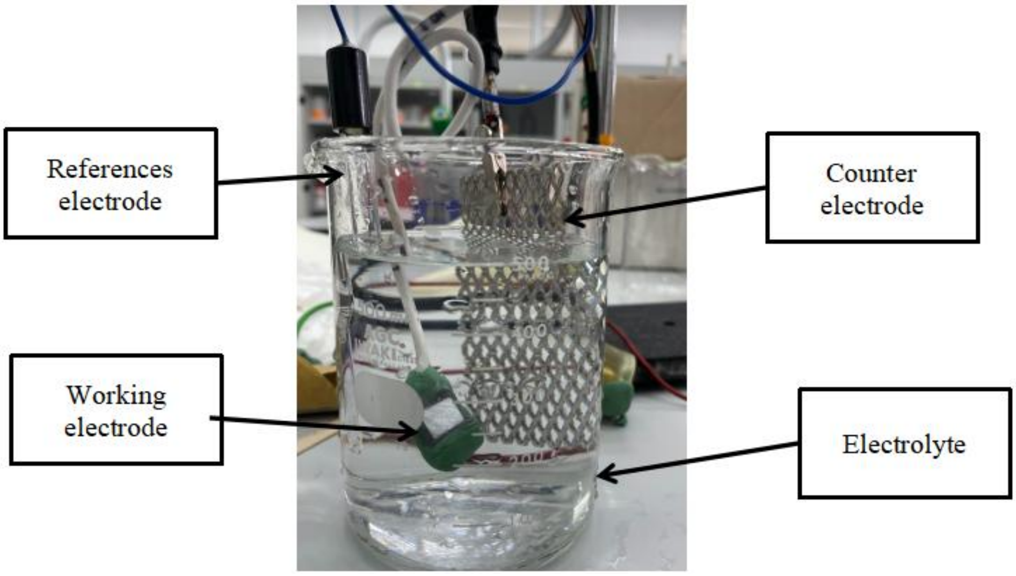


Figure 3.25: Experiment electrochemical test using LSV

3.3.4.5 Wear analysis

Wear testing as show in figure 3.26 is a crucial aspect of evaluating the performance and durability of materials, particularly in the context of friction stir welding (FSW). The methodology for wear testing involves subjecting the materials or welded joints to controlled wear conditions to assess their wear resistance. The following steps and considerations are typically included in the wear testing methodology. The pin-on-disk method is a commonly used tribological characterization technique to estimate the coefficient of friction and the wear mechanism of materials. In the context of FSW, pin-on-disk testing can be used to evaluate the wear behavior of the FSW joints. The test can be performed on the FSW joints to assess their wear resistance and to determine the wear mechanisms. The pin-on-disk test can provide valuable insights into the wear characteristics of FSW joints and the effects of process parameters on the wear behavior of the welds.

Pin-on-disk testing involves the following steps:

1. Selection of Test Parameters:Pin-on-disk testing involves the selection of appropriate test parameters such as load, sliding speed, and sliding distance. These parameters are chosen based on the specific application and the expected operating conditions of the materials or welded joints being tested.
2. Preparation of Test Specimens:The test specimens are prepared according to the specific requirements of the pin-on-disk test. The specimens are typically machined to a specific size and shape and polished to a specific surface finish.
3. Measurement of Coefficient of Friction:During the pin-on-disk test, the test specimen is subjected to controlled wear conditions, and the resulting friction force or the coefficient of friction is measured continuously. The coefficient of friction is a critical parameter in FSW, affecting the heat generation, material flow, and weld quality.
4. Measurement of Wear:The wear is subsequently determined by measuring the wear track and the abrasion of the test. This may involve measuring the mass loss, wear width, or scar depth, depending on the specific test method being employed.
5. Data Analysis:Once the pin-on-disk testing is complete, the data obtained from the measurements are analyzed to determine the wear characteristics of the materials or welded joints. This analysis may include calculating the wear rate, wear coefficient, or other relevant parameters to quantify the wear behavior.
6. Reporting of Results:The findings from the pin-on-disk testing are then reported, including the test parameters, the measured coefficient of friction, the measured wear characteristics, and any relevant conclusions drawn from the analysis. This

information is essential for evaluating the wear resistance of the materials or welded joints and informing design and material selection decisions.

In summary, pin-on-disk testing is a commonly used tribological characterization technique to estimate the coefficient of friction and the wear mechanism of materials. The test can be used to evaluate the wear behavior of FSW joints and to determine the wear mechanisms. The pin-on-disk test can provide valuable insights into the wear characteristics of FSW joints and the effects of process parameters on the wear behavior of the welds.

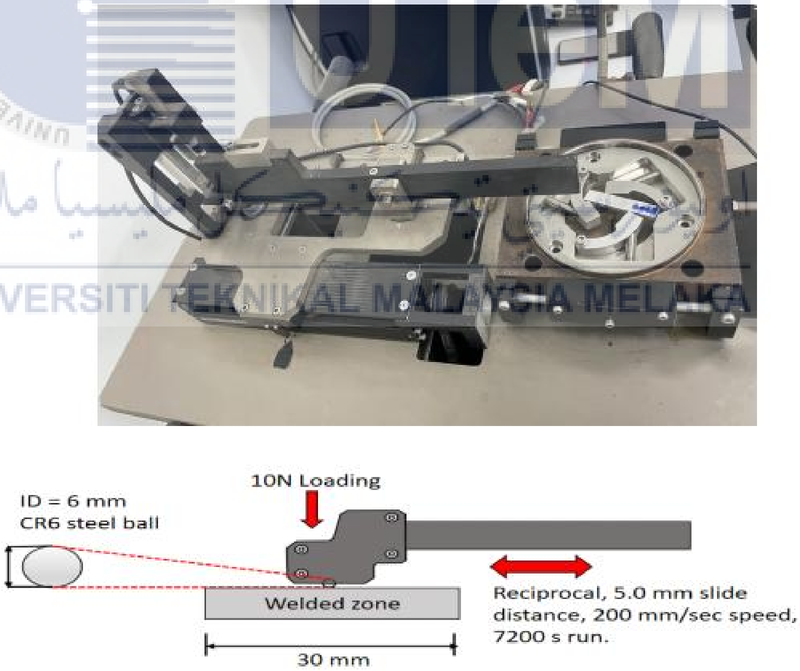


Figure 3.26: Pin-on-disk experiment.

3.4 Equipment

1. Friction stir welding (FSW) machine - To fabricate FSW joints of AA5052 and AA6061 aluminum alloy samples. The FSW machine would allow adjusting welding parameters like tool rotation speed, welding speed, etc.
2. Milling machine - To prepare the aluminum alloy samples to the required size and dimensions prior to welding. Cutting, facing and milling operations can be done.
3. Universal testing machine - To conduct tensile testing of welded samples and determine properties like yield strength, tensile strength.
4. Microhardness tester - Vickers hardness tester to map the microhardness across welded cross-sections.
5. Potentiostat - To perform electrochemical tests like linear scanning voltammetry for evaluating corrosion resistance of welded zones.
6. Imaging/analytical equipment - Microscopes, profilometer etc. for qualitative and quantitative analysis of corroded surfaces.
7. Field emission scanning electron microscope (FESEM) - Used for microstructural characterization of the welded zone.
8. Energy dispersive X-ray spectroscopy (EDX) - Used alongside FESEM for chemical analysis.
9. Mirror polishing equipment - To prepare and polish welded joint surfaces for microscopy.
10. Olympus Epoch 650 ultrasonic flaw detector - Employed for ultrasonic thickness measurements to detect flaws/porosity.

3.5 Limitation of Proposed Methodology

While the methodology aims to characterize the mechanical and electrochemical properties of the weld samples systematically, some limitations should be acknowledged:

1. Sample Size and Geometry:Only samples of specific dimensions (20x20x4 mm) were tested. Larger or differently shaped samples may yield different results.
2. Testing Conditions:Hardness, tensile and LSV tests were conducted under controlled laboratory conditions. Variations in testing environments could impact measurements.
3. Equipment Capabilities:Testing was limited to the measurement capabilities and accuracies of the specific equipment used (e.g. load cell rating for tensile tests).
4. Environmental Effects:Corrosion performance was assessed based on short-term potentiodynamic polarization only. Long-term corrosion behavior under different environmental conditions was not evaluated. Preparation and testing of samples involved some manual processes which introduce possibility of human errors.
5. Data Interpretation:Results analysis relies on generally accepted understanding of corrosion and mechanical failure mechanisms but alternatives are possible.

Further investigation with modified procedures, additional tests, and statistical analysis techniques could help address some of these limitations. The methodology provides a basis for initial evaluation, but refined approaches may be needed for comprehensive characterization.

3.6 Summary

The methodology involved characterization of friction stir welded (FSW) dissimilar alloy joints between 4 mm thick brass and aluminum alloy plates. FSW was conducted using a machine at fixed parameters to fabricate the joints.

Sample preparation included cutting, grinding and polishing specimens measuring 20x20x4 mm from the FSW joints. Microstructural analysis of welded zones was performed using FESEM-EDX. Ultrasonic thickness measurements also evaluated potential defects.

Electrochemical corrosion testing by Linear polarization voltammetry (LSV). The experiment used a three-electrode cell and potentiostat to apply voltages from -1.5v to 1V vs reference and analyze corrosion behavior of the FSW sample as working electrode.

Characterization involved mechanical properties analysis, microstructure examination, LSV polarization curves, and immersion test results to provide a comprehensive multi-level evaluation of the FSW dissimilar alloy joints fabricated under controlled laboratory conditions. This integrated approach assessed microstructure, defects and corrosion performance.

CHAPTER 4

RESULT AND DISCUSSION

This chapter discusses and analyzes the results obtained from friction stir welding (FSW) of dissimilar materials (AA5052 and AA6061) and similar materials (AA6061). The analysis compares the two types of material joints by examining the surface morphology, tensile strength, hardness, wear resistance, and electrochemical properties using linear scanning voltammetry. It is crucial to observe and analyze the differences in microstructure, chemical composition, and new phases formed due to the welding technique. The changes in these properties can significantly impact the mechanical and corrosion behavior of the welded joints.

The mechanical properties, including tensile strength and hardness, will be discussed in detail. These properties are critical in determining the suitability of the welded joints for various applications. Furthermore, the corrosion behavior of the welded joints will be analyzed using Tafel polarization curves, and the corrosion rates will be calculated using Nova Software. Corrosion resistance is a vital consideration, especially in harsh environments where the materials are exposed to corrosive media.

