

Ministry of Higher Education
and Scientific Research
University of Babylon
Faculty of Materials Engineering
Department of Metallurgical Engineering



Characterization of AA6061/ Low carbon steel friction stir spot welds

Dissertation

Submitted to Council of the faculty of Materials Engineering
/University of Babylon in Partial Fulfillment of the Requirements for
the Master Degree in Materials Engineering / Metallurgical
Engineering

By

Reyam Hasan Hadi Zair

Supervised by

Prof. Dr. Ahmed O. Al-Roubaiy

Asst. Prof. Dr. Basem Mohysen Mohammed Al-Zubaidy

2021 A.D

1443 A.H

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ
﴿ يَرْفَعُ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ ۗ وَاللَّهُ بِمَا
تَعْمَلُونَ خَبِيرٌ ﴾

Dedication

I am proud to dedicate this dissertation to:

Muhammed (pouh) , who led human beings and their minds to safety, the teacher of mankind.

Imam Ali (As) who is the gate of the knowledge city.

My father—the light of my way and joy of my life—who gave almost everything he had. He taught me patience and how to succeed in reaching this important degree.

My Mother, whose prayers were the reason I shine. She is my comfort and place of rest.

Mustafa, my “path mate” who was with me step by step. He was a great supporter every time I felt down or got tired. He is my partner in the struggle and in hope.

Sama, my sweetheart, little butterfly and tomorrow’s hope.

Shahad and Farah, who are my best friends. They were there for me every time I needed them.

My father-in-law (may he RIP). I miss his warm applause and celebration of my achievements.

My dearest Professors, who are the faithful purveyors of knowledge.

My class mates who have supported and encouraged me, even with just with smile.

The researcher

Acknowledgments

At First all thanks, be to ALLAH Who guide me to achieve this work.

Sincere gratitude and thanks from the depths to my supervisors Prof. Dr. Ahmed O. Al-Roubaiy and Asst. Prof. Dr. Basem Mohysen Mohammed Al-Zubaidy for continuous support in my M.Sc. study, and also for their scientific interest and valuable guidance for the completion of this research

I'd like to express thanks to the staff and laboratories of my department for thier helps

I'm so grateful and especially to my big and small family for their assistance, encouragement and support during of preparing this research

Abstract

In this research, friction stir spot welding (FSSW), the process of joining solid materials with each other was used. Two dissimilar sheets of aluminum Al6061 and low carbon steel with a thickness of thickness of 1.0 mm were joined using a standard FSSW tool (consists of a shoulder and pin) with a diameter of 10 mm.

This research aims to improve the performance of the dissimilar joints by adding an interlayer containing Zr and study effect of the welding parameters on this performance. Therefore, three rotational speeds (1200-1600-2000) rpm and three welding time (1.0, 2.0, 3.0 s) were used.

The welding process was carried out for a sample uncoated with zirconium for comparison, in addition to other samples coated with two different thicknesses (0.001 and 0.005) g . This coating was used to avoid the problem of the formation of the inter-metallic compounds.

Several preliminary experiments were conducted to achieve the best welding operation parameters.

The welded joints with an interlayer containing additions of Zr showed noticeable improvement in tensile strength compared to the original samples (welded without any interlayer). For instance, when using 1600 rpm rotational rate, 3.0 s welding time, and 0.005 g Zr interlayer addition, the joint fracture force was about 1.8 kN compared to only 0.5 kN for a joint prepared with the same welding parameters but without any Zr addition. However, the samples still show brittle fracture during the tensile- shear test with an interfacial fracture mode. the maximum hardness value in AA6061 sheet at SZ (151 HV) , and LCS (185 HV) .

List of Abbreviations

Abbreviations:

Abbreviation	Express
ASTM	American Society for Testing and Materials
BM	Base Metal
FZ	Fusion Zone
HAZ	Heat Affected Zone
LCS	Low Carbon Steel
RSW	Resistance Spot Welding
RW	Resistance welding
S.S	Stainless Steel
SW	Spot Welding
TS	Tensile strength
FSSW	Friction Stir Spot Welding
FSW	Friction Spot Welding
TWI	The Weld Institute of Welding
TMAZ	Thermo Mechanical Affected Zone
SZ	Stir Zone
SSS	Super Saturated Solid Solution

List of Content:

AbstractI

List of Abbreviation and SymbolsII

List of TablesVI

List of FiguresVII

Chapter One: Introduction1

1.1 General View1

1.2 The Aims of this Work2

1.3 Dissertation Overview3

Chapter Two: Theoretical Part and Literature Survey4

2.1 Introduction4

2.2 Joining Overview4

 2.2.1 Resistance spot welding6

2.3 Solid State Welding6

 2.3.1 Ultrasonic spot welding7

 2.3.2 Friction Stir Welding (FSW)8

2.4 Advantages and Disadvantages of Solid State Welding9

 2.4.1 Advantages of Solid-State Welding9

 2.4.2 Disadvantages of Solid State Welding9

2.5 Friction Stir Spot Welding (FSSW) Technique9

2.6 Heat Generation in FSSW12

2.7 Friction Stir Spot Welding Benefits14

2.8 Welding Parameters of the FSSW process	14
2.8.1 The Parameters of the Process	15
2.8.2 Tool Geometry	15
2.9 Al Alloys	16
2.9.1 Overview and Classification of Al Alloys	17
2.9.2 Precipitation Hardening of Al Alloys	17
2.9.3 Aluminum Alloy 6061.....	19
2.10 Microstructure Formation of Dissimilar Low Carbon Steel – Al alloy FSSWs	21
2.11 Literature Review	22
Chapter Three: Experimental Part	31
3.1 Introduction	31
3.2 Materials Used	32
3.3 Welding Machine	33
3.4 Welding Tool	34
3.5 Surface Preparation.....	35
3.6 Microstructural Examination.....	35
3.7 Scanning Electron Microscope (SEM) Analysis	35
3.8 Micro-Hardness Test	36
3.9 Shear Tensile Test	37
Chapter four: Results and Discussions	39
4.1 Introduction	39
4.2 Welding Parameters Window	39

4.3 Macrostructure and Microstructure of Welded Joint40

4.4 Scanning Electron Microscopy Analysis of Optimum Sample (SEM) ..41

**4.5 Effect of Welding Variables on the Joint Hardness Profile of the Al-Steel
Dissimilar Weld in the Naturally Aged Condition44**

4.6 Effect of Welding Parameters on the Weld Strength46

4.7 The Failure Modes for the Welded Joints51

Chapter five: Conclusions and Recommendations53

5.1 Conclusions53

5.2 Recommendations for Future Research54

List of Tables

Tables

2.1	Typical welding problems in aluminum alloys
2.2	Typical forms and uses of aluminum alloys
2.3	The common aluminum precipitation hardening systems
2.4	Compositions of 6061 aluminum alloys
3.1	the chemical composition of the materials used in this research

Table of Figures

Figures

2.1	A schematic drawing of friction stir welding in a butt joint configuration
2.2	Schematic illustration of conventional FSSW process
2.3	(FSSW) regions Micrograph
2.4	Spot friction stir welding appearance and cross-section
3.1	Block diagram of the experimental work
3.2	The milling machine
3.3	The dimensions of the overlap sheets to be joined
3.4	The universal testing machine
3.5	Scanning electron microscopy (SEM) devise
4.1	A typical example of a dissimilar AA6061 to LCS welded joint
4.2	A typical example of a cross section of dissimilar AA6061 to LCS welded joint a) joint cross section and b) a region at the side of the keyhole
4.3	FE-SEM micrographs of the half cross-section of Al to LCS welds produced using welding conditions of 1600 rpm, 3.0 s
4.4	FE-SEM micrographs of the cross-section of Al to LCS welds produced using welding conditions of 1600 rpm, 3.0 s. with hook defect
4.5	FE-SEM micrographs of the half cross-section of Al to LCS welds produced using welding conditions of 1600 rpm, 3.0 s
4.6	An example of hardness profiles for samples naturally aged for 3 months, welded with a tool rotation rate of 1600 rpm and welding time of 3 s.
4.7	An example of the load-extension curve for the tensile-shear test from Al-Steel joints. The joint was produced using welding conditions of a 1600 rpm tool rotation speed and a 3.0 s welding time
4.8	Effect of tool rotation rate and welding time on the average lap shear peak load joints produced without any additions
4.9	Effect of tool rotation rate and welding time on the average lap shear peak load joints produced with the addition of interlayer containing 0.001 g Zr

4.10	Effect of tool rotation rate and welding time on the average lap shear peak load joints produced with the addition of interlayer containing 0.005 g Zr
4.11	The compined effect of Zr content and tool rotation rate on the average lap shear peak load for joints produced with welding time of 3.0 s
4.12	Effect of tool rotation rate and welding time on the average lap shear peak load. joints produced with the addition of interlayer containing 0, 0.001 and 0.005 g Zr
4.13	Examples of typical joint failure mode, showing upper and lower sheets of the fractured lap-shear test samples produced using 1600 rpm tool rotation rate and 3.0 s welding time (a) without interlayer (b) with an interlayer containing 0.001 g Zr; and (c) with an interlayer containing 0.005 g

Chapter One

Introduction

1.1 General View

The increasing demands for energy saving and weight reduction in automotive and aerospace industry has led to replacing certain ferrous parts with lightweight alloys .This interest has created the need to develop a reliable joining technology which can produce aluminum-steel dissimilar joints of high quality instead of conventional fusion welding processes [1]

Bearing in mind that dissimilar joining of these materials by a conventional fusion welding is rather complicated and difficult due to their different chemical and physical properties, particularly the difference in melting temperatures [2].

Aluminum alloys are difficult to be fusion welded due to the requirement of gas shielding of weld pool and removal of oxide layers before or during welding process. In addition to these limitations, there are several weld defects associated with the conventional fusion welding of aluminum alloys such as porosity, hot cracking, brittle solidification, distortion due to residual stresses, and liquation cracking in the weld region [3,4].

These defects deteriorate the weld quality and mechanical properties of the weld joints. Therefore, solid state welding processes, such as friction welding, explosion welding, hot pressure welding, etc. were developed in order to overcome a variety of problems and weld defects related to melting and solidification in fusion welding of aluminum alloys [1,5].

Friction stir welding (FSW) is a solid-state welding process that was invented by Wayne Thomas at the welding institute, United Kingdom in 1991 [6]. It has emanated as a

welding technique used in high strength alloys (2XXX, 5XXX, 6XXX, and 7XXX series) for aerospace and automotive applications. [7].

In conventional FSSW process, a rotation tool is plunged into the overlapped work pieces to be joined, held for a certain duration time , and finally retracted from the work piece with no lateral movement or transition. The frictional heat generated at the tool- workpiece interface softens the surrounding material. The rotational action and the downward force of the tool cause the material flow and mixing of the plasticized materials of upper and lower sheets which result in the formation of a solid-state weld region. Recently, friction stir spot welding (FSSW) has shown that it is an alternative method for spot welding of aluminum alloys, magnesium alloys, titanium alloys and copper alloys as well as advanced high strength steel and polymers. It has been successfully integrated into mass production of body frames of automobiles, in addition to a wide range of applications such as fuselage, structural parts, panels in aircraft industry and shipbuilding , These advantages such as low heat input, low operating costs, clean working environment and short cycle time (usually a few seconds). In addition, FSSW provides safety for human operators because there is no residual radiation, no fume and very low operational hazards .

1.2 The Aims of this Work

This work focuses on the joining of AA6061 and mild steel using friction stir spot welding , the conventional method involving penetration of the pin into the upper aluminium sheet only. The investigation includes the study of the effects of an interlayer containing different Zr additions. Then, compare the effects of welding time and tool rotational rate on the mechanical properties and the microstructure of the welded joints.

1.3 Dissertation Overview

Chapter 2: Theoretical part and Literature Survey

Chapter 3: Experimental Methods

Chapter 4: Results and Discussions

Chapter 5: Conclusions and Recommendations

Chapter Two

Theoretical Part and Literature Survey

2.1 Introduction

This chapter contains a review of the literature related to the present study. Firstly, the different joining techniques that can be used in automotive spot joining are briefly reviewed, focusing on the friction stir spot welding (FSSW) technique as a specific solid-state welding technique. The following sections then review information related to the FSSW and RFSSW processes, including heat generation, and the effects of welding parameters on microstructure formation. The latter two main sections include information about the materials used in this study.

2.2 Joining Overview

The need for joining dissimilar metals arises from the complex functionality of many modern industrial applications. As manufacturers focus on reducing production and operational costs, search for enhanced mechanical and thermal properties, and lightweight solutions for sectors like the shipping, aviation, and automobile industries, multiple material combinations are increasingly being used for many products [13]. An emerging field of joining dissimilar metals is transportation, where multi-material solutions consisting of steel, aluminum, magnesium, and composites are replacing monolithic steel structures, thus reducing the weight of vehicles and improving fuel efficiency [13,14]. Fig presents methods commonly used for the purpose of joining dissimilar metals. Low dilution and non-fusion joining methods are generally used for high production and special application joining in which there is minimum alloying between the dissimilar materials. Dissimilar welds encountered in the power and process industries are more often done by fusion welding [13]. In the case of fusion welding of dissimilar materials, alloying between the base metals and filler metal is a major

consideration that has to be taken into account. The weld metal formed can exhibit entirely different characteristics from one or both of the base metals. The main factors that contribute to the failure of joints between dissimilar metals by arc welding are alloying problems (formation of the brittle phase and limited mutual solubility), improper joint design, great differences in the melting temperature or the coefficient of thermal expansion (CTE) of the materials involved, thermal conductivity differences, and corrosion problems including galvanic corrosion, oxidation, hydrogen-induced cracking, and sensitization, Conflicts may arise when the optimum heat control of the metals differs, and compromises are thus required. In light of the complexity of the process and the compromises required, dissimilar metal welding (DMW) requires more careful study than conventional, similar-metal welding procedures [16].

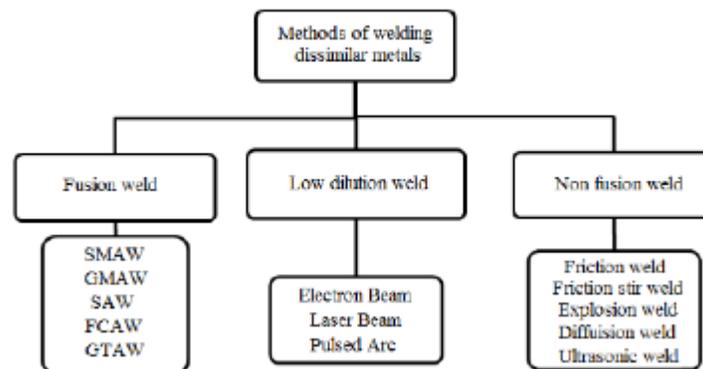


Figure Welding methods most commonly used for dissimilar metals ,

methods of dissimilar materials, essential considerations for the feasibility of dissimilar joining .

2.2.1 Resistance Spot Welding

Resistance spot welding (RSW) is a type of the oldest electric resistance welding operations that is used to weld two or more overlapping sheets of metals by the local

fusion of material at one or more locations without using any filler material as required by many types of welding. The heat that results from this kind of welding generates a local fusion that occurs through sheets that are held together under two electrodes force, As the production rate of RSW process is fast that is attributed to the accessibility of semi and automatic machines for the process, spot welding is the most commonly used in automotive manufacture nowadays [13]. Resistance welding (RW) has a similar principle to the heating coils that are used in the operation which includes a current passage through a material to generate heat [14].

2.3 Solid State Welding

Solid-State Welding is a welding process, in which two workpieces are joined under a pressure providing intimate contact between them and at a temperature essentially below the melting point of the parent material. Bonding of the materials is a result of the diffusion of their interface atoms [15].

Dissimilar metal joints are necessary for applications that require a variety of material properties within the same component. For example, heat exchangers often require different types of stainless steels at each end, because of temperature-induced corrosion. Under laboratory conditions, dissimilar materials can be chosen based on physical or material properties that influence the phenomenon being studied. For whatever reason, an appropriate method of producing dissimilar metal joints can usually be determined (assuming it is even possible) by examining the phase diagram. If the diagram indicates difficulty in joining the materials (intermetallic compounds, and so on), then a solid-state (non-melting) process may be applicable. When a non-melting process is chosen, it is only successful if a relatively strong joint is produced [16].

2.3.1 Ultrasonic Spot Welding

In ultrasonic welding, invented in 1938, a metal tip is made that vibrates at an ultrasonic frequency (i.e. vibrations that produce sound outside the range of human hearing). to join a thin piece to a thicker piece supported on an anvil. The frequency used is primarily around 20 kHz although higher frequencies up to 170 kHz are used [18] .

Due to the ultrasonic vibrations, the oxide layer is cracked over the metal and a clean metallic mineral is obtained. The temperature at the interface rises to 35-50% of the absolute melting point temperature of the metal, thus annealing welding is achieved.

Weld strength is 65 to 100% of the strength of base metals. This process is fast and scratch welding at speeds of up to 10 m/min has been reported. The required energy (E) of the ultrasonic welding unit depends on the thickness (t) and hardness (h) of the material to be welded , and can be calculated from the following relationship.

$$E = Kt^{3/2} h^{3/2} \quad \text{Eq. 2.1}$$

With sufficient power spot welding can be made within less than a second but the maximum thickness of the thinner piece should not exceed 3 mm.

Ultrasonic welding can be used to weld thin to thick parts as well as to weld various metal combinations such as aluminium to steel, aluminium to tungsten, aluminium to molybdenum, nickel, copper and others. electrical circuits and electrical industries. It is also used in the automotive and aerospace industries. [18]

2.3.2 Friction Stir Welding

Friction stir welding (FSW), a relatively modern welding technology, was invented by Thomas et al. (1991) at the Institute of Welding (TWI), Cambridge, United Kingdom. The FSW technique (shown in Figure 2-3) uses a non-consumable rotating tool to generate heat through friction and mechanical deformation in the welding area,

resulting in the joining of weld members without reaching their melting point. FSW can be classified as one of the most important innovations in solid-state welding, as it has considerable advantages compared to traditional welding processes.

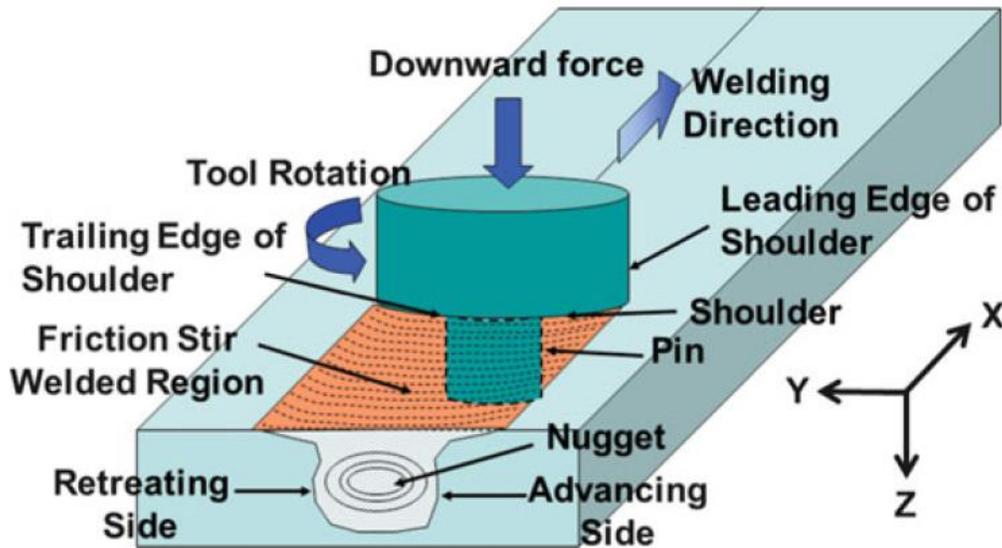


Fig (2.1): A schematic drawing of friction stir welding in a butt joint configuration [19]

It can also produce significant differences, compared to fusion welding, in terms of the weld zone microstructures, the size of the heat-affected zone (HAZ) and residual stresses [18].

2.4 Advantages and Disadvantages of Solid State Welding

2.4.1 Advantages of Solid-State Welding

- Weld (bonding) is free from microstructure defects (pores, non-metallic inclusions, segregation of alloying elements),
- Mechanical properties of the weld are similar to those of the parent metals,
- No consumable materials (filler material, fluxes, shielding gases) are required,
- Dissimilar metals may be joined (steel - aluminium alloy steel - copper alloy). [17]

2.4.2 Disadvantages of Solid State Welding

- Thorough surface preparation is required (degreasing, oxides removal, brushing/sanding),
- Expensive equipment. [17]

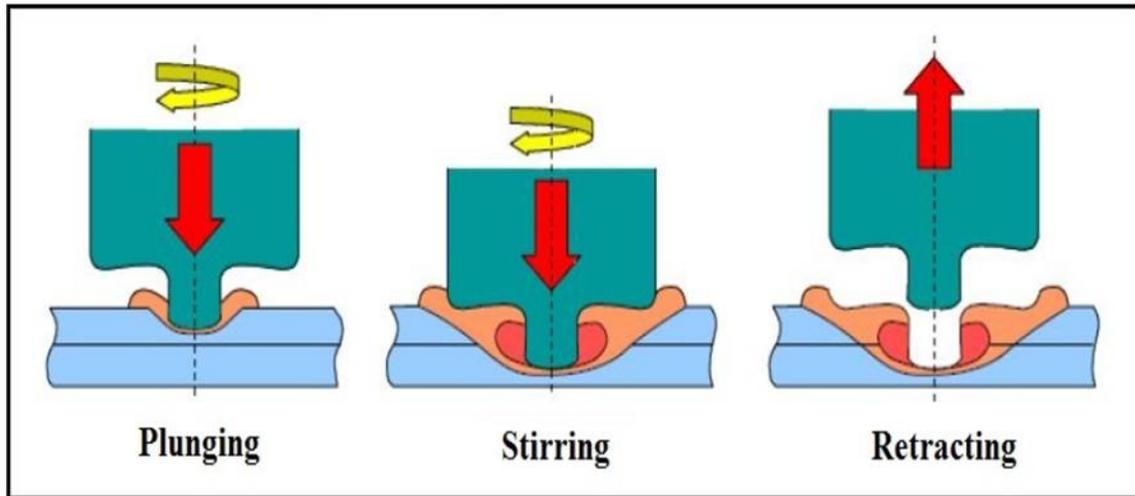
2.5 Friction Stir Spot Welding (FSSW) Technique

FSSW is a solid-state joining method, the part or sample doesn't melt during welding, this method is a very important and novel variant of the linear friction stir welding (FSW) [31, 32] Friction stir spot welding (FSSW) is a very important variant of the linear friction stir welding (FSW) which gives higher potential to be a replacement of single-point joining processes such as riveting and resistance spot welding. There have been many reports and wider applications about FSSW in aviation, automobile and aerospace fields.

The conventional friction stir spot welding (CFSSW) consists of three stages : plunging, stirring, and retracting as shown in Figure 2.2, [20].

The FSSW technique starts when the tool spinning at a constant speed. After that, the tool plunges into work-pieces even the tool shoulder contacts the weld surface. The plunging movement of the tool causes the displacement of materials. After plunging, the stirring stage starts when the tool reaches the desired depth. In this stage, the tool keeps rotating into work-pieces, the frictional heat is generated in the contact and penetrating stages, in this time the materials around and underneath the tool are heated, softened and mixed where a solid-state joint will be formed. When a joint is obtained, the tool is retracted from the workpieces. When welding has happened, the tool is drawn out from the work-pieces. This welding process shows as a keyhole in the middle, which decreases the mechanical properties of the welding. Three distinctive regions were noted in the FSSW process: thermomechanical affected zone (TMAZ) , heat affected zone(HAZ) and the stir zone(SZ).

[32,33]. as shown in Figure (2.6).



Figure

2.2: Schematic illustration of the conventional FSSW process [20]

After a certain hold time, the tool is retracted from the plunged zone, a solid-state spot weld is produced between the upper and the lower workpieces with a keyhole in the centre of the joint [20].

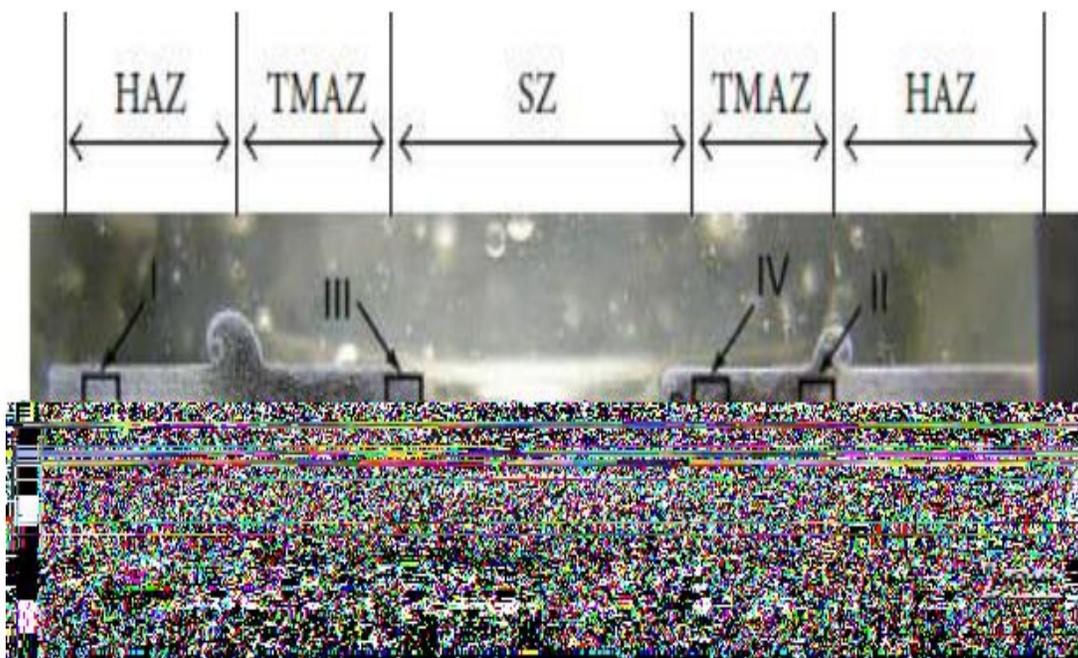


Figure 2.3: FSSW regions micrograph [32].

The process is applied to a lap joint consisting of upper and lower sheets. A rotating tool with a probe is plunged into the material from the top surface for a certain time to generate frictional heat. At the same time, the backing plate contacts the lower sheet from the bottom side to support the downward force. Heated and softened material adjacent to the tool causes the plastic flow. In addition, the tool shoulder gives a strong compressive force to the material. After the tool is drawn away from the material, a solid-phase bond is made between the lower and the upper sheets. Figure 2.4 shows the appearance and the cross-sectional configuration of the FSSW. The upper surface of the weld looks like the bottom with a hole, and the bottom surface is kept almost flat. In the cross-section, there is a hole that is made by the probe and reaches into the lower sheet [29].

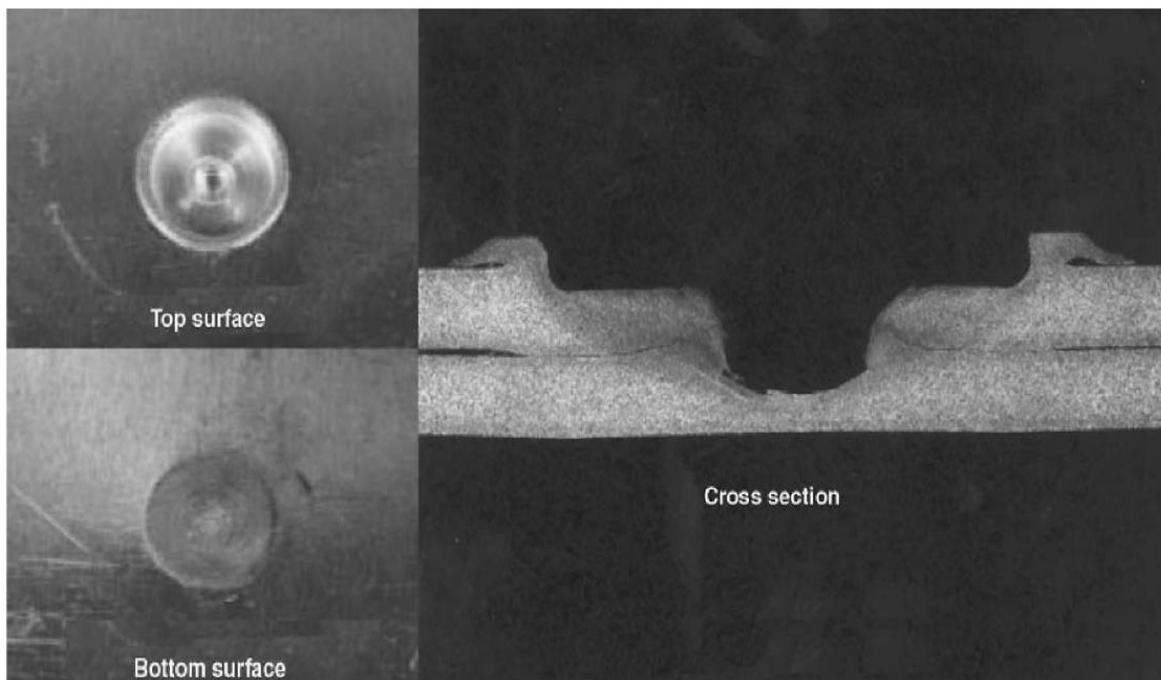


Figure 2.4: FSSW appearance and cross-section [30]

The friction spot joins method takes up between 2 to 5 sec, this short time is enough to generate heat and form stir zone leading to create a weld between the two contact sheets. Notice high peak temperatures give a good contact interface between the adjacent material and the rotating pin within the stir zone [34].

2.6 Heat Generation in FSSW

Heat is generated in FSSW by two sources: the friction between the rotating tool and the workpiece, and the plastic deformation in the region of the welding [22]. During the FSSW process, several variables can affect the energy generation, such as the axial force, penetration depth, tool rotation rate, and tool design. The tool rotation has the greatest influence on the heat generation which is about 200 times the energy dissipated by the tool penetration. Therefore, the energy generated due to the downward motion of the tool can be ignored [23]. The total energy generated during friction stir spot welding (Q_{total}) can be determined using the relation (2-3) [24]

$$Q_{total} = \delta Q_{sticking} + (1 - \delta) Q_{sliding} \quad \text{Eq. 2.2}$$

$$Q_{total} = (2/3)\pi\omega[\delta\tau_{yield} + (1 - \delta)\mu p][(R_{shoulder}^3 - R_{probe}^3)(1 - \tan\alpha) + R_{probe}^3 + 3R_{probe}^2 H_{probe}] \quad \text{Eq. 2.3}$$

Where:

δ is the contact state variable (dimensionless slip rate),

τ_{yield} is material yield stress at the welding temperature.