By the end of this chapter, the differences between the two types of material joints produced using FSW will be concluded based on the analysis of surface morphology, tensile strength, hardness, corrosion behavior, and wear resistance. This comprehensive analysis will provide insights into the advantages and limitations of dissimilar and similar material joining using FSW, enabling informed decision-making for future applications.

4.1 Tribiology Analysis

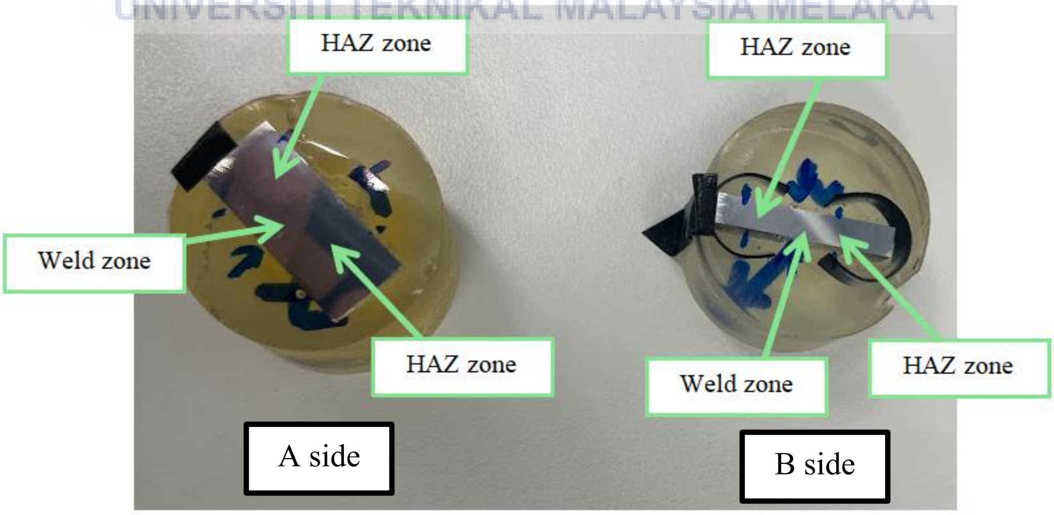


Figure 4.1: Specimens for FESEM-EDX for similar and dissimilar FSW.

Surface morphology and wear behavior play crucial roles in understanding the tribological performance of friction stir welded joints. This section examines the surface characteristics, microstructural features, and wear resistance of the similar (AA6061) and dissimilar (AA6061-AA5052) aluminum alloy joints produced by friction stir welding (FSW) as per figure 4.1. The analysis of surface morphology provides valuable insights into the material mixing, grain refinement, and potential defect formation that occur during the FSW process, all of which significantly influence the wear resistance and friction properties of the welded joints.

Scanning Electron Microscopy (SEM) was employed to obtain high-resolution images of the weld surfaces, revealing detailed topographical features and microstructural characteristics across different weld zones. This technique allowed for the visualization of grain structures, material flow patterns, and any defects or irregularities resulting from the welding process. Additionally, Energy Dispersive X-ray Spectroscopy (EDX) analysis complemented the SEM observations by providing elemental composition information, crucial for understanding the distribution of alloying elements and any potential formation of intermetallic compounds at the weld interface.

To evaluate the wear resistance of the welded joints, reciprocating pin-on-disk wear tests were conducted. This testing method involves subjecting the welded specimens to controlled wear conditions, providing quantitative data on wear rates, friction coefficients, and wear track characteristics. The wear tests were performed using a 10N load, 200 mm sliding distance, 5 mm ball size, and a running time of 7200 seconds.

The following subsections present a comprehensive analysis of the surface morphology and wear behavior for both similar and dissimilar FSW joints, focusing on:

1. Weld zone microstructure and grain characteristics

2. Material flow patterns and mixing effectiveness

3. Presence and distribution of any defects or irregularities

4. Elemental composition across the weld zones

5. Wear rates and friction coefficients

6. Wear track width and morphology

7. Correlation between microstructure and wear performance

This analysis forms the foundation for understanding how the surface morphology and microstructural features influence the tribological behavior of the FSW joints, including their wear resistance and friction characteristics. The combination of surface analysis and wear testing provides a comprehensive evaluation of the joints' performance under simulated service conditions.

4.1.1 SEM Analysis

The SEM analysis of the similar AA6061 alloy weld zone revealed a uniform and defect-free surface with fine grains as show in figure 4.2 and figure 4.3.

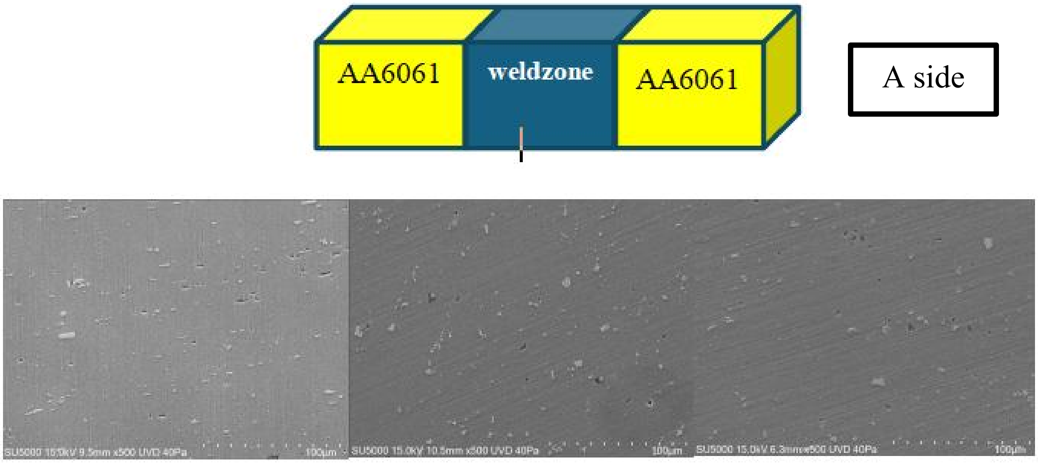


Figure 4.2: SEM result for similar FSW(A side) scale in 100µm

Figure 4.3: SEM result for similar FSW (B side) scale in 100µm

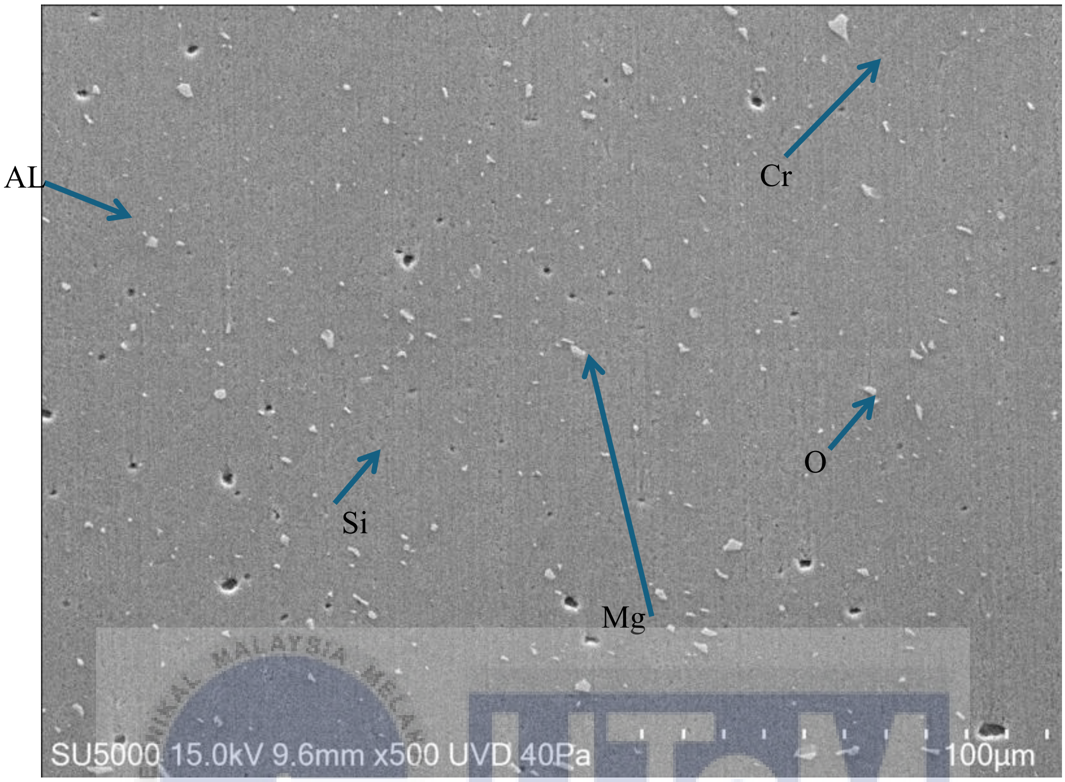
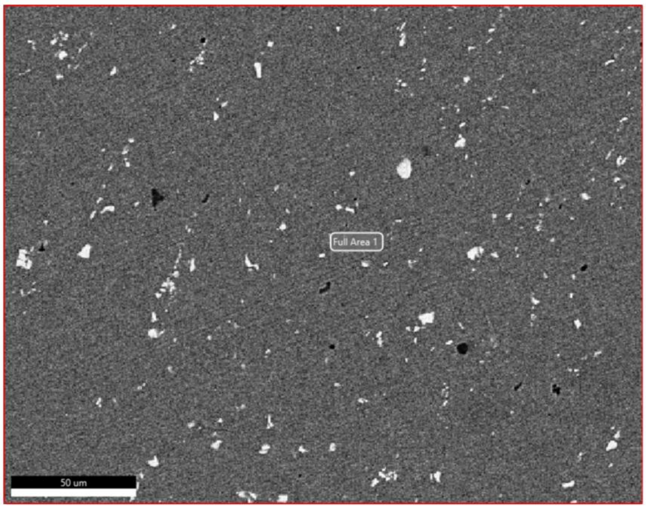


Figure 4.4: SEM image base on composition for Similar FSW scale in 100µm

The stir zone exhibited a characteristic swirl pattern indicative of good material mixing. Grain refinement was observed in the weld zone compared to the base material show in figure 4.4 and 4.5, suggesting dynamic re-crystallization during the FSW process.

Sample Name: similar

Area 2



eZAF Quant Result - Analysis Uncertainty: 99.00 %

Element	Weight %	Atomic %
C	12.7	24.4
O	2.0	2.9
M g	1.4	1.3
A l	83.6	71.2
S i	0.3	0.2

Figure 4.5: SEM image and composition % for Similar FSW scale in 100µm

The elemental composition analysis showed the presence of carbon (12.7% weight, 24.4% atomic), oxygen (2.0% weight, 2.9% atomic), magnesium (1.4% weight, 1.3% atomic), aluminum (83.6% weight, 71.2% atomic), and silicon (0.3% weight, 0.2% atomic) as show in figure 4.6.

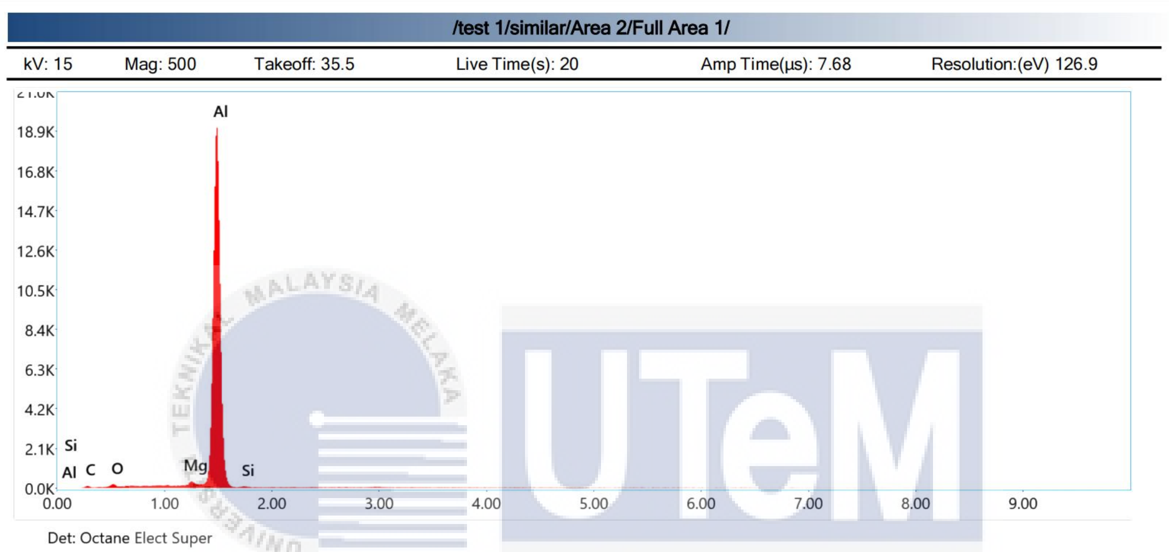


Figure 4.6: SEM image and composition % for Similar FSW

In the case of the dissimilar AA6061 and AA5052 alloy joint, the SEM analysis displayed distinct regions corresponding to each alloy.

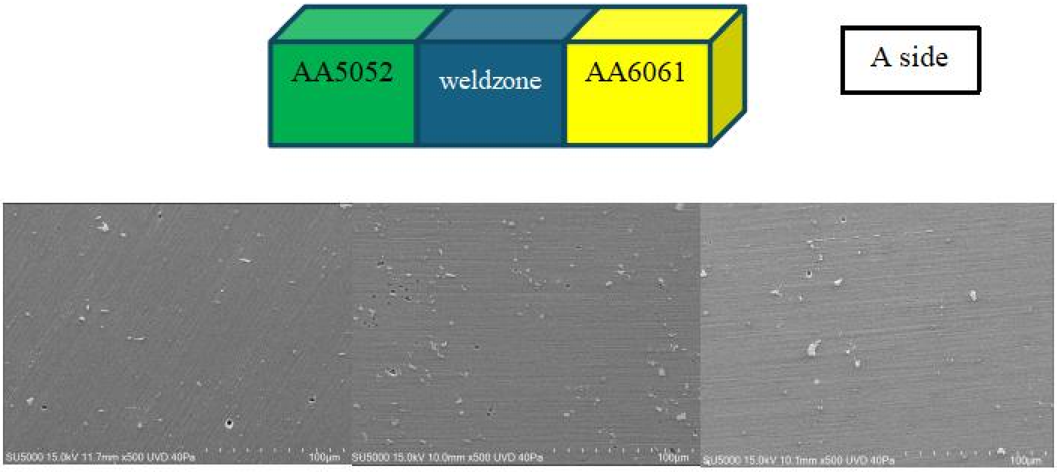


Figure 4.7: SEM result for dissimilar FSW(A side) scale in 100µm

Figure 4.8: SEM result for dissimilar FSW(B side) scale in 100µm

The interface between AA6061 and AA5052 showed good metallurgical bonding without visible cracks or voids as show in figure 4.7 and figure 4.8. A transition zone was evident, with intermixed grains from both alloys, indicating effective stirring and bonding as show in figure 4.9 and 4.10.

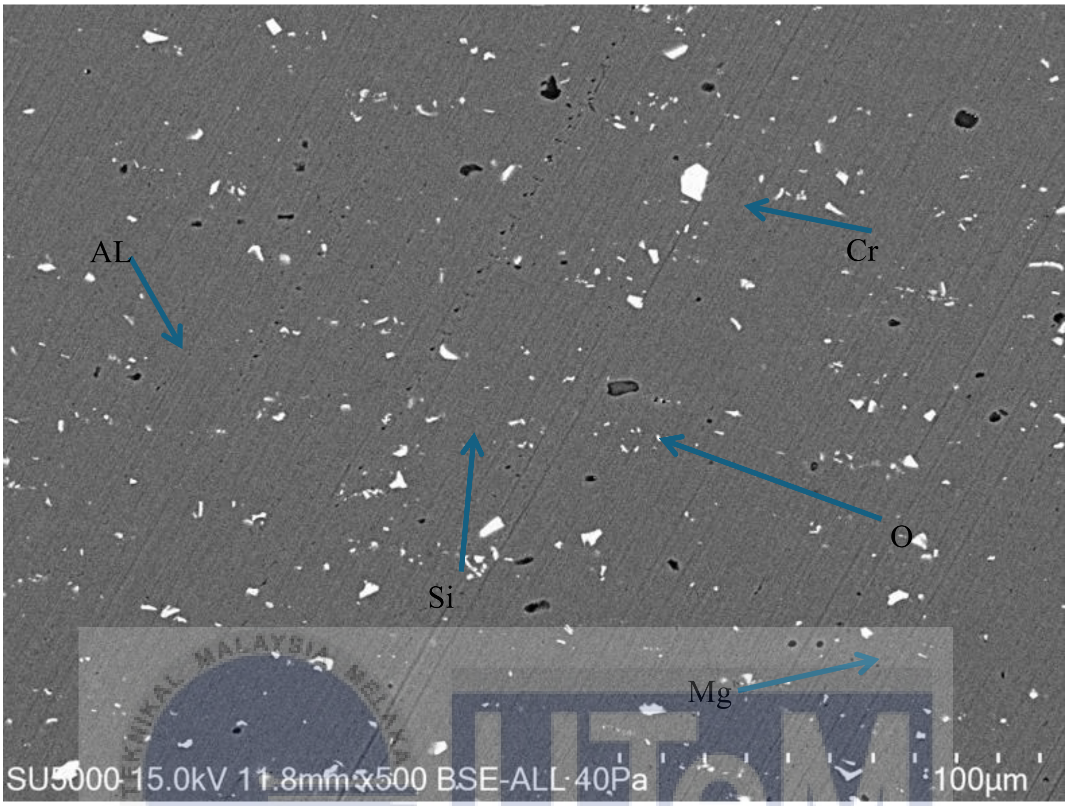


Figure 4.9: SEM image base on composition for Dissimilar FSW scale in 100µm

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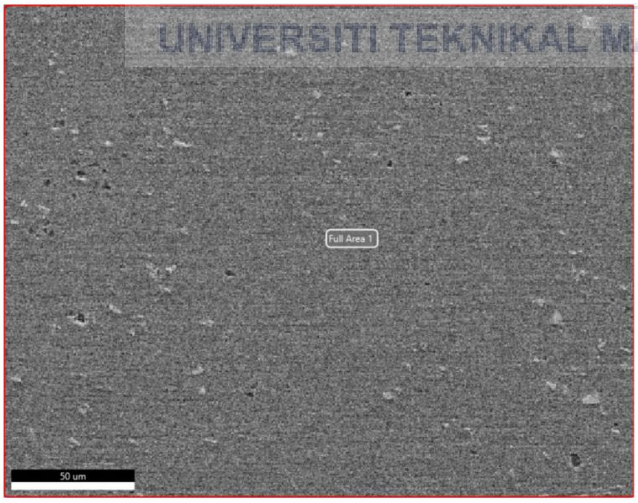
Sample Name: dissimilar

Area 1



eZAF Quant Result - Analysis Uncertainty: 99.00 %

Element	Weight %	Atomic %
C	12.2	23.6
O	1.4	2.1
Mg	1.5	1.4
Al	84.6	72.7
Si	0.3	0.3

Figure 4.10: SEM image and composition % for dissimilar FSW.

The elemental composition in this zone included carbon (12.2% weight, 23.6% atomic), oxygen (1.4% weight, 2.1% atomic), magnesium (1.5% weight, 1.4% atomic), aluminum (84.6% weight, 72.7% atomic), and silicon (0.3% weight, 0.3% atomic) as show in figure 4.11.