μ is the friction coefficient,

p is the uniform pressure at the contact interface,

ω is the angular rotation speed,

α is the cone angle,

$R_{shoulder}$ is the shoulder radius,

R_{probe} is the probe radius, and

H_{probe} is the probe height [24].

This equation is conceptually very useful, but it has some problems related in particular to the values of slip rate (δ) and the material yield stress (τ_{yield}), which are not constant

and are difficult to calculate. With FSSW in particular, the tool contact area and the slip rate (δ) are not constant and change during the steps of the welding process due to the tool plunging. Meanwhile, the material yield stress (or flow stress) (τ_{yield}) is not constant either, and it changes with changing temperature and strain rate which in turn changes in line with the progress of the welding process [25].

In FSSW, the temperature profiles and cooling rates are affected by the material properties and welding variables. The maximum temperature in the weld zone should be high enough to soften the metal and reduce the resistance to the pin, but low enough to prevent melting of the metal. On the other hand, the amount of heat transferred to the tool affects its lifespan, besides if the heat generated is insufficient, this can cause pin breakage due to insufficient material softening [26, 27].

It has been found that only a small amount of the energy generated during FSSW is consumed to create the stir zone [28]. Su et al. have also reported that a small percentage (about 4.03%) of the total energy generated during the FSSW process is involved in the stir zone formation in Al 6061-T6 welds, and most of the remainder dissipates into the clamp, anvil support, tool assembly and the aluminium sheets [23].

2.7 Friction Stir Spot Welding Benefits

this contain Metallurgical Benefits (Solid-phase process, low distortion ,good dimensional stability and repeatability , no loss of alloying elements ,better mechanical properties in the joint area ,replace multiple parts joined by fasteners , and weld all aluminium alloys) , Environmental Benefits (no shielding gas is required , minimal surface cleaning required , eliminate grinding wastes , eliminate solvents required for degreasing, consumable materials saving, such as rugs, wire, or any other gases, and no harmful emissions) and Energy Benefits (Improved materials use (e.g., joining different thicknesses) allows a reduction in weight , only 2.5% of the energy needed for a laser weld

, and decreased fuel consumption in lightweight aircraft, automotive, and ship applications) [21].

2.8 Welding Parameters of the FSSW Process

Many factors can influence the mechanical and microstructural properties of welds. Process parameters, tool geometry, and lap joint configuration (positioning of sheet materials to be welded) have a direct effect on the heat generation, temperature profile, material flow, and mechanical properties of weld joints [43].

2.8.1 The Parameters of the Process

The main process parameters used to control the FSSW are tool rotational speed, tool plunging rate, tool plunging depth, downward force, and dwell time. Appropriate selection of welding parameters is an essential step to obtain a large bonded area for getting high weld strength [44, 45].

The tool rotational speed and dwell time are the key parameters that provide the required heat input during FSSW, and thereby affect the quality of welds. It was found that the increase in weld strength was obtained by increasing the tool rotational speed to a certain level [46, 47].

The tool plunging rate is the most dominant process parameter for determining the weld strength after the effect of dwell time and tool rotational speed [48]. The compressive force generated as a result of the tool plunging is responsible for consolidating the overlapped materials to form the solid-state weld [49].

2.8.2 Tool Geometry

The FSSW process includes the rotation of a non-consumable tool, which consists of two main parts: shoulder and pin. FSSW tool serves two primary functions, which are

heating of workpiece and movement of material to produce the joint [43]. One of the most important factors that influence the weld strength is the tool geometry. The tool shoulder provides the bulk of the frictional heat needed to soften the upper surface of the workpiece. The shape and diameter of the tool shoulder have a significant influence on the welding quality because it produces the downward forging action necessary for the welding consolidation and constrains the plasticized material beneath the bottom shoulder surface. The tool pin facilitates material flow between the overlapped workpieces in the stir zone, and by this action produces the deformational heat [49,50]. The pin profile of the FSSW tool is a predominant factor in determining the weld strength of the joint and the geometry of the weld zone [51].

Heat generation in FSSW is strongly dependent on the shoulder size. When the shoulder diameter is large, the frictional heat will be high due to the large contact area [52]. The localized heating softens the material around the rotating pin and combined with the rotational speed effect, leads to the movement of material from the front to the back of the tool pin. As a result of the tool pin action and the effect of the shoulder on the workpiece, a solid-state joint is produced [53].

2.9 Aluminium Alloys

For over fifty years, aluminium ranks at second to steel in the metal market. The demand for aluminium grows rapidly because it is attributed to a unique combination of properties which makes it become one of the most versatile engineering and construction materials. Aluminium is light in weight, the specific gravity of aluminium is 2.7; which is only 30% heavy of copper and one-third of iron. Except for magnesium, it is the lightest of all common metals. Some of its alloys even have greater strengths than structural steel. Besides, it has good electrical and thermal conductivities and high reflectivity to both heat and light. It is non-toxic and highly corrosion-resistant under any service conditions [56].

Aluminium alloys are more frequently welded than any other type of nonferrous alloys because of their widespread applications and fairly good weldability. In general, higher strength aluminium alloys are more susceptible to (i) hot cracking in the fusion zone and the PMZ and (ii) losses of strength/ ductility in the HAZ. The problems of the Al alloys are listed in Table 2.1. [42].

TABLE 2.1 Typical welding problems in aluminum alloys [42]

Typical problems	Alloy type
Porosity	Al-Li alloys Powder-metallurgy alloys (severe) Other types (less severe)
Solidification cracking in FZ	Higher-strength alloys (e.g., 2014, 6061, 7075)
Hot cracking and low ductility in PMZ	Higher-strength alloys
Softening in HAZ	Work-hardened materials Heat-treatable alloys

2.9.1 Overview and Classification of Al Alloys

The existence of aluminium (Al) was postulated by Sir Humphrey Davy in the first decade of the nineteenth century and the metal was isolated in 1825 by Hans Christian Oersted. One of the first alloys to be produced was aluminium–copper. It was around 1910 that the phenomenon of age or precipitation hardening in this family of alloys was discovered, with many of these early age-hardening alloys finding a ready use in the fledgling aeronautical industry. Since that time a large range of alloys has been developed with strengths that can match that of good quality carbon steel but at a third of the weight. Several alloys, [54].

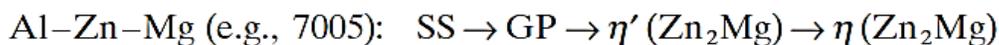
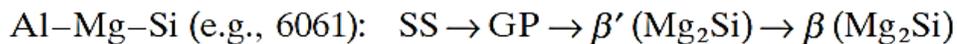
2.9.2 Precipitation Hardening of Al Alloys

Precipitation hardening in aluminum base alloys was discovered almost 70 years ago by Alfred Wilm in Germany' who was trying to imitate the hardening of steel. Precipitation hardening is a process that enhances the strength and hardness of metal

alloys by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix. In other way, the general requirement for precipitation strengthening of the supersaturated solid solution involves the formation of finely dispersed [56]. The precipitate particle nucleates and grows; by the diffusion of solute atoms into it from the matrix phase. It is called precipitation because the small particles of the new phase are termed “precipitates” [57, 59].

Artificial ageing will be accomplished not only below the equilibrium solvus temperature, but below a metastable miscibility gap called Guinier- Preston (GP) zone solvus line.

The basic requirement of a precipitation hardening alloy system is that the solid solubility limit should be decreased by decreasing the temperature. During the precipitation hardening, the aluminum alloy 6061-T6 was heated up at high temperature and subsequently cooled by quenching it into the water or some other cooling medium. The rapid cooling suppresses the separation of the θ -phase so that the alloy exists at a low temperature under an unstable supersaturated state. If, however, after quenching, the alloy is allowed to ‘age’ for a sufficient time, the second phase precipitates out [58, 59].



The decomposition of the supersaturated solid solution (SSS) of Al-Mg-Si alloys containing excess Si is believed to proceed in the following sequence. $\text{SSS} \longrightarrow (\text{Mg}+\text{Si}) \text{ clusters /GP(I)}_{\text{platelike/spherical}} \longrightarrow \beta''/\text{GP(II)}_{\text{needles}} \longrightarrow \beta'_{\text{rods}} + \text{Si} + \text{others} \longrightarrow \beta_{\text{plates}} + \text{Si}$

The decomposition process begins with the formation of two types of (Mg₂Si) clusters or zones. The first to form is a coherent Si-rich (Mg₂Si) cluster, which is then enriched by

diffusion of Mg atoms to form the Si-depleted platelike or spherical (Mg₂Si) clusters or GP(I) zones. As ageing proceeds, the clusters and zones become ordered and develop the needle-shaped GP(II):b'' phase. There is considerable disagreement regarding the number, structure and composition of the metastable phases and their effect on hardening following the b'' formation. Upon prolonged ageing, the formation of B' and B'' with Mg: Si ratio between 0.9 and 1.2 together with Si has been suggested [60].

Table 2.3: The common Aluminum precipitation hardening systems [18]

Base Metal	Solute	Transition Structure	Equilibrium Precipitate
Al	Cu	(i) Plate-like solute-rich GP[1] zones on $\{100\}_{Al}$; (ii) ordered zones of GP [2]; (iii) θ' -phase (plates).	θ -CuAl ₂
	Ag	(i) Spherical solute-rich zones; (ii) platelets of hexagonal γ' on $\{111\}_{Al}$	γ -Ag ₂ Al
	Mg, Si	(i) GP zones rich in Mg and Si atoms on $\{100\}_{Al}$ planes; (ii) ordered zones of β' .	β -Mg ₂ Si (plates)
	Mg, Cu	(i) GP zones rich in Mg and Cu atoms on $\{100\}_{Al}$ planes; (ii) S' platelets on $\{021\}_{Al}$ planes .	S-Al ₂ CuMg (laths)
	Mg, Zn	(i) Spherical zones rich in Mg and Zn; (ii) platelets of η' on $\{111\}_{Al}$	η -MgZn ₂ (plates)

2.9.3 Aluminum Alloy 6061

6061 is a precipitation-hardened aluminum alloy, containing magnesium and silicon as its major alloying elements. Originally called "Alloy 61S", it was developed in 1935. It has good mechanical properties, exhibits good weldability, and is very commonly extruded (second in popularity only to 6063). It is one of the most common alloys of aluminum for general-purpose use [61].

It is commonly available in pre-tempered grades such as 6061-O (annealed), tempered grades such as 6061-T6 (solutionized and artificially aged) and 6061-T651 (solutionized, stress-relieved stretched and artificially aged).

6061 alloy is commonly used for the following:

- construction of aircraft structures, such as wings and fuselages, more commonly in homebuilt aircraft than commercial or military aircraft. 2024 alloy is somewhat stronger, but 6061 is more easily worked and remains resistant to corrosion even when the surface is abraded, which is not the case for 2024, which is usually used with a thin Alclad coating for corrosion resistance.
- yacht construction, including small utility boats.
- automotive parts, such as the chassis of the Audi A8.
- flashlights
- aluminum cans for the packaging of food and beverages.

6061 alloy is highly weldable. Typically, after welding, the properties near the weld are those of 6061-T4, a loss of strength of around 40%. The material can be re-heat-treated to restore near -T6 temper for the whole piece. After welding, the material can naturally age and restore some of its strength as well. Most strength is recovered in the first few days to a few weeks. Nevertheless, the Aluminum Design Manual (Aluminum Association) recommends the design strength of the material adjacent to the weld to be taken as 165 MPa/24000 PSI without proper heat treatment after the welding [62] and the composition listed in Table 2.4.

Table 2.4 Compositions of 6061 Aluminum Alloys [55]

Alloy	Si	Cu	Mg	Cr
Al 6061	0.6	0.3	1.0	0.2

2.10 Microstructure Formation of Dissimilar Low Carbon Steel – Al alloy FSSWs

The jointing aluminum alloy and LCS was recognized as a challenge due to the big difference in chemical and physical properties between them. Resulting from the large difference in thermal expansion between aluminum alloy and LCS, fusion welding would introduce large residual stress, not to mention the brittle intermetallic compound (IMC) would be inevitably formed at the joint.

The main mechanisms for controlling the sound bi-metallic joint formation during the FSW process include the following [63, 64]: (i) severe plastic deformation to promote material intermixing and refining of the constituent phases in the dissimilar materials which can control the thickness of the intermetallic compound layer and subsequently the joint strength as well, (ii) processing temperature controlling the solid solubility of two alloys and subsequently the formation of shrinkage porosities, oxidation, and impurities, and (iii) final hot consolidation stage to form a fully dense and homogenize solid.

Tool profile, work material properties, and process parameters (tool rotational speed, traverse velocity, plunge depth, tilt angle, etc.), all play an important role in determining the temperature distribution and material flow in the welding zone which in turn determine the microstructure of the weld region, e.g., the grain size, state of precipitates, etc. [65].

Microscopic examination of the dissimilar weld cross-section, after FSW, reveals four distinct regions: (i) weld nugget (WNZ) or SZ consisting of fine equiaxed recrystallized grains, (ii) TMAZ with relatively large, elongated, deformed grains, (iii) HAZ, and (iv)

the BM. Peak temperatures in the SZ can increase up to about 0.6–0.95 T_m depending on the processing parameters, where T_m denotes the melting point of the BM. The high temperatures and large deformations in the SZ result in dynamic recrystallization in this region [66]. Further, the grains produced during recrystallization increase in size with increasing tool rotational speed and decreasing the welding traverse velocity. The TMAZ experiences smaller strains and strain rates as well as lower peak temperatures than the SZ, and no recrystallization occurs in this region. HAZ, as the name is suggested, only experiences a thermal cycle. There is no noticeable plastic deformation in this region, and the grain sizes are so similar to those in the base metal. Nevertheless, the thermal cycle experienced by the material in the HAZ can lead to a significant change in its material properties from the ageing process [67].

2.11 Literature Review

Several studies have been carried out on Friction Stir Spot Welding of different types of aluminum alloys. Some of them have studied the effect of FSSW parameters on the mechanical and microstructural properties of the welded joints. The most important parameters considered in these studies are the tool geometry, tool rotational speed, tool plunge depth, tool plunge rate and dwell time which plays a critical role in determining the weld strength. The keyhole remaining at weld nugget is the main limitation of the FSSW process, which promoted many researchers to work on removing the keyhole from the welds by a newly developed technique known as the FSpW process with a double-acting tool. On the other hand, some investigators have invented other techniques to eliminate the keyhole instead of the complex FSpW machine. This method is called Friction Stir Spot Welding with refilling by Friction Forming Process (FSSW-FFP). Some of these studies as well as other successful attempts.

E. Taban et al. in (2009) joined Al alloy (6061-T6) to steel (AISI 1018) by using friction stir spot welding process using different parameters. These weldings were evaluated by

metallurgical analysis such as microstructural and (SEM) scanning electron microscopy, in addition to mechanical testing such as microhardness test. Results of these tests as the failures were seen on the aluminium side in the plasticized layer of the joint. Further, bond lines were seen by a thin layer of formed Al–Fe inter-metallic [38].