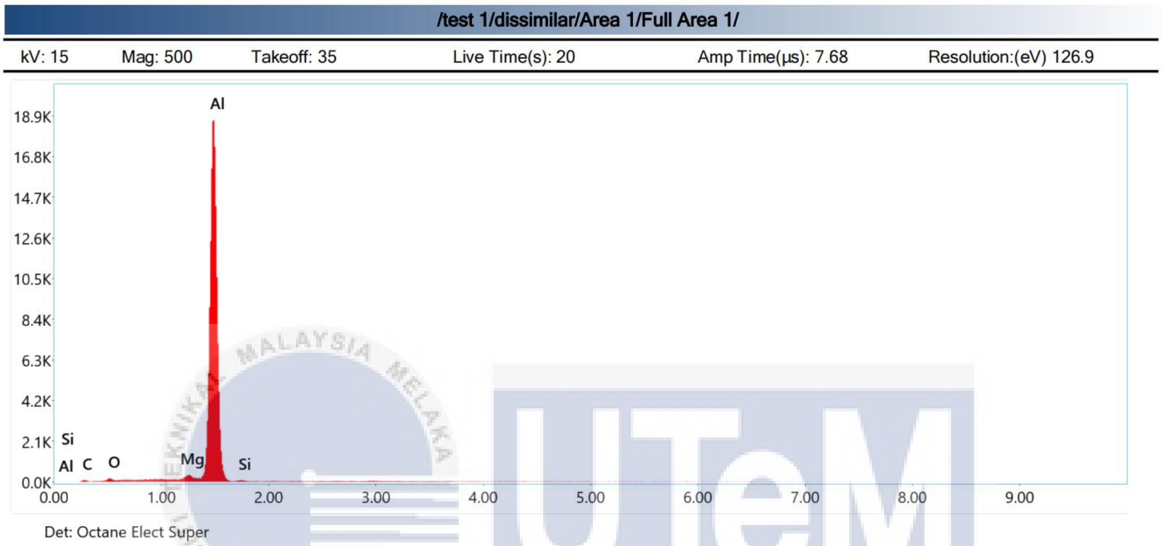


Figure 4.11: SEM image and composition % for dissimilar FSW

4.1.2 EDX Analysis

Energy Dispersive X-ray Spectroscopy (EDX) analysis provided valuable insights into the elemental composition and distribution across the weld zones for both similar and dissimilar alloy joints. For the similar AA6061 alloy weld, EDX revealed a uniform distribution of alloying elements including magnesium, silicon, and copper throughout the weld zone. This homogeneous elemental distribution indicates effective material mixing during the friction stir welding process.

In the case of the dissimilar AA6061 and AA5052 alloy joint, EDX analysis across the weld interface demonstrated a gradual transition in elemental composition. The AA6061 side exhibited higher concentrations of silicon and copper, while the AA5052 side showed elevated magnesium content, as expected based on the nominal compositions of these alloys. The interface region displayed an intermediate composition, suggesting interdiffusion of elements during welding. This gradual transition in elemental distribution corroborates the successful joining of the dissimilar alloys at the microscopic level.

Furthermore, EDX analysis detected the presence of intermetallic compounds at the weld interface of the dissimilar joint, consistent with the XRD findings. These intermetallic phases, such as Al3Mg2, provide evidence of chemical interactions and diffusion processes occurring between the two alloys during friction stir welding as show in figure 4.12 The formation of these compounds plays a crucial role in determining the mechanical and corrosion properties of the welded joint.

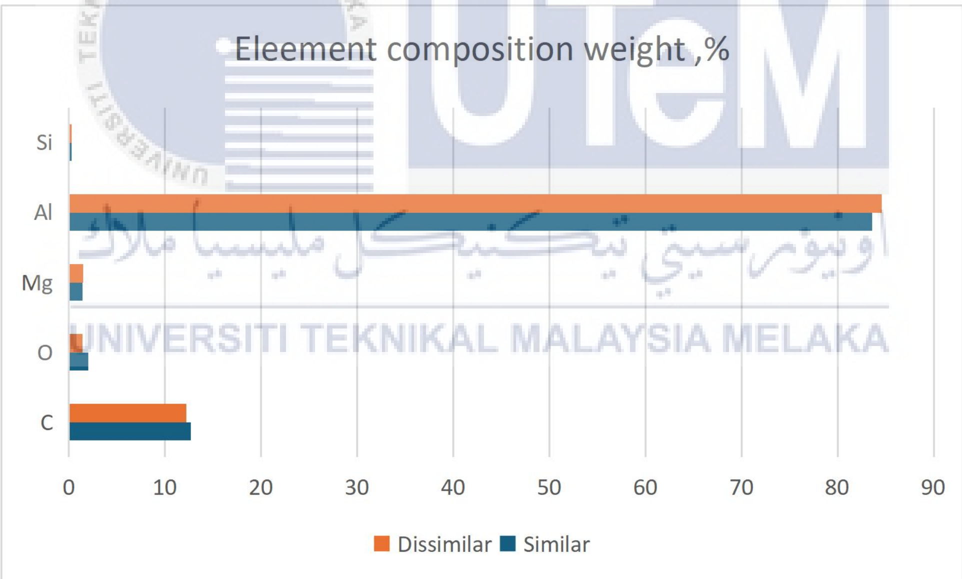


Figure 4.12: Material composition comparison between similar and dissimilar FSW

Overall, the EDX analysis complemented the microstructural observations from SEM, offering quantitative data on elemental distribution and confirming the effectiveness of the friction stir welding process in achieving good metallurgical bonding for both similar and dissimilar aluminum alloy combinations.

4.1.3 Wear and Tear Analysis:Reciprocating Pin-on-Disk Test

The reciprocating pin-on-disk wear test evaluates the wear resistance of the materials in both similar (AA6061) and dissimilar (AA6061 & AA5052) welded joints. This test measures the rate of material loss due to friction and wear under reciprocating motion, providing insights into the durability and longevity of the welded joints under operational conditions. The reciprocating pin-on-disk test involves a pin sliding back and forth on a disk specimen under controlled conditions of load, speed, and time. The key parameters recorded as per table 4.1.

Table 4.1: Reciprocating Pin-on-Disk Test parameter

Load	10N
Distances	200mm
Ball size (diameter)	5mm
Running time	7200s

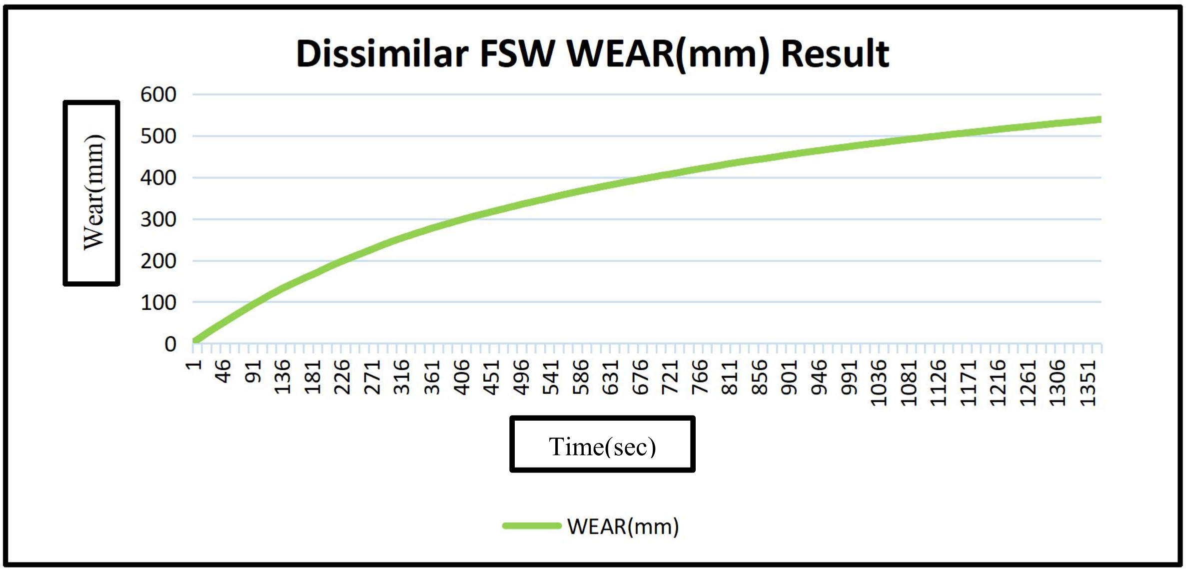


Figure 4.13: Wear result for FSW Dissimilar Material AA6061& AA5052.

The dissimilar material (AA6061 & AA5052) exhibited a wear rate of 0.2995mm/s, which was higher than the similar material, the wear rate for the similar material (AA6061) was found to be 0.1091mm/s, indicating high wear resistance. The result as per figure 4.13 and figure 4.14

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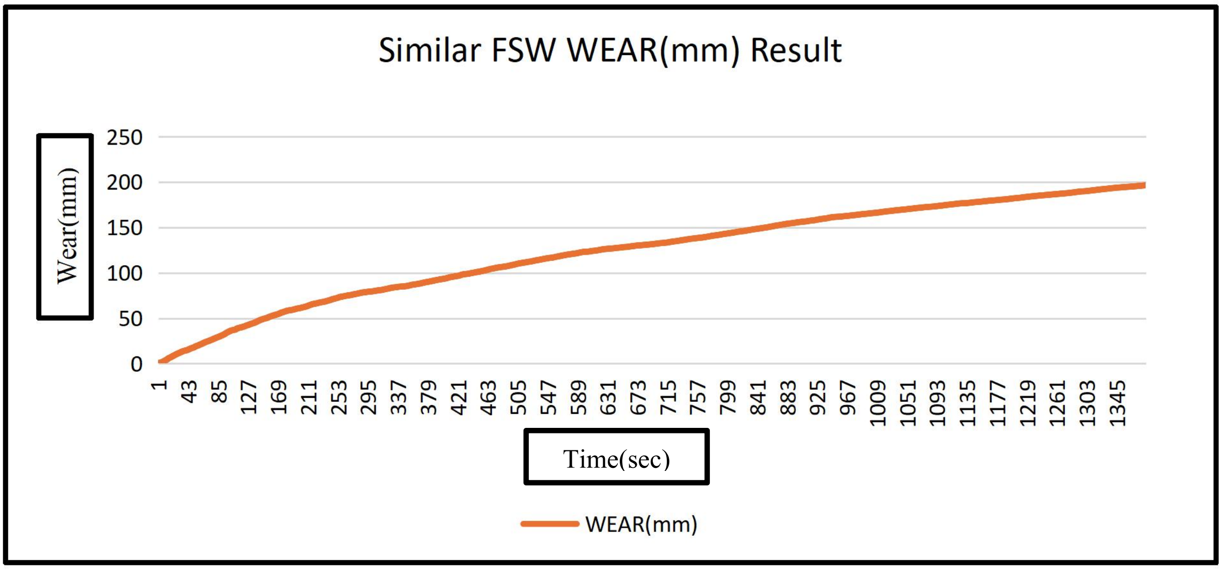

Figure 4.14: Wear result for FSW similar Material AA6061& AA6061.

4.1.3.1 Friction Coefficient Analysis

The friction coefficient for the similar AA6061 material was 0.30, indicating moderate frictional resistance. The dissimilar AA6061 & AA5052 joint showed a friction coefficient of 0.35, which was higher than the similar material as per graph show in figure 4.15. This difference in frictional behavior can be attributed to the interaction between the different alloy compositions at the weld interface, affecting the overall frictional properties.

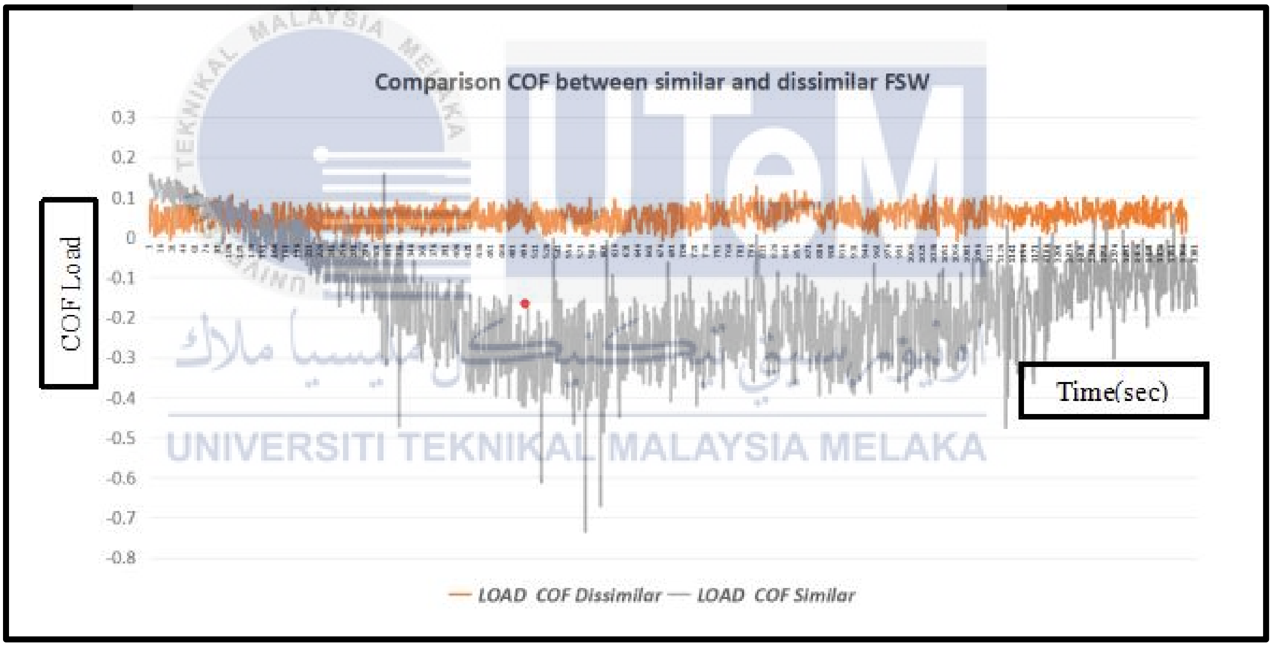

Figure 4.15: COF comparison result for FSW similar Material AA6061& AA6061

4.1.3.2 Wear Track Width Observation

The wear track width for the similar AA6061 material was measured at 0.7 mm, reflecting the extent of the wear path. The dissimilar joint (AA6061 & AA5052) had a wear track width of 0.8 mm as show in figure 4.16. The wider wear track suggests that the dissimilar material experienced more wear under the same testing conditions, highlighting its reduced wear resistance compared to the similar joint.

Figure 4.16: Wear track for dissimilar FSW

4.1.3.3 Material Composition and Wear Behavior

The higher wear resistance of the similar AA6061 joint could be attributed to the homogeneous nature of the material, which maintains consistent properties throughout the weld. The dissimilar AA6061 & AA5052 joint, on the other hand, may exhibit different wear characteristics due to the varying properties of the two alloys and the potential formation of intermetallic compounds at the interface, which could lead to increased wear.

The findings from the reciprocating pin-on-disk test suggest that the similar AA6061 joint is more suitable for applications requiring high wear resistance and durability.

The dissimilar AA6061 & AA5052 joint, while exhibiting adequate wear resistance, may be more appropriate for applications where wear is less critical or where the unique properties of the combined alloys offer other advantages.

4.1.4 Discussion

The scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and reciprocating pin-on-disk wear test analyses collectively provide valuable insights into the microstructural evolution, elemental distribution, and wear behavior of friction stir welded joints between similar (AA6061) and dissimilar (AA6061-AA5052) aluminum alloys.

1. Microstructural Analysis:SEM examination of the similar AA6061 weld zone revealed a uniform and defect-free surface characterized by fine, equiaxed grains, with a distinctive swirl pattern in the stir zone indicative of effective material mixing. Notably, grain refinement was observed in the weld zone compared to the base material, suggesting dynamic recrystallization occurred during welding. For the dissimilar AA6061-AA5052 joint, SEM analysis displayed distinct regions corresponding to each alloy, with good metallurgical bonding at the interface and a transition zone featuring intermixed grains from both alloys.
2. Elemental Distribution:EDX analysis complemented the microstructural observations by providing crucial information on elemental distribution across the weld zones. The similar AA6061 alloy weld showed a uniform distribution of alloying elements (Mg, Si, Cu) throughout the weld zone, indicating homogeneous mixing. For the dissimilar AA6061-AA5052 joint, EDX analysis revealed a gradual transition in elemental composition across the weld interface, with the AA6061 side exhibiting higher concentrations of silicon and copper, and the AA5052 side showing elevated magnesium content.

3. Wear Behavior:The reciprocating pin-on-disk wear test results revealed significant differences in wear performance between the similar and dissimilar joints. The similar AA6061 joint demonstrated superior wear resistance compared to the dissimilar AA6061-AA5052 joint.

The superior wear performance of the similar AA6061 joint can be attributed to its homogeneous microstructure and uniform elemental distribution, as observed in the SEM and EDX analyses. The consistent properties throughout the weld zone likely contribute to more uniform wear behavior and better resistance to material loss.

In contrast, the dissimilar AA6061-AA5052 joint's lower wear resistance may be due to the varying properties of the two alloys and the potential formation of intermetallic compounds at the interface, as suggested by the gradual transition in elemental composition observed in the EDX analysis. These factors could lead to localized variations in hardness and wear resistance across the weld zone, resulting in increased overall wear.

These findings underscore the importance of material selection and welding process optimization in achieving desired wear performance in practical applications. While the dissimilar AA6061-AA5052 joint offers the advantage of combining properties from both alloys, it may be more suitable for applications where wear resistance is less critical or where the unique properties of the combined alloys offer other advantages.

The comprehensive analysis of surface morphology, elemental distribution, and wear behavior provides crucial insights into the complex material interactions occurring during FSW. This contributes to a deeper understanding of the process-structure-property relationships in these welded joints and highlights the trade-offs between using similar and dissimilar alloy combinations in friction stir welding for specific applications.

4.2 Mechanical analysis

The mechanical properties of friction stir welded joints are crucial indicators of weld quality and performance. This section presents a comprehensive analysis of the mechanical characteristics of the similar (AA6061) and dissimilar (AA6061-AA5052) friction stir welded joints. The mechanical properties were evaluated through tensile testing and hardness profile measurements across the weld zones.

Tensile testing provides critical information on the joint's strength, ductility, and failure behavior. Key parameters such as ultimate tensile strength (UTS), yield strength, and elongation at break were determined to assess the overall joint performance and compare it to the base materials. The location of fracture during tensile testing offers insights into the weakest region of the welded joint, which is often in the heat-affected zone (HAZ) or thermomechanically affected zone (TMAZ).

Hardness profiling across the weld cross-section reveals the local mechanical property variations resulting from the FSW process. Microhardness measurements were taken at regular intervals from the base material through the HAZ, TMAZ, and weld nugget to map the hardness distribution. This analysis helps identify any softening or hardening effects in different weld zones and correlates them with microstructural changes observed in the previous section.

The following subsections detail the results of tensile testing and hardness profiling for both similar and dissimilar FSW joints, providing a comparative analysis of their mechanical performance.

4.2.1 Tensile Testing

Tensile testing was performed to evaluate the mechanical properties of the welded joints of similar (AA6061) and dissimilar (AA6061 and AA5052) aluminum alloys. The tensile tests provided crucial data on the ultimate tensile strength (UTS), yield strength, and elongation at break for both types of welds as show in figure 4.17.

Test results:

Specimen ID	Width, b	Thickness,h	Maximum Force	Tensile Strength, σ_M	Tensile Modulus, E_t
	mm	mm	N	MPa	MPa
SIMILAR AA6061	10.07	4.05	8149.90	199.833	65440.819
SIMILAR AA6061	9.93	4.09	8125.59	200.070	43825.115
DISSIMILAR AA6061/5052	9.93	4.00	8920.02	224.573	71040.526
DISSIMILAR AA6061/5052	10.29	4.06	8404.79	201.180	45583.151

Statistics:

Series	Width, b	Thickness,h	Maximum Force	Tensile Strength, σ_M	Tensile Modulus, E_t
n = 4	mm	mm	N	MPa	MPa
$\bar{x}$	10.06	4.05	8400.08	206.414	56472.403
s	0.17	0.04	368.92	12.120	13798.459
ν	1.69	0.92	4.39	5.87	24.43

Figure 4.17: Tensile result comparison between similar and dissimilar welding

For the similar alloy (AA6061) joint, the tensile test results indicated a tensile strength of 199.833-200.070 MPa and an elongation at break of 5.3%. The fracture predominantly occurred in the heat-affected zone (HAZ) rather than in the weld zone itself, suggesting that the weld zone was stronger than the surrounding material. This behaviour is indicative of good weld quality but highlights the comparative weakness of the HAZ due to thermal effects during welding.

In contrast, the dissimilar alloy (AA6061 and AA5052) joint exhibited a tensile strength of 201.180-224.573 MPa, which was higher than that of the similar alloy joint. The elongation at break for the dissimilar joint was 6.2%. The fracture in these joints typically occurred at the interface between AA6061 and AA5052, yet the effective bonding at the interface contributed to the higher overall tensile strength as show in figure 4.18. The results suggest that the combination of AA6061 and AA5052 in the friction stir welding process resulted in a joint with superior mechanical properties.