S. Prakash et al., (2010), used a modified FSSW process, named Friction Stir Spot Welding with refilling by Friction Forming Process (FSSW-FFP). This new technique includes two stages: welding and refilling. Welding is the first stage, where the workpieces are welded using a conventional FSSW tool, and after retracting it, the plasticized material gets extruded into the hole of a backing plate. In the second stage, the welded joint is tilted 180° and fixed on another solid backing plate. Then, the hole generated due to the pin was refilled by squeezing the extruded material by a specially designed friction forming tool. In their work, they welded lap joints of AA6061-T6 aluminium alloy with a thickness of 3mm. The results showed that the maximum tensile-shear failure loads of welded joints with - and without - pin hole were 3600 N and 5200 N, respectively. They concluded that the weld strength was improved by FSSW-FFP due to the increase in the effective cross-sectional area of the weld nugget [41].

Yuan et al (2011), studied the friction stir spot welding (FSSW) of Al alloy 6016-T4 sheet using a conventional pin (CP) tool and off-centre feature (OC) tool. Tool rotation speed and plunge depth were varied to determine the effect of individual process parameters on lap-shear separation load. A maximum separation load of about 3.3kN was obtained by using a 0.2mm shoulder penetration depth with 1500rpm tool rotation speed for the CP tool and 2500rpm for the OC tool. Three different weld separation modes under lap-shear loading were observed: interfacial separation, nugget fracture separation and upper sheet fracture separation. The Microhardness profile for weld cross-section indicated no direct relationship between microhardness distribution and separation locations [44].

Sun et al. in (2013) welded AA6061-T6 with mild steel sheets at (1mm) of thickness by using friction spot welding process. They estimated that the ideal dwell time and rotational speed were 2second and 700 rpm, respectively. when used 3 different pin lengths (1, 1.3 and 1.5) mm to join the specimen. The max. tensile shear strength (3200 N) was achieved for the tool at (1mm) pin length at the ideal rotational speed and dwell time. Adding that the results seen no notice intermetallic layer found along with welding between Al alloy and steel. [37]

Muna K.Abbass et al in 2015 studied the Friction stir spot welding (FSSW) was performed for welding of an aluminium alloy AA2024T3 sheet to commercial pure copper sheet of 2mm thick. Friction stir spot welding is carried out at different tool rotational speeds(800,1000 &1250) rpm, plunging times (30,60 &90) sec and tool pin profile or geometry (Threaded cylindrical with the flute, Tapered cylindrical and straight cylindrical). Process parameters were optimized by using the Taguchi technique and depending on the design of the experiment (DOE). The aluminium alloy sheet was overlapped on the copper sheet. It was found that maximum shear force was (1527 N) obtained at optimum welding parameters: 1250 rpm rotation speed,90 sec plunging time and straight cylindrical pin profile which is obtained from the analysis of response optimizer. Pareto chart the standardized effects of tensile shear results showed that the plunging time was the most effective parameter than other welding parameters(rotation speed and pin profile). From temperatures distributions measurements in three points in the nugget zone of spot weld, base aluminium alloy(AA2024T3) and base pure copper, it was found that the maximum measured temperature was 383 °C in the nugget zone of weld [72].

E. Fereiduni et al. in (2015), studied the effect of the dwell time and rotational speed on microstructure and mechanical properties of friction stir spot welded aluminium alloy AA5083 and 12 steel alloy sheets, it was taken the dwell time (from 5 to 15 sec) for both

rotation tool speed (900, 1100 r.p.m) and found the optimum condition when using (900 r.p.m, 12 sec) reached to the max. the failure load of 4020N [36].

Zheng et al. (2016) studied the FSLW of aluminium and steel using Zn as filler metal In this study, sound Al-Zn-steel "sandwich" joints were achieved. With the tool pin inserted into zinc foil, vast zinc was stirred into the aluminium fabricating Al-Zn mixing layer structure in the upper part of the aluminium side. A thin steel-Zn mixing layer structure was discovered at the interface. No intermetallic compound interlayer was discovered at the interface. The lap joints with zinc foil as filler metal showed better strength than joints without filler metal [68].

M. Hamzah et al., 2017 investigated the effects of tool pin geometry and tool rotational speed on the mechanical and microstructural properties of friction stir spot welded joints of AA6061-T6 aluminium alloy sheets with 1.6mm thickness. Different tool pin profiles; cylindrical, taper, and triangular and rotational speeds 800, 1000, 1200, and 1400 rpm were used as welding parameters with constant tool-shoulder plunging depth of 0.3mm, tool plunging rate of 15mm/min, and dwell time of 11.2 sec. FSSW tools consisted of a flat shoulder with pin and shoulder diameters of 5mm and 15mm, respectively. For the three-pin shapes, the results showed that the tensile shear load increased to the maximum value with increasing tool rotational speed from 800 to 1200 rpm, then, it decreased at 1400 rpm. They found that the highest tensile shear load (3200 N) was obtained from the welded joint made by the triangular pin at the optimum tool rotational speed of 1200 rpm. Also, they observed that the triangular pin resulted in a stir zone with the highest microhardness at all rotational speeds used in their work [39].

L. Zhou et al., 2017, investigated the effect of tool rotational speeds (1100, 1300, 1500, and 1700 rpm) on microstructure and mechanical properties of refill friction stir spot welded joints of AA6061-T6 aluminium alloy with sheet thickness of 2mm. The microscopic examination revealed that the grain size in weld zones increased with

increasing tool rotational speed. Weld defects such as partial bonding, bonding ligament, and voids were also observed in the cross-section of all refill FSSWed joints. Microhardness results showed that the hardness of the weld zones decreased with increasing tool rotational speed as a result of the increase in grain size. Based on the tensile shear test results, they found the tensile shear failure load increased to the maximum value of 7522 N with increasing tool rotational speed from 1100 rpm to 1500 rpm, and then, it decreased significantly at 1700 rpm. Two typical failure modes of plug-type fracture and tensile-shear mixed fracture were observed in failed specimens after tensile shear tests [40].

K. O. Sanusi et al. in (2017) evaluated the material characterization of dissimilar (FSSW) process between Al and Cu alloy. The condition of this process (800 rpm) of rotational speed (50, 150, 250) mm/min of transverse speeds and the total number of specimens used was 9 altogether. The spot welds were characterized by using (SEM)scanning electron microscopy and (OEM)optical microscope. In addition to the microstructure of the cross-section of the weld, the shear test of the spot welding was done. Show from the results that welding between metals and alloys was successful [35].

Zandsalimi et al. (2018), studied the effect of friction-stir welding parameters on the microstructure and the mechanical properties of the dissimilar 430 stainless steel and 6061 aluminium alloy joints were investigated. Optical and scanning electron microscopes in conjunction with energy dispersive X-ray analysis were employed to study the microstructure of the joints. Tensile and microhardness tests were used to evaluate the mechanical properties. The results showed that the best appearance quality was achieved at a rotational speed of 900 r/min, a traverse speed of 120 mm/min, and a tool offset of zero. The tool offset was the most effective parameter affecting the weld quality. The stir zone of the joints had a composite structure in which the dispatched steel particles were distributed in aluminium. The tensile fracture of the joints occurred in the heat-affected

zone of the aluminium part, which had the lowest hardness amount between the microstructural zones [69].

Abbass M. K. and Raheef K.(2018) studied friction stir welding (FSW) is solid-state welding used for joining similar and dissimilar aluminium alloys which are hard to weld by conventional fusion welding processes. In this study friction stir lap welding (FSLW) Joints are made for similar aluminium alloys (AA1100 to AA1100) and (AA6061to AA6061) sheets of 3mm thickness and those alloys have low to medium strength and have a difference in melting temperature and other physical properties' processes were carried out by conventional technique. The friction stir lap welding of similar aluminium alloys was carried out by varying the welding parameters, such as tool rotation speeds (1000, 1250 and 1600rpm) and travel speeds (35, 75 and 100mm) and a pin length of (5.4 mm) with using cylindrical threaded pin geometry or profile. Many tests and inspections were performed such as X-Ray radiographic and tensile shear tests. Microhardness and microstructure observations by using optical and SEM were carried out at the best welding parameters. The above tests were used to evaluate the weld quality and joint efficiency under different welding parameters. The best welding parameters that appeared in FSLW were 1250rpm and travel speed 100 mm/min. It was found that a higher hardness value was (94.38HV) for 6061-T6 and 49HV for 1100-H112 in stir zone for both FSLW joints of AA6061-T6 and AA1100-H112 and that decrease toward the HAZ and base metals of AA1100 and AA6061[43].

Abbass M. K. and Raheef K.2018 Study the friction stir lap welding (FSLW) joints are made for similar and dissimilar aluminium alloys (AA1100 to AA6061-T6) sheets of 3mm thickness by varying the welding parameters, such as tool rotation speeds (1000, 1250 & 1600 rpm) and welding speeds (35, 75 & 100 mm/min) and a pin length of (2.8, 5.4 & 5.7mm) with using cylindrical threaded tool pin profile. Many tests and inspections were

performed such as X-Ray radiographic and tensile shear tests to evaluate the weld quality and joint efficiency under different welding parameters. Microhardness and microstructure observations were carried out at the best welding parameters. The maximum tensile shear force (4.93 KN) and joint efficiency (93%) were obtained when the welding process was conducted by a new technique using friction stir diffusion welding process at the welding speed of 75 mm/min., tool rotation speed of 1250 rpm and using pin length of 2.8 mm. It was found that the Vickers hardness of the similar and dissimilar joints reached the maximum value at the stir zone and drop toward the base metals [72].

Concluding Remarks

The most important remarks which can be drawn from the above previous studies are:

1. There are no typical process parameters that can be selected for all FSSW applications because they depend on several factors such as type of materials to be welded, thickness, and performance of the welding machine.
2. Some studies found that the mechanical and microstructural properties of friction stir spot welded joints were improved with increasing tool rotational speeds. While other studies found that the weld properties deteriorated with that increase in tool rotational speeds.
3. All studies indicated that the triangular tool pin profile produced FSSW joints with higher shear force than those welded using the straight cylindrical pin.
4. Some FSSW studies indicated that the weld strength increased with increasing tool shoulder diameter.

5. Many studies found that the weld strength improved with increasing tool plunging depth for all welding materials with various thicknesses in similar and dissimilar friction stir spot welded joints.
6. A finite element based thermal model using different programs; i.e. DEFORM and ANSYS was developed to simulate the temperature distribution during the FSSW process.
7. The friction forming process with or without filler material was suggested by other researchers to refill the keyhole formed in conventional FSSW joints using a specially designed tool and backing plate.

Chapter Three

Experimental Part

3.1 Introduction

This chapter includes general description of the experimental work steps and equipment's used. It also involves the experimental procedures which concentrated on preparing and joining of low carbon steel and AA6061 sheets using friction spot welding. In addition to the evaluation of some mechanical properties of the resultant joints, such as micro-hardness and tensile-shear tests were studied. Also, the micro-structural change. The procedure of the experimental work is shown in Figure (3.1)

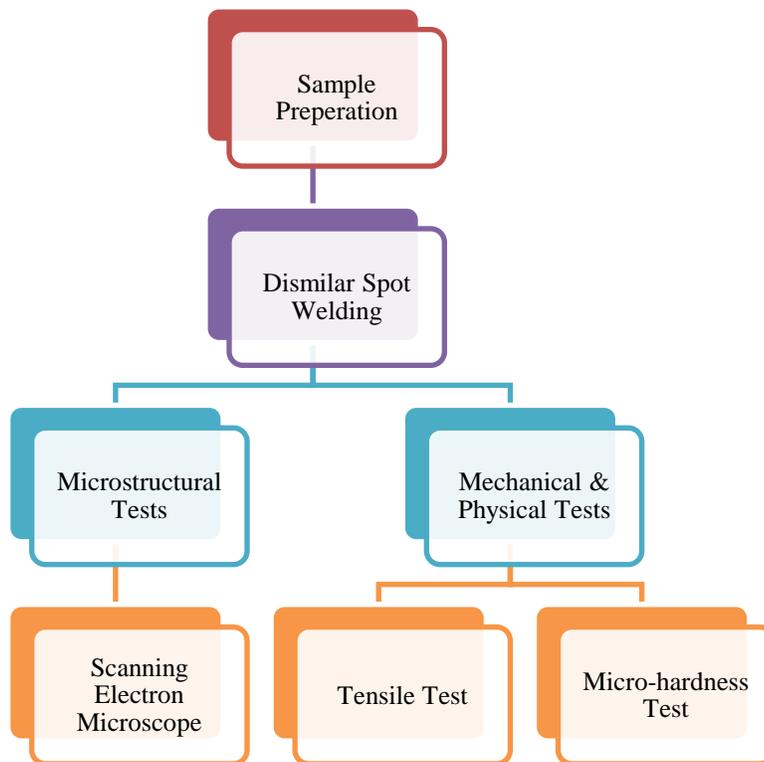


Figure (3.1): Block diagram of the experimental work

3.2 Materials Used

Low carbon steel and AA6061 sheets with the chemical composition shown in Table 2.1 were used in this research.

Table 2.1 the chemical composition of the materials used in this research

Elements	Aluminium Alloy
Mg	1.05
Al	> 93.60
Si	0.685
P	0.00092
S	< 0.0020
Ti	0.15
V	< 0.00082
Cr	0.21
Mn	0.124
Fe	0.389
Co	0.129
Ni	0.0662
Cu	0.3609
Zn	0.1522
As	<0.00009
Zr	0.1348
Nb	<0.00067
Mo	0.226
Ag	<0.00066
Cd	0.0050
Sn	0.0096
Sb	<0.0010
W	<0.00094
Pb	<0.0011

3.3 Welding Machine

All of the friction stir spot welding procedure in the research was done on the milling machine shown in Figure (3.2), which is available in the workshops of the College of the Materials Engineering – The University Babylon. Welding was done using two

metal sheets from low carbon steel and aluminum. The dimensions of the sheets were (100 mm * 25 mm * 1 mm) and 25 mm overlap as shown in Figure 3.3.