Figure 4.18: Tensile failure of Dissimilar FSW

The improved performance of the dissimilar alloy joint can be attributed to the effective mixing and metallurgical bonding facilitated by the FSW process, which resulted in a strong and ductile interface. Additionally, the presence of intermetallic compounds such as Al3Mg2 at the interface, although typically considered brittle, may have contributed to the strengthening effect observed in the tensile tests. The detailed tensile properties of both similar and dissimilar alloy joints are summarized in graph below as show in figure 4.19.

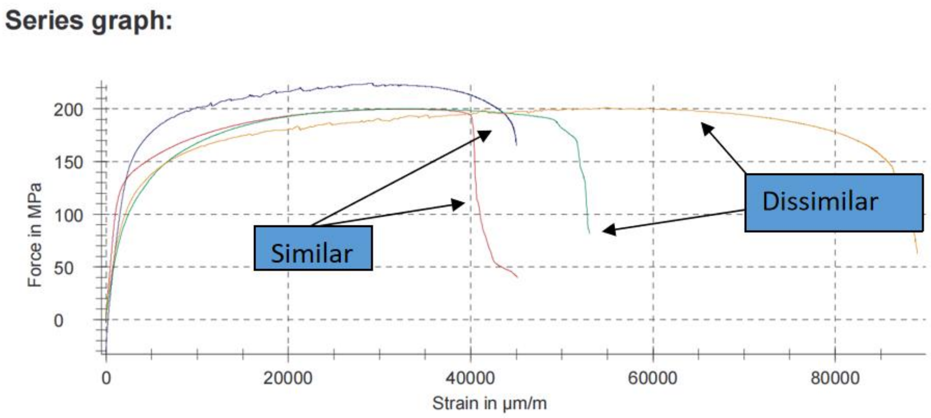

Figure 4.19: Graph result comparison between similar(AA6061 joining) and dissimilar(AA6061& AA5052 joining) by using FSW

4.2.2 Hardness test

The hardness testing results for both similar (AA6061) and dissimilar (AA6061 and AA5052) alloy joints are discussed below. Hardness measurements provide insight into the material's resistance to deformation and can be indicative of the strength and durability of the welded joints.

For the similar alloy (AA6061) joint, the hardness values were measured at various locations:the base material, heat-affected zone (HAZ), and the weld zone. The results are as follows:

	AA6061		AA6061	
Base material	HAZ	weldzone	HAZ	Base material
33.1	29.7	11.5	24.4	30.9

Figure 4.20: Hardness result for similar FSW

The hardness profile shows a significant reduction in the weld zone (11.5 Kgf) compared to the base material (33.1 Kgf). This decrease in hardness in the weld zone is likely due to the thermal cycle experienced during the FSW process, leading to softening of the material. The HAZ also shows a decrease in hardness, but to a lesser extent, indicating the thermal effect is less pronounced further from the weld zone as show in figure 4.20.

	AA6061		AA5052	
Base material	HAZ	weldzone	HAZ	Base material
30.5	21.9	29	29.4	37.6

Figure 4.21: Hardness result for dissimilar FSW

The hardness profile for the dissimilar alloy joint shows a different trend. The weld zone (29.0 Kgf) maintains a hardness value closer to the base materials (30.5 Kgf for AA6061 and 37.6 Kgf for AA5052), indicating better retention of hardness properties across the weld. The HAZ on the AA6061 side shows a noticeable decrease (21.9 Kgf), suggesting some softening, while the HAZ on the AA5052 side (29.4 Kgf) remains relatively close to the base material's hardness as show in figure 4.21.

The hardness test results reveal distinct differences in the behavior of similar and dissimilar alloy joints under the FSW process. The significant of Similar Alloy (AA6061) Joint reduction in hardness in the weld zone highlights the softening effect due to the thermal cycle of FSW. This reduction can negatively impact the joint's mechanical properties, making it less resistant to deformation and potentially weaker in service.

The hardness Dissimilar Alloy (AA6061 and AA5052) Joint in the weld zone remains relatively high, closer to the base materials' hardness values. This suggests that the welding parameters used for the dissimilar alloys are effective in retaining the hardness and, by extension, the strength of the joint. The presence of AA5052, with its higher base material hardness (37.6 Kgf), likely contributes to the overall higher hardness in the weld zone compared to the similar alloy joint.

In both joints, the HAZ shows a decrease in hardness compared to the base materials. However, the extent of this decrease is more pronounced in the similar alloy joint. The dissimilar alloy joint shows better hardness retention, especially on the AA5052 side, indicating that the thermal effects are less detrimental.

The higher hardness in the weld zone of the dissimilar alloy joint suggests better performance in terms of wear resistance and strength. This is consistent with the tensile test results, where the dissimilar alloy joint exhibited superior tensile strength and ductility.

The similar alloy joint, with its lower weld zone hardness, might be more susceptible to deformation under load, which could limit its application in environments where high strength and durability are required.

4.2.3 Discussion

The mechanical property analysis of similar (AA6061) and dissimilar (AA6061-AA5052) friction stir welded joints reveals interesting insights into the performance of these welds. Tensile testing demonstrates that while both joint types exhibit good tensile properties, the dissimilar AA6061-AA5052 joint outperforms the similar AA6061 joint in terms of strength and ductility. The dissimilar joint achieved a higher tensile strength range of 201.180-224.573 MPa compared to 199.833-200.070 MPa for the similar joint. Additionally, the dissimilar joint showed superior ductility with an elongation at break of 6.2% versus 5.3% for the similar joint.

This enhanced performance of the dissimilar joint can be attributed to several factors:

1. Effective material mixing:The FSW process likely achieved optimal mixing of the two alloys, creating a strong metallurgical bond at the interface.
2. Complementary properties:The combination of AA6061's higher strength with AA5052's better ductility may have resulted in a synergistic effect, improving overall mechanical properties.
3. Microstructural refinement:The interaction between dissimilar alloys during FSW could lead to finer grain structures or beneficial intermetallic formations, enhancing strength and ductility.

Hardness testing results further support the advantages of the dissimilar joint. The weld zone of the AA6061-AA5052 joint maintained a hardness (29.0 Kgf) closer to the base materials (30.5 Kgf for AA6061 and 37.6 Kgf for AA5052), indicating better retention of material properties across the weld. In contrast, the similar AA6061 joint showed a significant hardness reduction in the weld zone (11.5 Kgf) compared to the base material (33.1 Kgf).

The combination of superior tensile properties and better hardness retention makes the dissimilar AA6061-AA5052 friction stir welded joint a promising option for applications requiring enhanced mechanical performance. However, the potential for increased stiffness should be considered when designing for specific loading scenarios.

Further studies on fatigue behavior and impact resistance would provide a more comprehensive understanding of the joint's performance under various service conditions.

4.3 Corrosion Testing

4.3.1 Linear Scanning Voltammetry (LSV) analysis

Corrosion testing was conducted using Linear Scanning Voltammetry (LSV) to assess the corrosion resistance of the welded joints. The LSV results provided insights into the corrosion rates and electrochemical behavior of both similar and dissimilar alloy welds in a corrosive environment.

Based on the provided search results, here is a report for the result and discussion chapter focusing on the corrosion results obtained using Linear Scanning Voltammetry (LSV), NOVA software, and the Autolab PGSTAT 101 as show in figure 4.22.

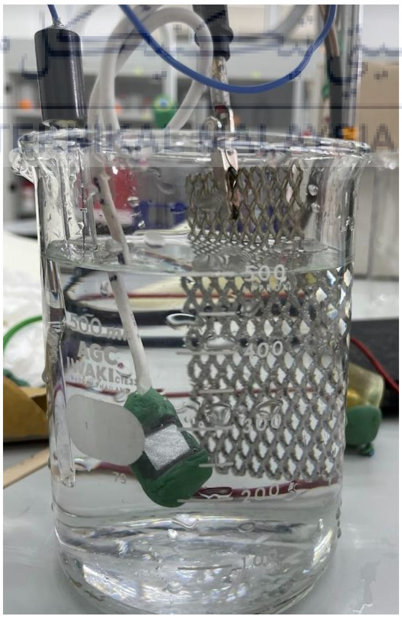

Figure 4.22: The VSL experiment for corrosion testing

The corrosion behavior of similar (AA6061) and dissimilar (AA6061 & AA5052) friction stir welded joints was investigated using Linear Scanning Voltammetry (LSV) with an Autolab PGSTAT 101 potentiostat and NOVA software.

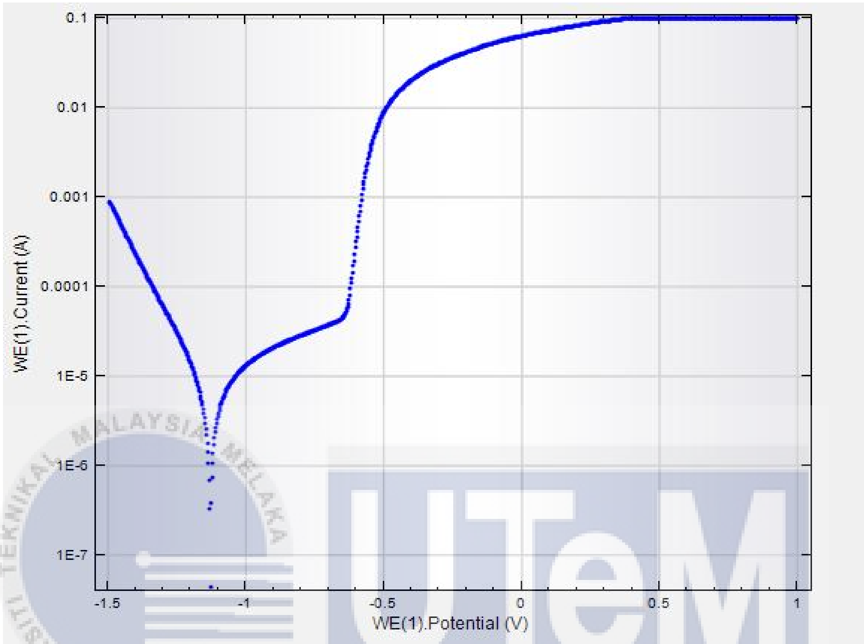

Figure 4.23: Result of similar FSW by VSL analysis.