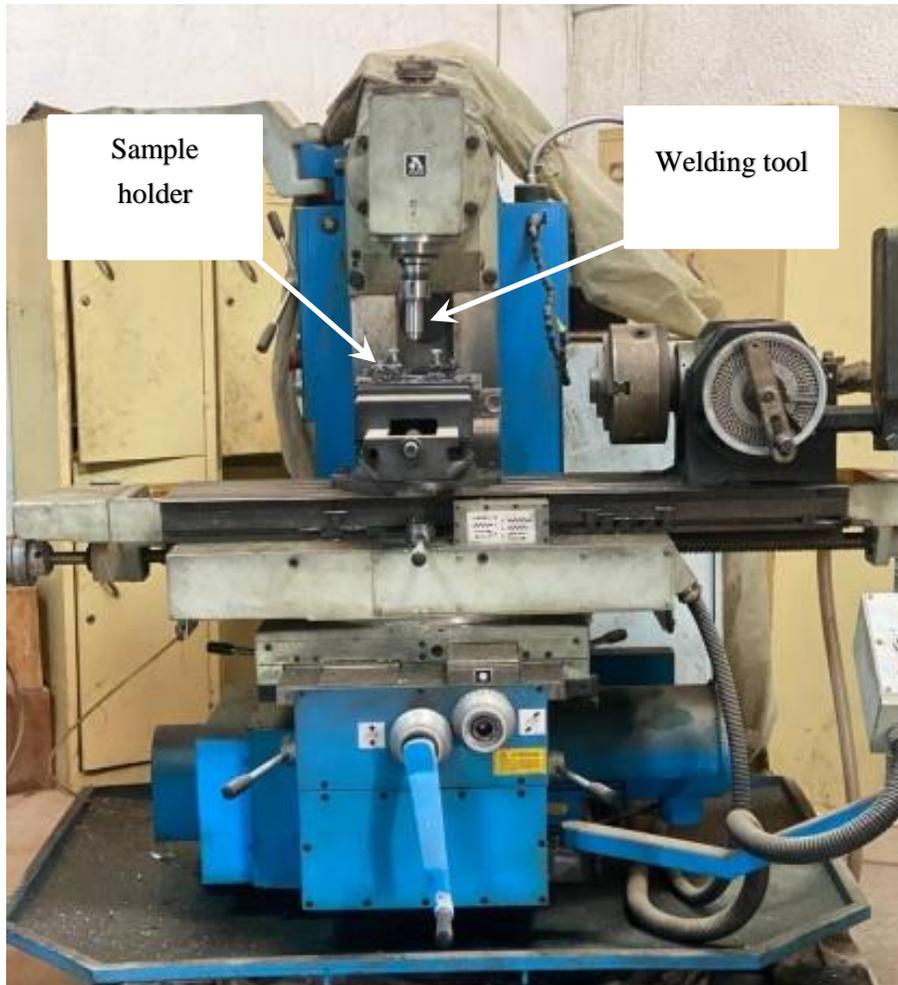


Figure (3.2) The milling machine used in the current research

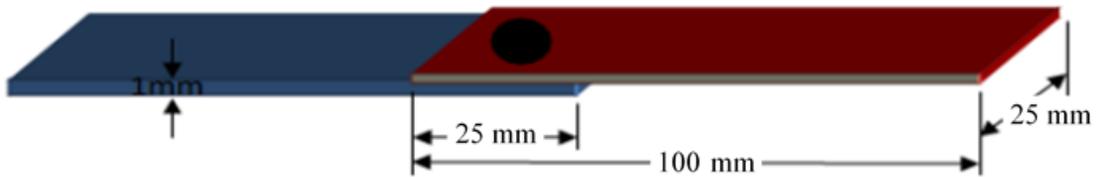


Figure (3.3): The dimensions of the overlap sheets to be joined

3.4 Surface Preparation for Welding

After cutting the samples to the required dimensions for each test, the surfaces were prepared for the welding process by grinding them using 1200 grit silicon carbide papers to remove the oxides layer then cleaned with ethanol to remove the grease and dust from the surface.

3.5 Microstructure Examination

The specimens were prepared for microstructure examination in consistent with the standard metallographic techniques which involves the following steps.

1. Sample must be cut to the cross-section area for easier handling and to know the variation in zones microstructure.
2. Wet grinding process was carried out by exposing the sample surface to rotary disk with using emery papers of (SiC) with different grades in sequence (180, 400, 800, 1000, 1200, 1500, 2000). Then the sample washed by water and dried by hot air.
3. Polishing process was carried out by exposing the sample surface to rotary disk, using polishing cloth and alumina (Al_2O_3) solution. This process continued until the sample surface becomes as a mirror, and then it is washed by the water and alcohol and dried by hot air.
4. Etching process was doing by immersion the sample for 30 s with Keller. Then they were washed in water and ethanol, then dried in stream of warm air.

3.6 Micro-Hardness Test

Micro-hardness Test using digital Vickers hardness tester type (HVS-1000) which is presented in the Metallurgy Eng. Laboratory in the College of the Materials Engineering in The University of Babylon. Measurements were done with transverse section to after grinding and polishing processes. This test was done by measuring the micro-hardness with load of 200 g and automatic loading of 10 seconds. Vickers Microhardness (HV) values were then calculated by the machine using the equation:

$$HV = 1.854 \left(\frac{P}{d^2} \right) \quad (3 - 1)$$

where P is the applied load and $d = (d_1 + d_2)/2$

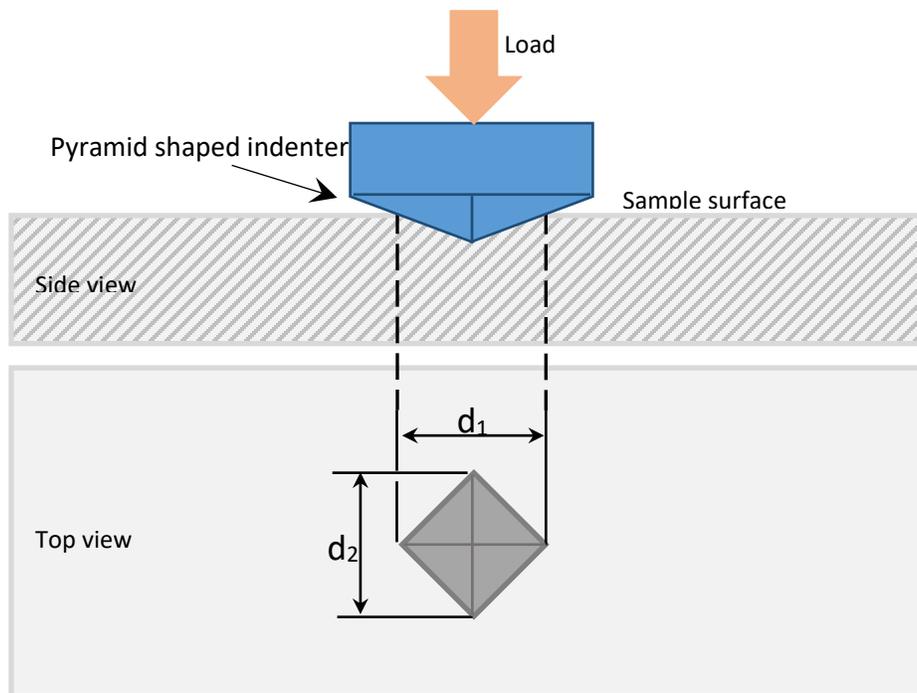


Figure 3.4: Schematic of the Vickers Microhardness indentation test

3.7 Tensile Test

The tensile tests were done for the base metal and the welded samples were done via universal type device with cross head speed of 1.0 mm/min and carried out according to (ASTM A370-03a). Figure (3.5) shows the universal testing machine



Figure (3.5): The universal testing machine

3.8 Scanning Electron Microscope (SEM) Analysis

SEM images were taken for samples cross-sectioned to investigate the microstructure. The samples were prepared by the same procedure followed in the OM microstructure samples. This test was carried out at Alkhora company. The device is shown in Figure (3.6).



Figure (3.6): Scanning electron microscopy (SEM) devise

Chapter Four

Results and Discussions

4.1 Introduction

In this chapter, experimental results and discussion are presented. Microstructural observation of dissimilar frictional stir spot-welded joints (LCS/AL6061) has been discussed. The results of mechanical tests such as micro-hardness and tensile-shear for FSSW joints discussed also. Furthermore, the results of the failure modes for these joints and the reasons behind these modes were discussed in this chapter.

4.2 Welding Parameters Window

FSSW of AA6061 to LCS sheets shows many challenges compared to the welding of similar sheets of an AA6061 aluminium alloy. In initial trials, it was found that the low rotation rates (lower than 1200 rpm) and low welding time (less than 1.0 s) could not result in sound joints and sometimes no joints could be result with these parameters. This result was found due to the low heat input because of the low rotation rate or welding time or both. To solve this problem, a welding parameter widow was designed to be extended from 1200 to 2000 rpm rotation rate and 1.0 to 3.0 s welding time. The upper limits for these parameters were chosen depending on three factors. Firstly, the machine capability decided the maximum tool rotation rate. Secondly, the industrial requirement suggested that the typical welding time for each single spot weld is about 1.0 s to be economical [13]. Finally, the results of the tensile-shear tests showed that increasing the rotation rate by more than 1600 rpm led to a clear decrease in the mechanical properties of the joints. A typical example of a dissimilar AA6061 to LCS welded joint is shown in Figure 4.1.

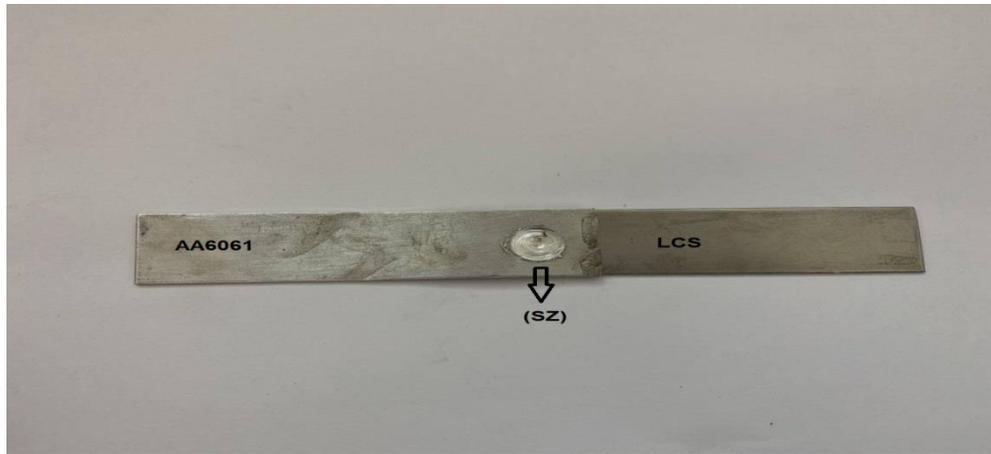


Figure 4.1: A typical example of a dissimilar AA6061 to LCS welded joint

4.3 Macrostructure and Microstructure of Welded Joint

The macrostructure and microstructure examination were conducted to evaluate the effect of friction stir spot welding on the microstructure of the welds produced by the FSSW.

Figure (4.2 a) shows the macrostructure of the joint cross section. This figure consists of a series of several microstructure images and then they merged together to form one image. The cross section shows a typical shape for the FSSW joints where it consists of three areas from the center of the joint. The first region is the area where the pin penetrated the material resulting in moving the material of the upper sheet (AA6061) to the sides. Also, it touches and deforms the lower sheet (LCS) resulting in the keyhole shape with some material interlocking from both sides of the keyhole bottom as can be seen in Figure (4.2 b) . This region is important because it increase the strength of the joint. The second and the most important region is the area under the tool shoulder. This area represents the region where the two metals are connected together due to the effect of rugging of the aluminium alloy by the tool against the steel sheet. The last but not the least region is the material out of the weld zone. This region also consists of two sub-regions including the

heat affected zone where material is affected by the heat generated during the weld cycle in the stir zone (SZ). The second sub-region is the base metal where the material remains without any change.

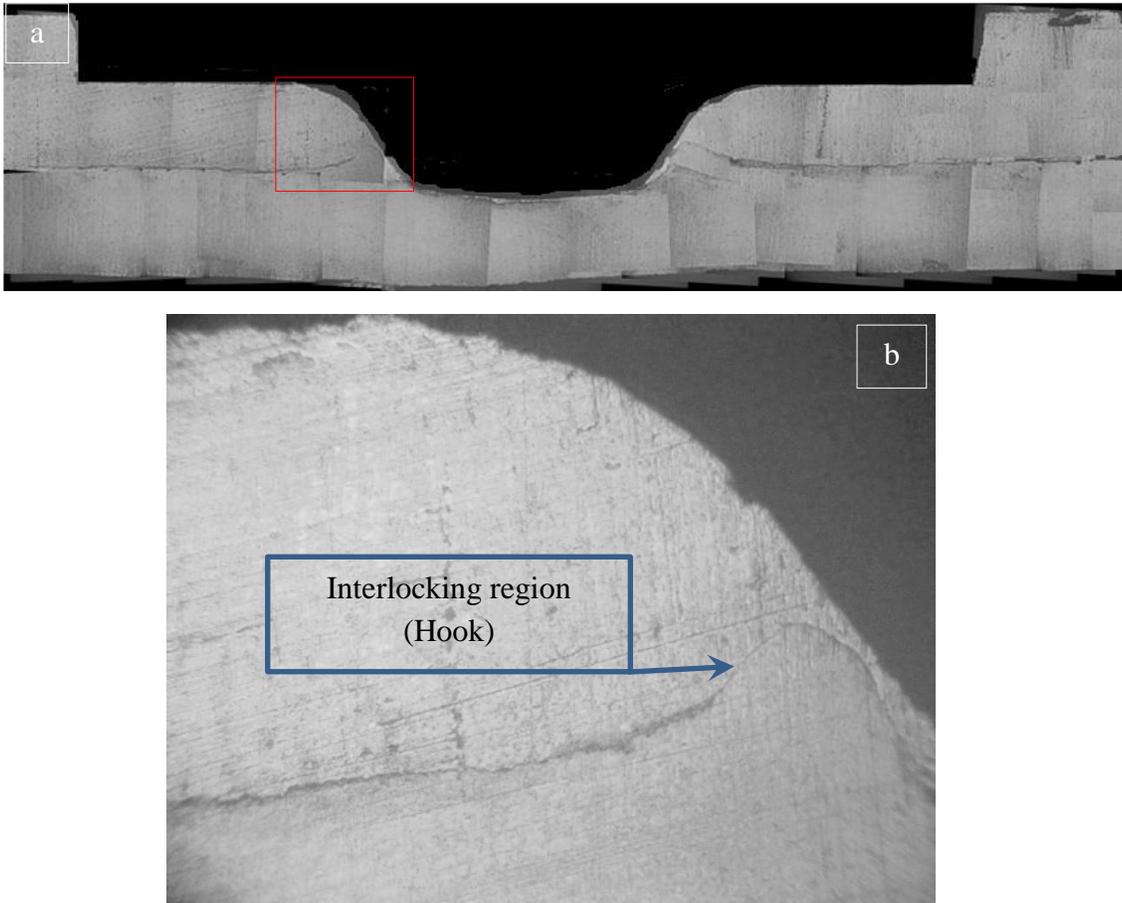


Figure 4.2: A typical example of a cross section of dissimilar AA6061 to LCS welded joint a) joint cross section and b) a region at the side of the keyhole

4.4 Scanning Electron Microscopy Analysis of Optimum Sample (SEM)

Scanning electron micrographs were taken for the cross-sections using FE-SEM focusing on the joint interface of the welded sample of the dissimilar metals Al6061 / LCS. Figure (4.3) shows an image of a half of a weld produced without interlayer and using welding conditions of a 1600 rpm tool rotation rate and 3.0 s welding time. The

thinning effect resulted from the tool shoulder is clear where about only 47 % of the total upper sheet thickness remained at the outer ring shape weld zone. On the other hand, at the center of the weld, AA6061 disappeared completely due to the presence of the pin which displaced aluminium and deformed the lower sheet (LCS). This action of the pin resulted in a deformed shape at its edge called “Hook” which can be clearly seen in Figure 4.4. The hook is not preferred in FSSW joint of similar materials, when welding Al-Al for example, because it represents a weld defect. However, in the situation of the welding of dissimilar materials, it has an advantage of the interlocking effect which increases the strength of the joint

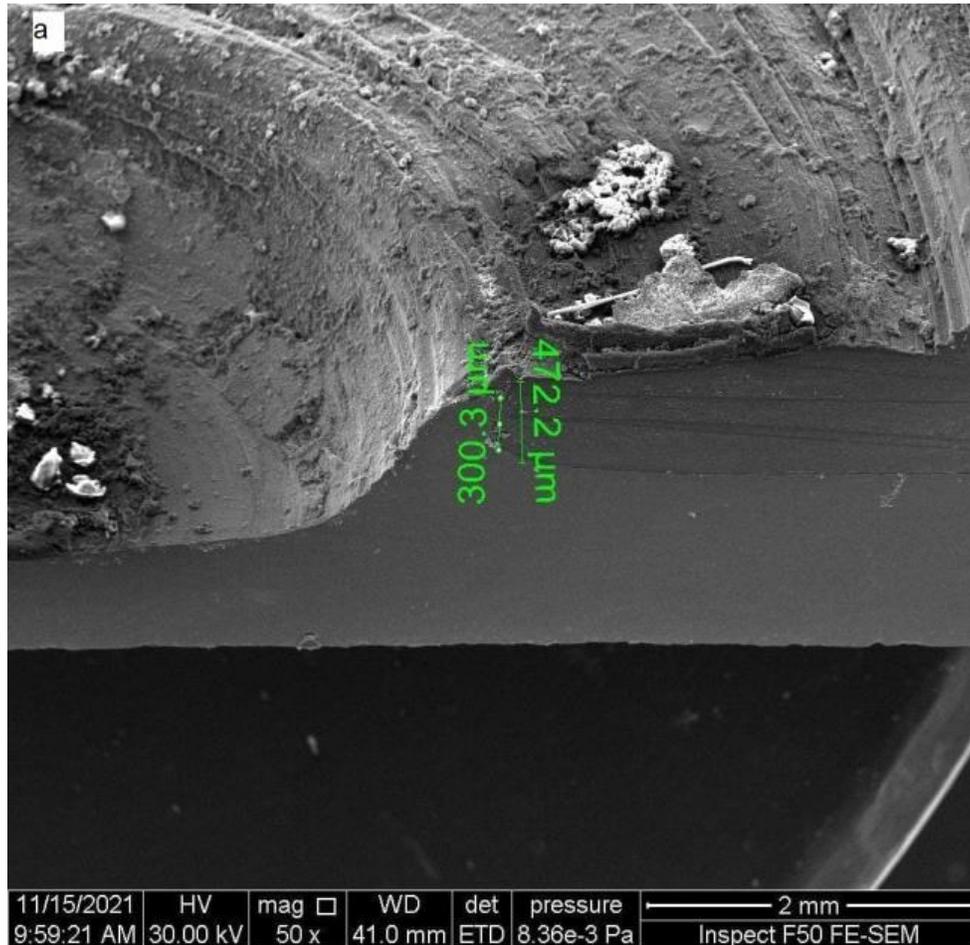


Figure (4.3): FE-SEM micrographs of the half cross-section of Al to LCS welds produced using welding conditions of 1600 rpm, 3.0 s

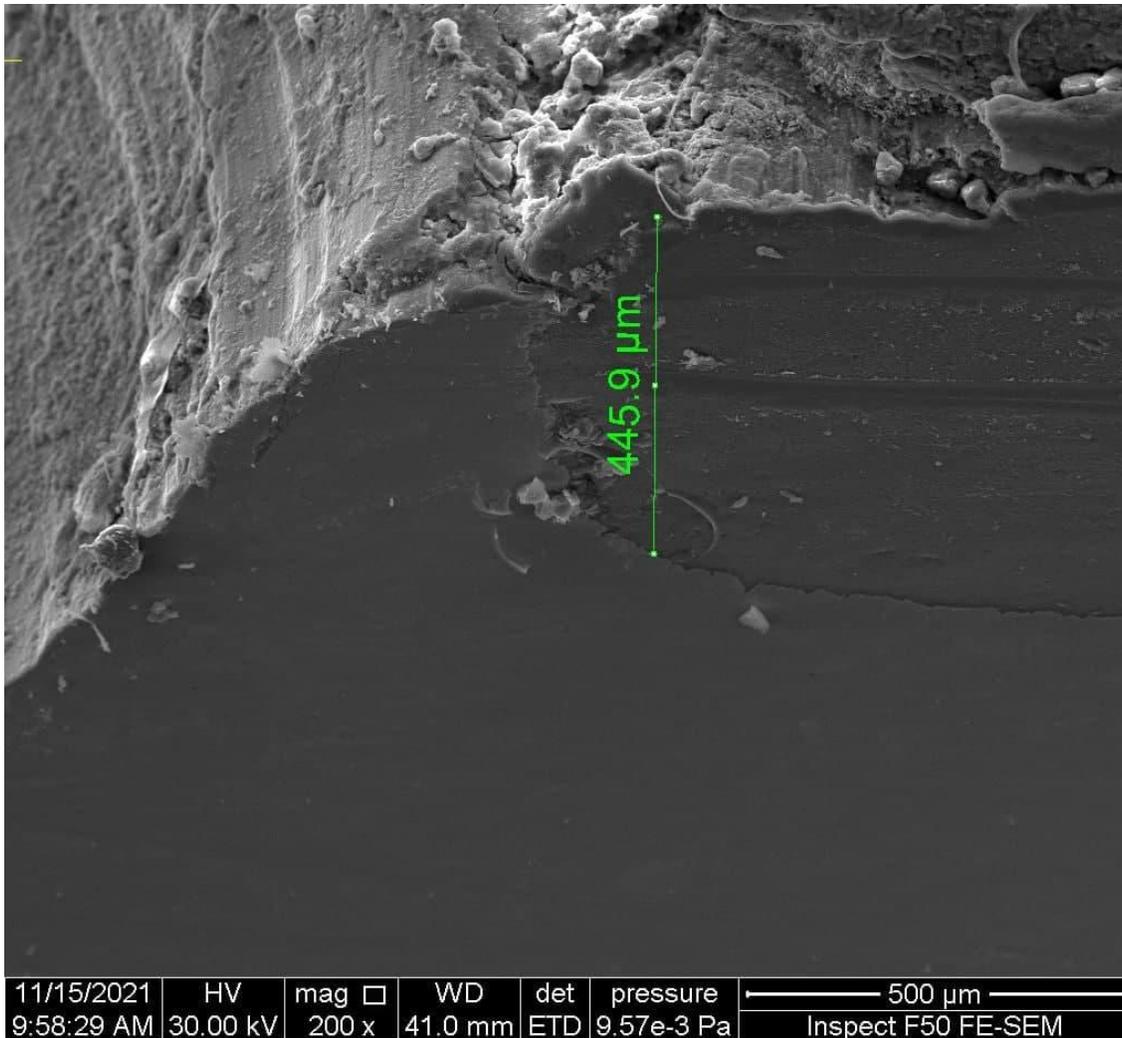


Figure (4.4): FE-SEM micrographs of the cross-section of Al to LCS welds produced using welding conditions of 1600 rpm, 3.0 s. with hook defect

The rapid formation of intermetallic phases during the spot welding of aluminium to steel is a well-known problem in different welding methods, such as friction stir welding and ultrasonic welding. A reaction layer present at the interface between the two sheets can clearly be identified because in the SEM it is a contrasting shade to the both alloys. In the example shown in Figure 4.5 which represents a higher magnification image for the same sample of Figures 4.3 & 4.4. The reaction layer can be seen to be non-uniform in thickness, and shows continuity at the interface.

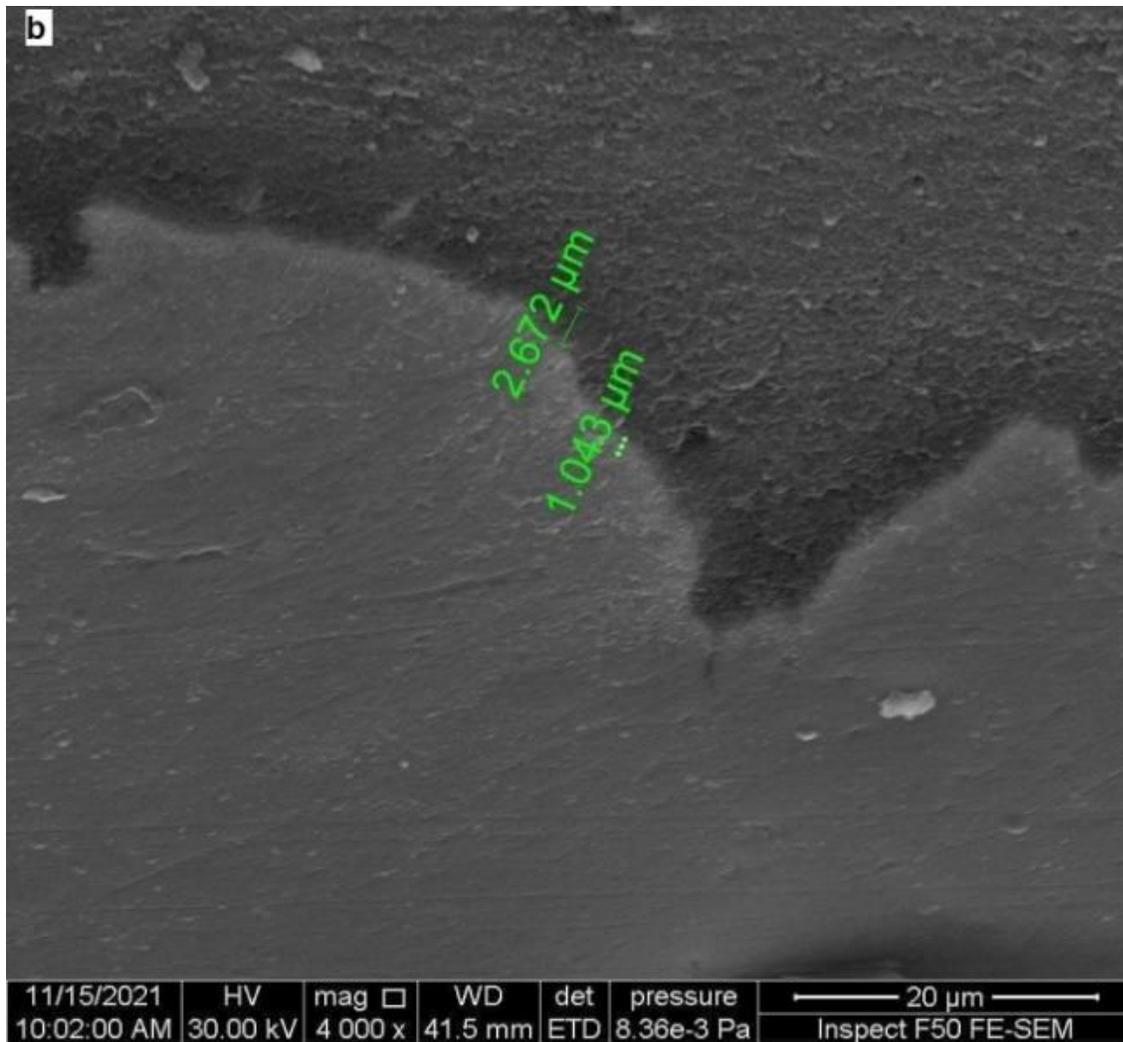


Figure (4.5): FE-SEM micrographs of the half cross-section of Al to LCS welds produced using welding conditions of 1600 rpm, 3.0 s

4.5 Effect of Welding Variables on the Joint Hardness Profile of the Al-Steel Dissimilar Weld in the Naturally Aged Condition

Microhardness testing was implemented to show the effect of the welding parameters used in this study on the local mechanical properties of the welded joint after natural ageing. Measurements were made in aluminium the steel sheets in the form of two parallel lines

of points in the mid-thickness of the upper (AA6061) and the lower (LCS) sheets passing through all the areas of the welded joints.

The effect of the FSSW parameters on the microhardness profiles of the AA6061 Aluminium alloy- LCS welds in the post-weld naturally aged condition is shown in Figure 4.6. This figure shows hardness profiles measured after three months of the welding process. In general, the hardness profile across the welds shows a very high level near the centre of both the upper and lower sheets despite the difference in material type. The hardness level of the upper sheet shows a very high level near the centre after the natural ageing in comparison to the predicted hardness levels in the as-welded condition. The main reason is the effect of severe plastic deformation near the pin of the tool with moderate heat generated at this region which leads to grain refinement and encourages the natural ageing response. By moving away from the centre of the weld, the heat generated during the welding cycle become higher leading to some stress relief resulting in a lower hardness level than the hardness near the keyhole. By moving further to the region out of the stir zone (SZ), it can be noticed that the hardness level shows a very low level compared to the central area. However, the hardness in this region (HAZ) has a value of about only 10 % less than the hardness for the base material (AA6061). This means that After natural ageing, the HAZ is still possible to be distinguished in the weld edges and the natural ageing could not recover the original hardness level of this material even after three months. In natural ageing, the hardness increases as a result of the precipitation of GPZs and solute clustering with ageing time [70].

The change in hardness level of the lower sheet is significantly higher than the change hardness level of the upper sheet. The reason for this difference is the effect on the response of steel to the plastic deformation and heat generated. The plastic deformation was very high especially in the area under the pin leading to an increase in the hardness significantly. On the other hand, the heat generated in such welding processes results in a

temperature as high as 540°C. This level does not result in phase transformation to the steel, i.e. most of the hardening results from the plastic deformation will retain after the welding process. Moreover, the thermal loss is also higher from the steel (lower sheet) due to the conduction heat transfer [71].

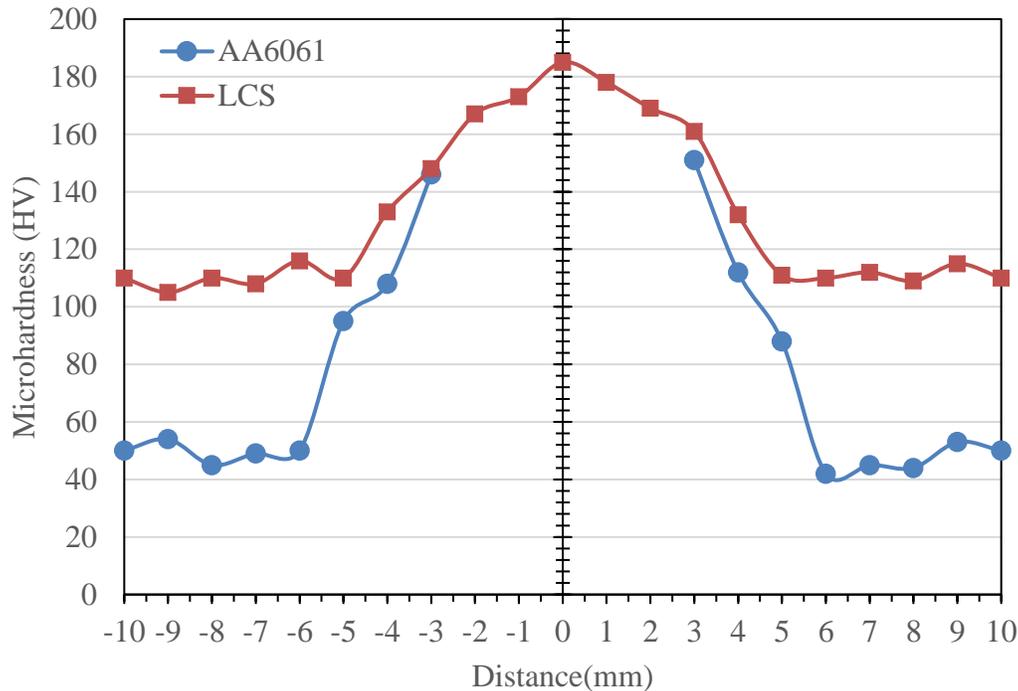


Figure 4.6: An example of hardness profiles for samples naturally aged for 3 months, welded with a tool rotation rate of 1600 rpm and welding time of 3 s.