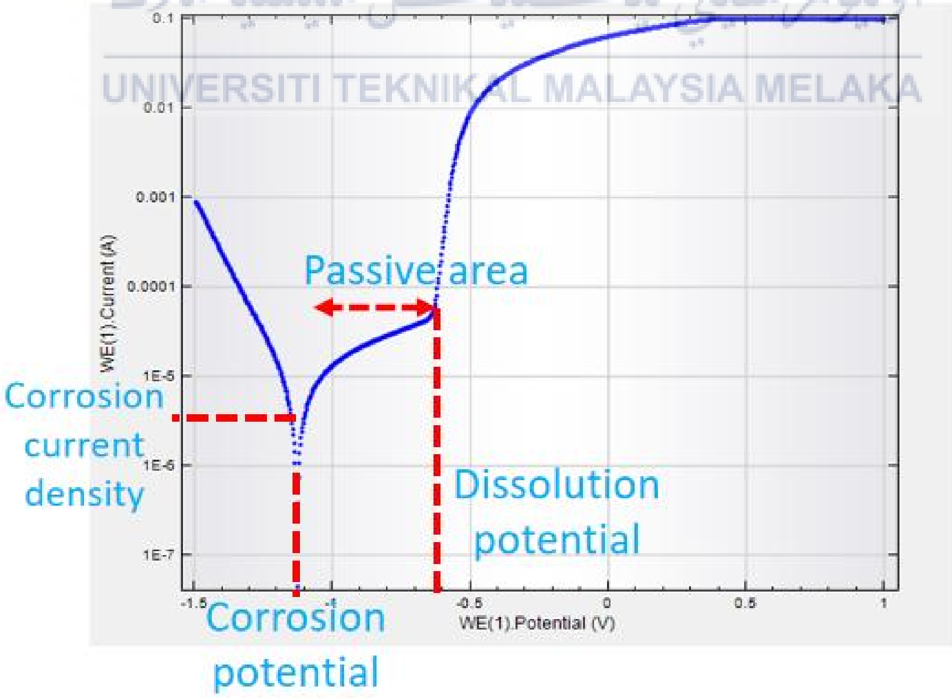

Figure 4.24: Result of similar FSW details slope

The LSV results for the similar alloy weld revealed an anodic Tafel slope (ba) of 0.10458 V/dec, a cathodic Tafel slope (bc) of 0.12263 V/dec, a corrosion potential (Ecorr) of -1.1234 V (calculated) and -1.1279 V (observed), a corrosion current density (jcorr) of 2.53E-06 A/cm², a corrosion rate of 0.029451 mm/year as show in figure 4.23,figure 4.24 and table 4.2, and a polarization resistance of 9671.6 Ω. The lower anodic Tafel slope indicates a slower dissolution rate and better corrosion resistance, while the moderate corrosion rate and high polarization resistance suggest good overall resistance to corrosion as show in figure 4.25.

Table 4.2: The LSV result after get tafel slope for similar FSW

ba (V/dec)	Bc (V/dec)	Ecorr, Calc (V)	Ecorr, Obs (V)	jcorr (A/cm²)	Icorr (A)	Corrosion rate(mm/year)	Polarization resistance (Ω)	E Begin (V)	E End (V)
0.10458	0.12263	-1.1234	-1.1279	2.53E-06	2.53E-06	0.029451	9671.6	-1.221	-1.059

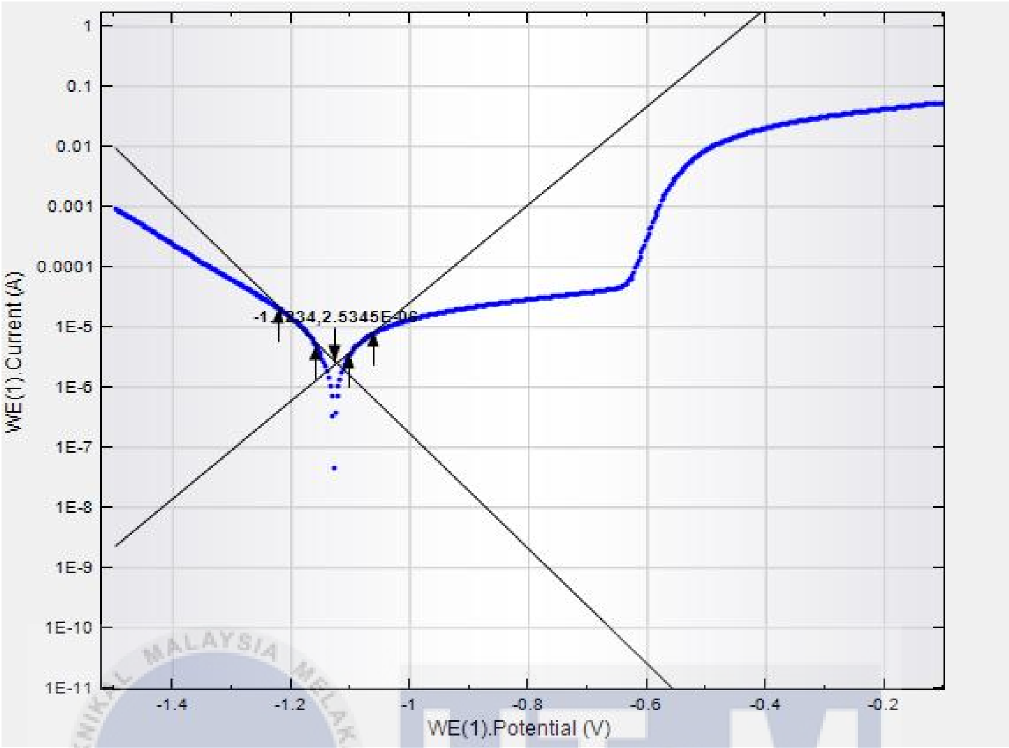

Figure 4.25: The result of similar FSW measuring corrosion rate by cathodic and anodic tafel slope

For the dissimilar alloy weld, the LSV analysis yielded an anodic Tafel slope (ba) of 0.13333 V/dec, a cathodic Tafel slope (bc) of 0.12318 V/dec, a corrosion potential (Ecorr) of -1.1994 V (calculated) and -1.2006 V (observed), a corrosion current density (jcorr) of 1.15E-06 A/cm², a corrosion rate of 0.013329 mm/year, and a polarization resistance of 24240 Ω. The slightly higher anodic Tafel slope suggests a faster dissolution rate compared to the similar alloy weld, but the lower corrosion rate and higher polarization resistance indicate effective passive film formation.

Figure 4.26: The result of dissimilar FSW by VSL analysis

A comparative analysis reveals that the similar alloy weld demonstrates a homogeneous and stable passive film, providing effective corrosion protection, while the dissimilar alloy weld shows potential for localized corrosion due to galvanic effects between AA6061 and AA5052 as show in figure 4.26 and figure 4.27.

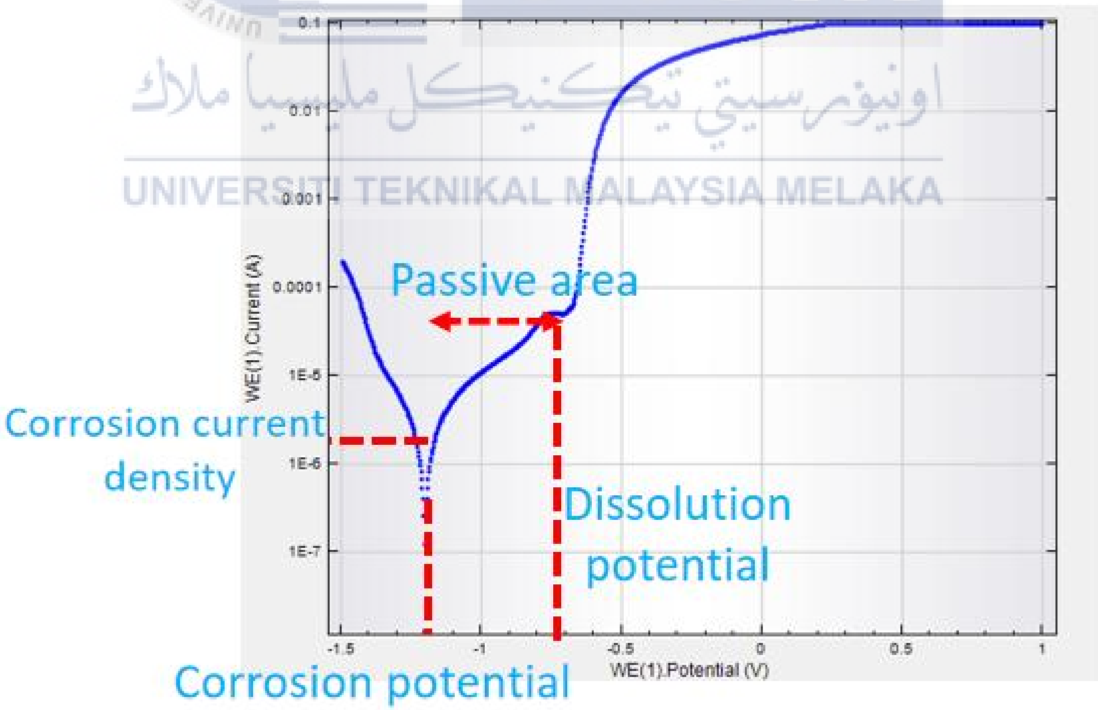

Figure 4.27: The result of similar FSW details slope.

The dissimilar alloy weld exhibits a lower corrosion rate (0.013329 mm/year) compared to the similar alloy weld (0.029451 mm/year) as show in figure 4.28 and table 4.3 suggesting better overall corrosion resistance in saltwater environments. However, the dissimilar weld has a more negative corrosion potential (-1.1994 V) compared to the similar alloy weld (-1.1234 V), indicating it may be more thermodynamically susceptible to corrosion as show in figure 4.28.