4.6 Effect of Welding Parameters on the Weld Strength

To study the mechanical performance of the dissimilar Al-Steel joints, many spot welds were produced using the FSSW process with a wide range of welding time and tool rotational speed. All of the tensile shear lap shear tests were at room temperature using a machine crosshead speed of 1.0 mm/min.

Figure 4.7 shows an example of a typical load-extension curve for the lap-shear tests of the welded joints. This joint was produced using welding conditions of a 1600 rpm

rotation rate and 3.0 s welding time. The curve of the joint shows very low ductile behaviour. Following the highest load, the joint showed a fast decrease in the load. This fast decrease in load represents evidence of a brittle fracture in the joint.

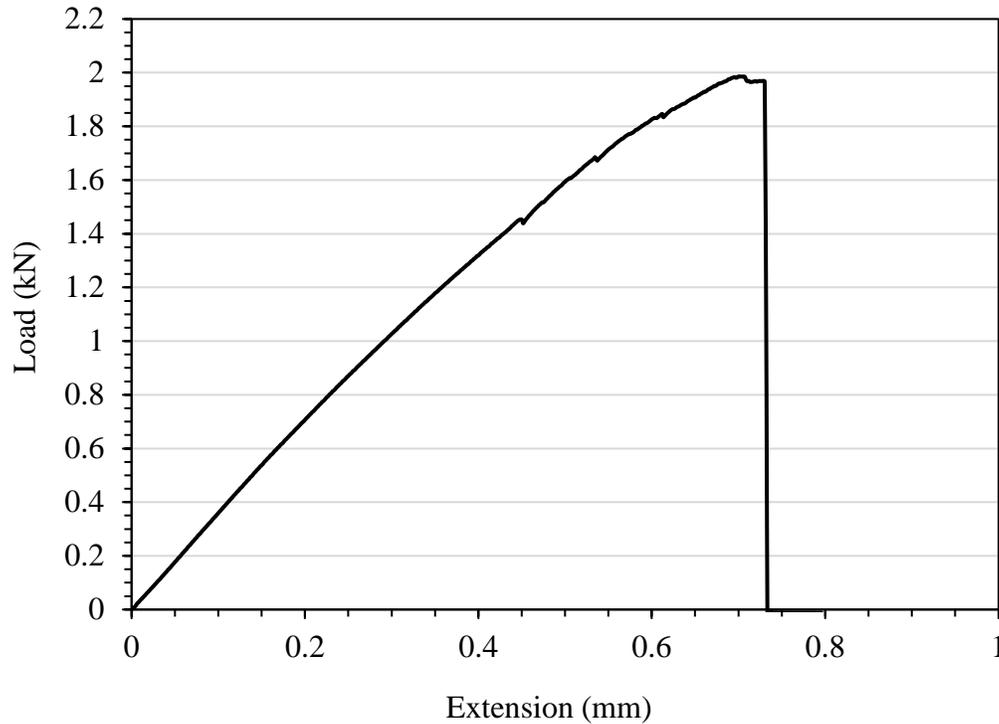


Figure 4.7: An example of the load-extension curve for the tensile-shear test from Al-Steel joints. The joint was produced using welding conditions of a 1600 rpm tool rotation speed and a 3.0 s welding time.

The effect of the welding time and tool rotation rate on the highest fracture load of the welded joints with the addition of Zr interlayer of (0, 0.001, and 0.005 g) are shown in Figures 4.8 to 4.10 . Figure 4.8 shows that the average peak loads of the joints welded without any interlayer. It is seen that the strength of the samples was slightly increased by increasing the welding time from 2 to 3 s while it shows some increase and then decreases in the values by increasing the rotation rate from 1200 to 1600 and then to 2000 rpm. This behaviour is highly linked to the production of the joint and its completeness. At a lower rotation rate, the heat generated might be not enough to produce sound joints, and this is

the same reason behind the disappearance of the data for the shortest welding time (1.0 s). On the other hand, the further increase in tool rotation rate (to 2000 rpm) had a clear impact in reducing the weld strength, which may be attributed to the production of more brittle intermetallic compounds between AA6061 and LCS at the interface.

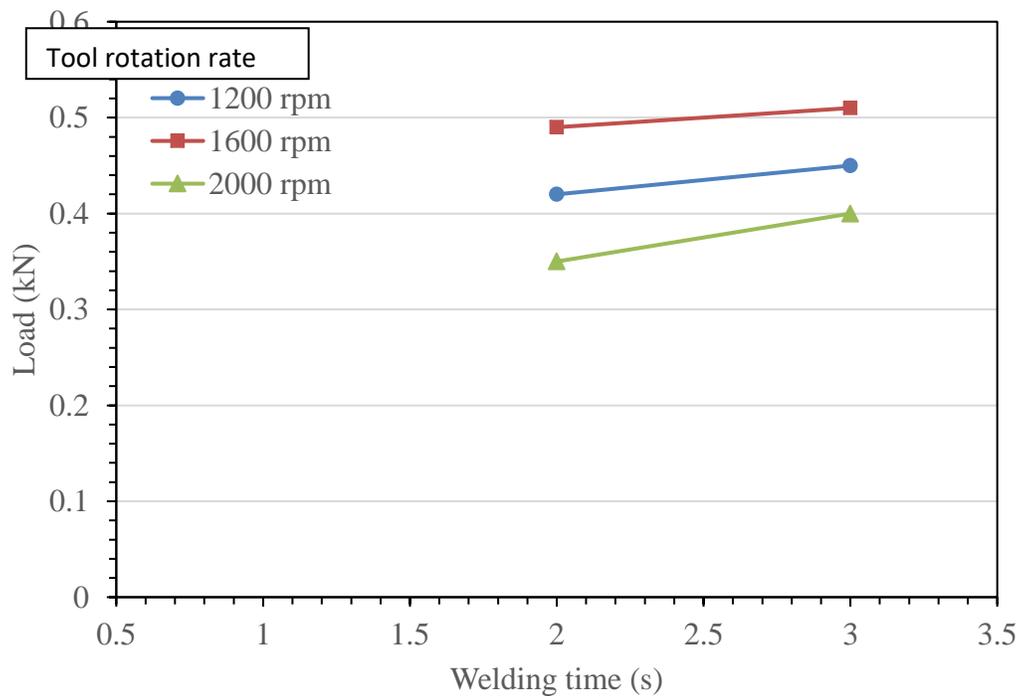


Figure 4.8: Effect of tool rotation rate and welding time on the average lap shear peak load for joints produced without any Zr additions

By adding an interlayer containing Zr powder, joints could be produced using welding time as low as 1.0 s. This can be seen in Figures (4.9) and (4.10). This can be attributed to two reasons. The first reason is the increase of the friction between the two sheets by the addition of an interlayer containing Zr powder, which led to an increase in the heat generated at the interface and improved the joint completeness. The second reason is the positive effect of the Zr addition in modification of the nature of the intermetallic compounds produced at the interface between aluminium and steel. This reason is more acceptable since the level of the fracture peak load of all the welded joints was increased

compared to that of joints without interlayer containing Zr. However, in general, the change in welding parameters show a similar effect on the joint strength i.e. the peak fracture load increased with increasing welding time for each rotation rate. But again the 1600 rpm rotation rate produced the highest levels compared with the others for the same reasons mentioned earlier.

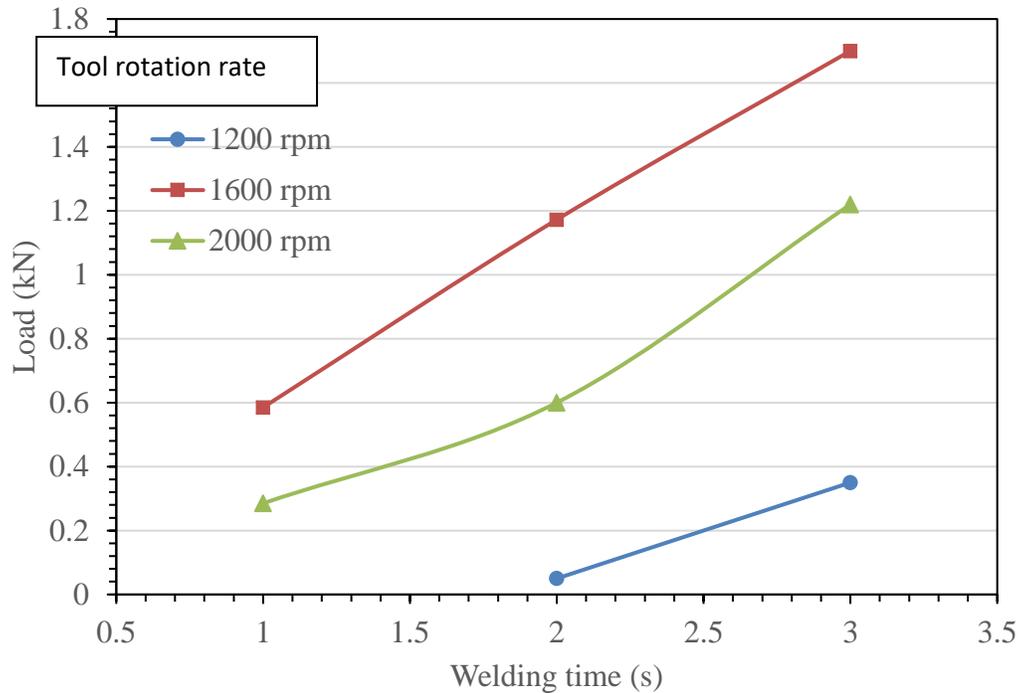


Figure 4.9: Effect of the tool rotation rate and welding time on the average lap shear peak load for joints produced with the addition of interlayer containing 0.001 g Zr

Figure 4.11 shows the combined effect of rotational rate and Zr additions, with constant welding time of 3.0 s, on the fracture load of the AA6061 to LCS joints. It is clear that the region of around 1600 rpm rotation rate shows the highest level of the weld failure load, due to the moderate heat input which resulted in completed joints without additional heat that resulted in thicker intermetallic compound layer at the interface between the two metals.

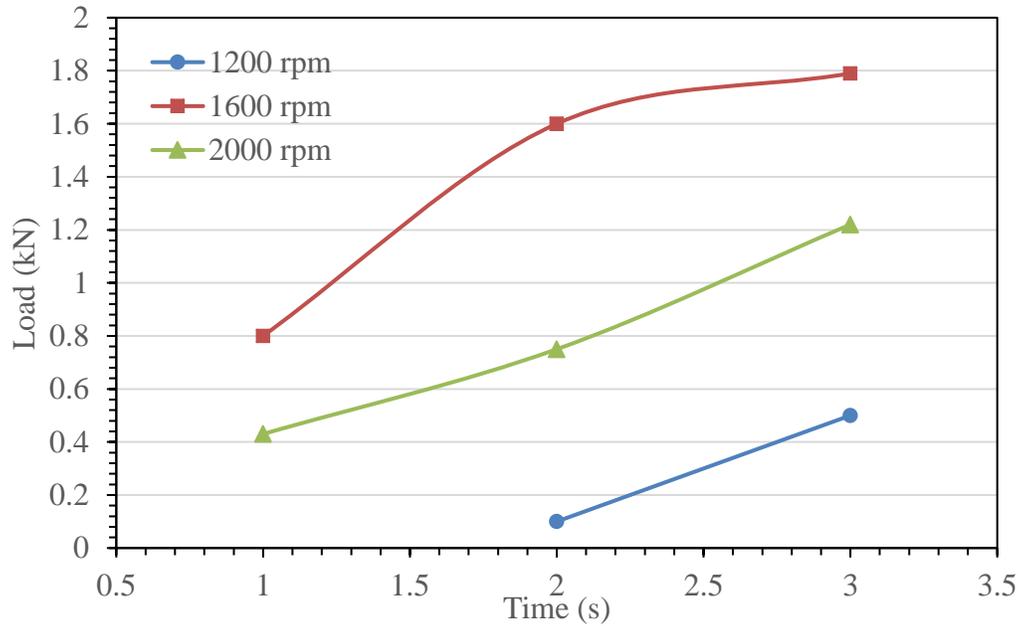


Figure 4.10: Effect of tool rotation rate and welding time on the average lap shear peak load joints produced with the addition of interlayer containing 0.005 g Zr

The effect of Zr addition on the strength of the joints is shown in Figure 4.12. The 1600 rpm rotation rate was chosen because it showed the highest strength levels in all previous welds. It can be noted that more Zr addition results in higher failure load for the joints. Due to the effect of which in modification of the nature of the intermetallic layer produced during the welding cycle.

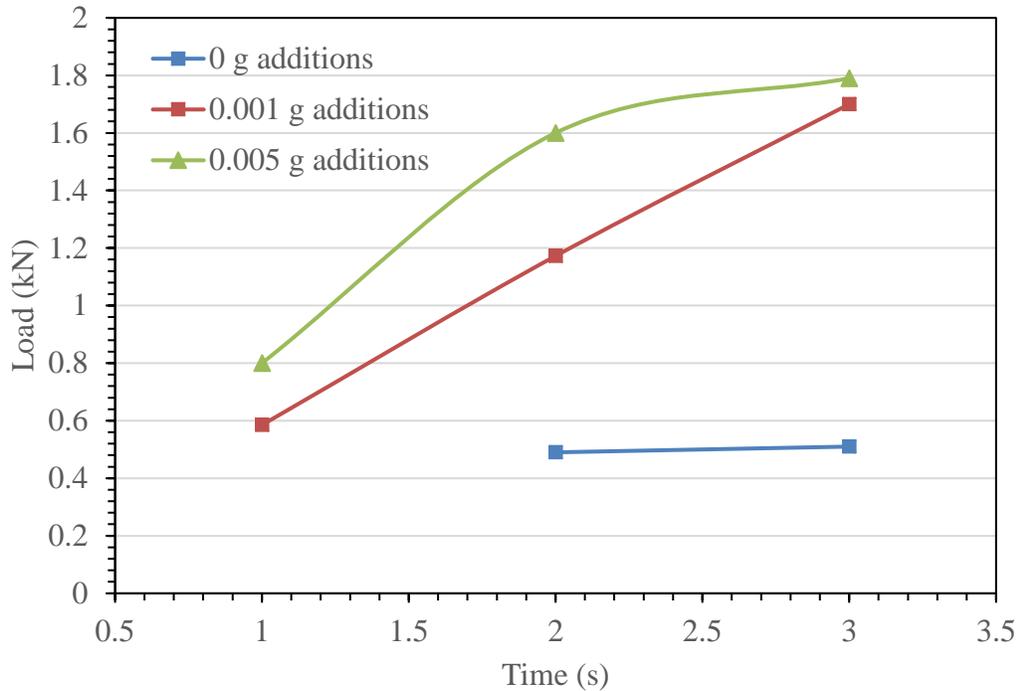


Figure 4.12: Effect of Zr addition (0,0.001 and 0.005g) and welding time on the average lap shear peak load.