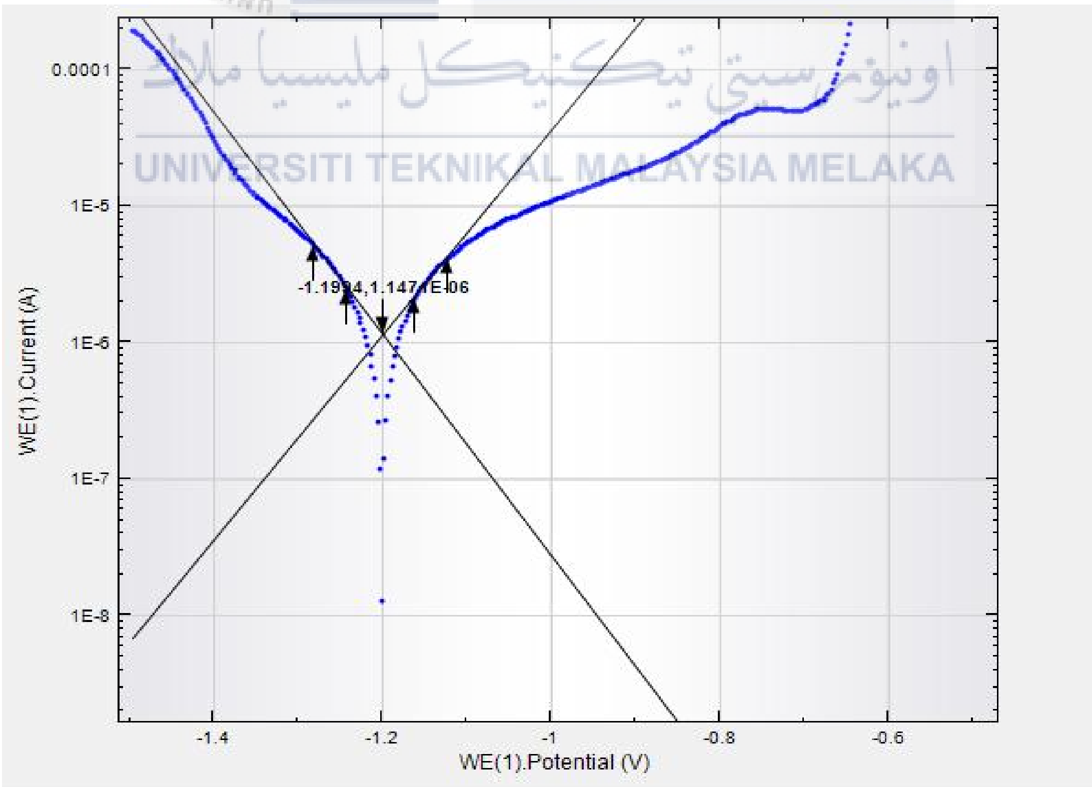

Figure 4.28: The result of similar FSW measuring corrosion rate by cathodic and anodic tafel slope

Table 4.3: The LSV result after get tafel slope for similar FSW.

ba (V/dec)	Bc (V/dec)	Ecorr, Calc (V)	Ecorr Obs (V)	jcorr (A/cm²)	Icorr (A)	Corrosion rate (mm/year)	Polarization resistance (Ω)	E Begin (V)	E End (V)
0.13333	0.12318	-1.1994	-1.2006	1.15E-06	1.15E-06	0.013329	24240	-1.2814	-1.1221

The corrosion behavior of friction stir welded joints is influenced by the microstructural changes induced during the welding process. While the dissimilar alloy weld demonstrates promising corrosion resistance in terms of lower corrosion rate and higher polarization resistance, the potential for localized corrosion due to galvanic effects cannot be overlooked. Further investigation into the long-term corrosion behavior and the development of strategies to mitigate localized corrosion in dissimilar alloy welds is recommended for applications in saltwater environments.

4.3.2 Discussion

The corrosion behavior of friction stir welded joints is influenced by the microstructural changes induced during the welding process. The similar alloy (AA6061) weld shows consistent corrosion behavior due to its homogeneous composition. However, the dissimilar alloy (AA6061 & AA5052) weld, despite showing lower overall corrosion rates, may be susceptible to localized corrosion due to galvanic effects between the two alloys or due to passive oxide film which dissolve at approximately -0.6v.

The higher polarization resistance of the dissimilar weld suggests a more stable passive film formation. However, this could be misleading as localized breakdown of the passive film may occur at the interface between the two alloys, leading to accelerated corrosion in specific areas.

These findings highlight the importance of considering both general and localized corrosion mechanisms when evaluating the performance of dissimilar alloy friction stir welds in saltwater environments.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter summarizes the key findings and contributions of the project on the tribological and saltwater corrosion behavior of dissimilar aluminum alloy AA5052 and AA6061 welded joints produced using friction stir welding (FSW). The study aimed to comprehensively characterize the tribiological behavior, mechanical properties, and corrosion behavior of these dissimilar FSW joints.The introduction restates the objectives, which focused on investigating the tribological performance, saltwater corrosion resistance, mechanical properties, and fracture characteristics of the dissimilar aluminum FSW joints.

It emphasizes the critical importance of understanding these properties, especially in demanding marine environments where the welded joints are exposed to harsh conditions.The section highlights the multi-faceted approach used to analyze the FSW joints, including tribological behavior, mechanical testing, and corrosion behavior. It also touches on the practical implications of the project in enabling optimization of FSW processes for dissimilar aluminum alloys to facilitate greater adoption in mechanical properties, corrosion-resistant marine structures.Finally, the introduction outlines the structure of the chapter, indicating that it will cover the key findings, discuss their significance, acknowledge limitations, and provide recommendations for future project directions.

5.2 Conclusion

The objectives of this study were to investigate the tribological behavior of dissimilar aluminum alloy welded joints produced using friction stir welding (FSW) when exposed to marine environments. Through these objectives, The tribological behavior of similar material welds (AA6061 to AA6061) exhibited a lower wear rate of 0.1091mm/s with mild abrasive wear characteristics. SEM analysis of these welds showed smooth wear tracks, indicating uniform wear, while (FESEM-EDX)analysis primarily revealed aluminum peaks with minimal phase changes. Dissimilar material welds (AA6061 to AA5052) demonstrated a higher wear rate of 0.2995mm/s with adhesive wear characteristics and material transfer. SEM analysis of dissimilar welds revealed deeper wear tracks and evidence of material pull-out, while (FESEM-EDX)analysis analysis indicated the formation changes of composition.

For Saltwater Corrosion Behavior, the similar welds (AA6061 to AA6061) showed higher overall corrosion rates, they exhibited more uniform corrosion behavior. The dissimilar welds (AA6061 to AA5052) demonstrated lower corrosion potential and higher corrosion rate than similar FSW. However, both welding forming passive oxide film which dissolve at approximately -0.6v.

Mechanical Properties show the similar material welds is significant hardness reduction in weld zone, tensile strength 199.833-200.070 MPa, 5.3% elongation at break. The Dissimilar material welds:Better hardness retention, improved tensile strength (201.180-224.573 MPa), higher ductility (6.2% elongation at break)

The specific application requirements, considering the trade-offs between wear resistance, corrosion behavior, and mechanical properties. Dissimilar welds offer advantages in mechanical performance and overall corrosion resistance, while similar welds provide better wear resistance and more uniform corrosion behavior.

5.3 Project Contributions

The study provides several key contributions to the understanding of the tribological and corrosion behavior of dissimilar aluminum alloy welding using FSW:

1. Comprehensive characterization of the microstructure, mechanical properties, wear mechanisms, and corrosion resistance of dissimilar AA5052-AA6061 aluminum alloy FSW joints.
2. Insights into the influence of FSW parameters on the microstructural evolution, mechanical attributes, tribological response, and corrosion behavior of dissimilar aluminum welds.

3. Evidence-based guidelines for optimizing FSW processes to enable greater adoption of lightweight dissimilar aluminum joints in demanding marine applications requiring excellent wear and corrosion resistance.
4. Fundamental advances in understanding microstructure performance relationships for dissimilar aluminum FSW joints, which can be extended to other heat treatable aluminum alloys and high-strength dissimilar material combinations.

5.4 Practical Implications and Beneficiaries

The findings from this Project provide valuable insights for engineers, designers, and manufacturers working with dissimilar aluminum alloy welding, particularly in marine applications. The optimized FSW parameters and enhanced understanding of the tribocorrosion behavior of dissimilar aluminum welds can enable:

1. Development of lightweight, corrosion-resistant, and high-performance marine structures using dissimilar aluminum alloy joints.
2. Improved reliability and durability of critical components in marine environments.
3. Cost savings through reduced maintenance and increased service life of aluminum structures.
4. Environmentally sustainable solutions by enabling aluminum alloy substitutions for heavier materials.
5. The Project also benefits the scientific community by advancing the fundamental knowledge of dissimilar aluminum FSW and providing a basis for further Project and modeling efforts.

5.5 Limitations of The Present Study

While the study provides comprehensive insights into the tribological and corrosion behavior of dissimilar aluminum alloy welding using FSW, some limitations should be acknowledged:

1. The Project focused on a specific dissimilar alloy combination (AA5052-AA6061) and may not be directly applicable to other aluminum alloy pairings.
2. The study was conducted under controlled laboratory conditions and may not fully capture the complexities of real-world marine environments.
3. The Project relied on a limited number of FSW parameters and did not explore the entire parameter space.
4. The study did not investigate the long-term durability and performance of the dissimilar aluminum welds under sustained loading and corrosive conditions.

5.6 Future Works

Based on the findings and limitations of the present study, several recommendations for future Project can be made:

1. Galvanic Corrosion Studies:Perform in-depth studies on the mechanisms of galvanic corrosion in dissimilar welds to develop strategies for mitigating these effects. This could include the use of barrier layers, coatings, or other innovative solutions.
2. Case Studies:Collaborate with industry partners to conduct case studies on the performance of similar and dissimilar welds in real-world applications. This will provide valuable practical insights and feedback for further project.

3. Environmental Impact:Examine how different environmental factors (such as pH, chloride concentration, and temperature) influence the corrosion behavior of similar and dissimilar welds, providing a comprehensive understanding of their performance in various environments.

5.7 Summary

This study provides a comprehensive investigation of the tribological and saltwater corrosion behavior of dissimilar aluminum alloy welding using friction stir welding (FSW). The Project demonstrates that dissimilar AA5052-AA6061 aluminum FSW joints exhibit superior mechanical properties and wear resistance compared to similar alloy joints, making them attractive for marine applications. However, the potential for localized corrosion due to galvanic effects between the alloys must be considered. The findings contribute to a better understanding of the structure performance relationships in dissimilar aluminum FSW joints and provide guidelines for optimizing the welding process to enable greater adoption of high-performance joints in demanding marine environments.

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