4.7 The Failure Modes for the Welded Joints

Examples of typical fracture mode of the dissimilar AA6061-LCS joints produced using the FSSW method with different welding parameters, after lap shear testing, are shown in Figure 4.13. An interfacial fracture mode was noted for all of the joints produced with different welding parameters, due to the formation of an IMC layer, especially, when joining the two materials without any interlayer. These structures show much more brittle behaviour than the base materials (LCS and AA6061); therefore, cracks can be easily propagated through them and result in low fracture energy for the joint [72].

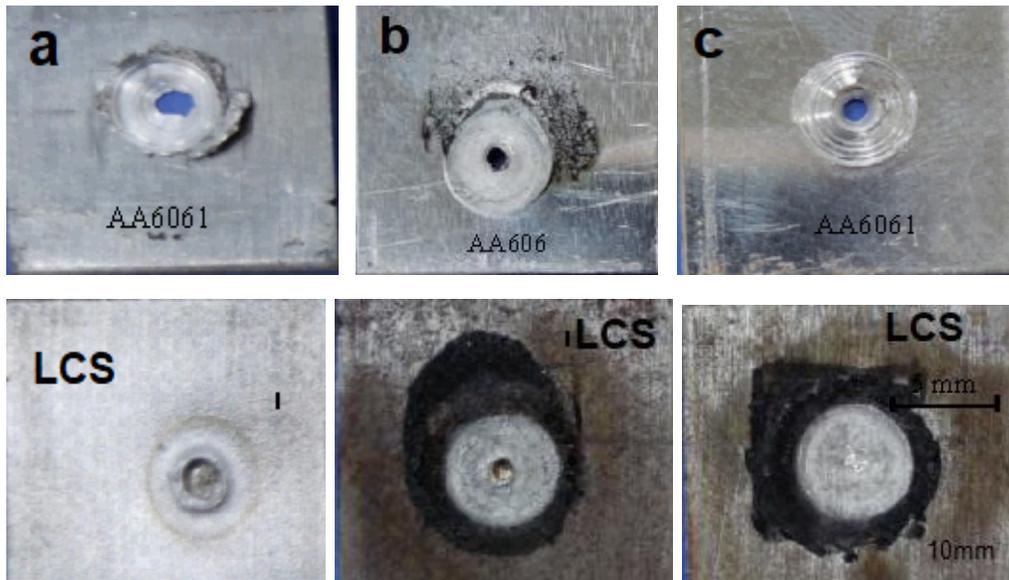


Figure 4.13: Examples of typical joint failure mode, showing upper and lower sheets of the fractured lap-shear test samples produced using 1600 rpm tool rotation rate and 3.0 s welding time (a) without interlayer (b) with an interlayer containing 0.001 g Zr; and (c) with an interlayer containing 0.005 g

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

- 1- The natural aging was successful in recovery of the original hardness of the AA6061 at the HAZ.
- 2- The welded cross section of the joint showed different regions in terms of macrostructure including keyhole, bonded region and base metal.
- 3- The addition of Zr as an interlayer was successful in improving the joint performance by altering the layer nature.
- 4- The joints showed brittle behavior during the tensile-shear test due to the presence of the intermetallic compounds at the interface between AA6061 and LCS sheets.
- 5- The joints strength increased with increasing the tool rotation rate from 1200 to 1600 rpm. However, the performance of the joints produced with higher rotation rate were decreased due to the increase of intermetallic compound layer.
- 6- With increasing welding time , the joints strength was increased.
- 7- The optimum conditions in terms of joints performance in this research were 1600 rpm rotation rate, 3 s welding time, and 0.005 g Zr interlayer addition. With these parameters the joint fracture force was about 1.8 kN compared to only 0.5 for a joint prepared with the same welding parameters but without any Zr addition.
- 8- The maximum hardness value in AA6061 sheet at SZ (151 HV) , and LCS (185 HV)

5.2 Recommendations for Future Research

- 1- Conduct other tests on the welded joints such as tensile-impact test and EDS , XRD for samples taken from the interfacial reaction layer.
- 2- Use different material combinations such as aluminium alloys with magnesium or titanium alloys , and study the effect of Zr additions on the interfacial reaction layers and mechanical behavior.
- 3- Use different filling material other than Zr , such as Si nano particles and study the effect of them on the joint performance.

Reference

- [1] A. Silva, E. Aldanondo, P. Alvarez, E. Arruti and A. Echeverri'a, "Friction Stir Spot Welding of AA1050 Al Alloy and Hot Stamped Boron Steel", *Science and Technology of Welding and Joining*, Vol.15, No. 8, 2010, pp. 682.
- [2] A. Ambroziak and M. Korzeniowski, "Using Resistance Spot Welding for Joining Aluminum Elements in Automotive Industry", *Archives of Civil and Mechanical Engineering*, Vol. X, No.1, 2010, pp. 5-13.
- [3] R. Mishra and Z. Ma, "Friction Stir Welding and Processing", *Materials Science and Engineering R*, Vol. 50, August 2005, pp. 1-78.
- [4] D. Wang and S. Lee, "Microstructures and Failure Mechanisms of Friction Stir Spot Welds of Aluminum 6061-T6 Sheets", *Journal of Materials Processing Technology*, Vol. 186, 2007, pp. 291-297.
- [5] M. Besharati-givi and P. Asadi, *Advances in Friction Stir Welding and Processing*, 1st ed. [S.l.]: Woodhead, 2017.
- [6] S. Pawar and M. Shete, "Optimization of Friction Stir Welding Process Parameter Using Taguchi Method and Response Surface Methodology: A Review", *International Journal of Research in Engineering and Technology*, Vol. 2, No. 12, 2013, pp. 551-554.
- [7] H. Patil and S. Soman, "Experimental Study on the Effect of Welding Speed and Tool Pin Profiles on AA6082-O Aluminium Friction Stir Welded Butt Joints", *International Journal of Engineering, Science and Technology*, Vol. 2, No. 5, 2010, pp. 268-275.

- [8] S. Khodir and T. Shibayanagi, "Microstructure and Mechanical Properties of Friction Stir Welded Dissimilar Aluminum Joints of AA2024-T3 and AA7075-T6", *Materials Transactions*, Vol. 48, No. 7, 2007, pp. 1928-1937.
- [9] A. Gupta and S. Patel, "Experimental Evaluation on the Effect of Welding Speed and Tool Pin Profiles on Friction Stir Welded Joints on AA 6082-T6", *International Journal of Engineering Research & Technology (IJERT)*, Vol. 3, No. 5, May 2014, pp. 2257-2262.
- [10] T. Iwashita, "Method and Apparatus for Joining", U.S. Patent 6,601,751 B2, August 2003.
- [11] J. Piccini and H. Svoboda, "Effect of Pin Length on Friction Stir Spot Welding (FSSW) of Dissimilar Aluminum-Steel Joints", *Procedia Materials Science*, Vol. 9, 2015, pp. 504-513.
- [12] T. R. C. Diego Fonseca Silva, Pedro Paiva Brito , Pedro Américo Almeida Magalhães Júnior, "Resistance Spot Welding of dissimilar Steels: Temperature Curves," *Int. J. Adv. Eng. Res. Sci.*, vol. 5, no. 3, pp. 252–255, 2018
- [13] Musarhad .A.S ,” Numerical and Experimental Fatigue Analysis of Similar and Dissimilar Spot Welding Joints ,2019
- [14] D. Alden, 2017 “Modal Analysis of Resistance Spot Welding for Dissimilar Plate Structure,” MSC Thesis, Faculty of Mechanical Engineering, Universiti Malaysia Pahang.
- [15] Shaw, C.B. “Welding Research for Aerospace in USA, in International Congress on Welding Research“, Boston, MA, 1984.

[16] ASM HANDBOOK, VOLUME 6, WELDING, BRAZING, AND SOLDERING

[17] Solid State Welding and Application in Aeronautical Industry Enes Akca*, Ali Gursel

[18] Al-Zubaidy, B. M., 2016 / Material Interactions in a Novel Refill Friction Stir Spot Welding Approach to Joining Al-Al and Al-Mg Automotive Sheets

[19] Mishra, R., Mahoney, M., Sato, Y., Hovanski, Y., & Verma, R. (Eds.). (2016). *Friction Stir Welding and Processing VII*. Springer.

[20] M. Bilici, "Effect of Tool Geometry on Friction Stir Spot Welding of Polypropylene Sheets", eXPRESS Polymer Letters, Vol. 6, No. 10, 2012, pp. 805-813.

[21] C.G. Rhodes, M.W. Mahoney, W.H. Bingel, R.A. Spurling, and C.C. Bampton, *Scr. Mater.*, Vol 36, 1997, p 69

[22] Commin, L., Dumont, M., Masse, J. -E. & Barrallier, L., 2009. Friction stir welding of AZ31 magnesium alloy rolled sheets: Influence of processing parameters. *Acta Materialia* 57, p. 326–334.

[23] Su, P., Gerlich, A., North, T. H. & Bendzsak, G. J., 2006a. Energy utilisation and generation during friction stir spot welding. *Science and Technology of Welding & Joining*, March, 11(2), pp. 163-169.

[24] Schmidt, H. B. & Hattel, J. H., 2008. Thermal modelling of friction stir welding. *Scripta Materialia*, Volume 58, p. 332–337.

[25] Colegrove, P. A., Shercliff, H. R. & Zettler, R., 2007. Model for predicting heat generation and temperature in friction stir welding from the material properties. *Science and Technology of Welding and Joining*, 12(4), pp. 284-297.

[26] Chao, Y. J., Qi, X. & Tang, W., 2003. Heat Transfer in Friction Stir Welding- Experimental and Numerical Studies. *Journal of Manufacturing Science and Engineering*, February, Volume 125, pp. 138-145.

- [27] Nandan, R., DebRoy, T. & Bhadeshia, H., 2008. Recent advances in friction-stir welding – Process, weldment structure and properties. *Progress in Materials Science*, Volume 53, p. 980–1023.
- [28] Awang, M. & Mucino, V. H., 2010. Energy Generation during Friction Stir Spot Welding (FSSW) of Al 6061-T6 Plates. *Materials and Manufacturing Processes*, 25(1-3), pp. 167-174.
- [29] Friction Stir Welding and Processing . Rajiv S.Mishra .Murray W.Mahoney, editors, p235.272, DOI:10.1316/FSWP 2007 P235
- [30] R. Sakano, K. Murakami, K. Yamashita, T. Huoe, M. Fujimoto, M. Inuzuka, Y. Nagao, and H. Kashiki, Development Of Spot Fsw Robot System For Automobile Body Members, Processing Of The Third International Symposium Of Friction Stir Welding (Jaban), Twi, Sept 27-28. 2001
- [31] Assembly Magazine Available Online at <https://www.assemblymag.com>.
- [32] X. W. Yang, T. Fu, and W. Y. Li, " Friction Stir Spot Welding: A Review on Joint Macro- and Microstructure, Property, and Process Modeling" *Advances in Materials Science and Engineering*, Vol. 2014, Article ID 697170, 11 pages, 2014.
- [33] Yuyang Chen, Refill Friction Stir Spot Welding of Dissimilar Al-loys", thesis of master for University of Waterloo, Waterloo, Ontar-io, Canada, 2015.
- [34] P. SU, A. Gerlich, T.H. North, and G.J. Bendzsak, " Intermixing in Dissimilar Friction Stir Spot Welds", *The Minerals, Metals & Ma-terials Society and ASM International*, Vol. 38A, March, 2007.
- [35] K.O. Sanusi and E.T. Akinlabi, " Material Characterization of Dis-similar Friction Stir Spot Welded Aluminium and Copper Alloy", *Materials Science and Engineering*, Vol. 225, 2017.
- [36] E. Fereiduni, M. Movahedi and A.H. Kokabi, " Aluminum/Steel Joints Made by an Alternative Friction Stir Spot Welding Process", *Journal of Materials Processing Technology*, Vol. 224, pp1–10, 2015. jmatprotec.2015.04.028.
- [37] Sun, Y.F., Fujii, H., Takaki, N. and Okitsu, Y., "Microstructure and Mechanical Properties of Dissimilar Al Alloy/Steel Joints Prepared by a Flat Spot Friction Stir

Welding Technique", *Material De-sign*, Vol. 47, pp 350–357, 2013. <https://doi.org/10.1016/j.matdes.2012.12.007>.

[38] E. Taban, J. E. Gould, J. C. Lippold, "Dissimilar Friction Welding of 6061-T6 Aluminum and AISI 1018 Steel: Properties and Micro-structural Characterization", *Materials and Design*, Vol.31, pp 2305–2311, 2010. <https://doi.org/10.1016/j.matdes.2009.12.010>.

[39] M. Hamzah, S. Bakhy and M. Fliayyh, "Effect of Pin Shape and Rotational Speed on the Mechanical Behavior and Microstructures of Friction Stir Spot Welding of AA6061 Aluminum Alloy", *Al-Nahrain Journal for Engineering Sciences (NJES)*, Vol. 20, No. 1, 2017, pp. 129 – 139.

[40] L. Zhou, L. Luo, T. Zhang, W. He, Y. Huang and J. Feng, "Effect of Rotation Speed on Microstructure and Mechanical Properties of Refill Friction Stir Spot Welded 6061-T6 Aluminum Alloy", *The International Journal of Advanced Manufacturing Technology*, 2017.

[41] S. Prakash and S. Muthukumaran, "Refilling Probe Hole of Friction Spot Joints by Friction Forming", *Materials and Manufacturing Processes*, Vol. 26, No. 12, 2011, pp. 1539-1545.

[42] Sindo Kou, *WELDING METALLURGY SECOND EDITION*, John Wiley & Sons, Inc, 2003, Canada

[43] Haider Kamal Ibrahim, Investigation the Microstructure and Mechanical Properties of Refill Friction Stir Spot Welding of AA2024-T3, MSC thesis, Welding Engineering Technology Engineering Technical College – Baghdad 2017

[44] W. Yuan, R. Mishra, S. Webb, Y. Chen, B. Carlson, D. Herling and G. Grant, "Effect of Tool Design and Process Parameters on Properties of Al Alloy 6016 Friction Stir Spot Welds", *Journal of Materials Processing Technology*, Vol. 211, 2011, pp. 972–977.

[45] Q. Yang, S. Mironov, Y. Sato and K. Okamoto, "Material Flow During Friction Stir Spot Welding", *Material Science and Engineering A*, Vol. 527, 2010, pp. 4389-4398.

- [46] S. Bozzi, A. Helbert-Etter, T. Baudin, V. Klosek, J. Kerbiguet and B. Criqui, "Influence of FSSW Parameters on Fracture Mechanisms of 5182 Aluminum Welds", *Journal of Materials Process Technology*, Vol. 210, 2010, pp. 1429-1435.
- [47] Y. Tozaki, Y. Uematsu and K. Tokaji, "Effect of Tool Geometry on Microstructure and Static Strength in Friction Stir Spot Welded Aluminum Alloys", *International Journal of Machine Tools & Manufacture*, Vol. 47, 2007, pp. 2230-2236.
- [48] R. Karthikeyan and V. Balasubramanian, "Predictions of the Optimized Friction Stir Spot Welding Process Parameters for Joining AA2024 Aluminum Alloy Using RSM", *The International Journal of Advanced Manufacturing Technology*, Vol. 51, No. 1-4, 2010, pp. 173-183.
- [49] Y. Zhang, X. Cao, S. Larose and P. Wanjara, "Review of Tools for Friction Stir Welding and Processing", *Canadian Metallurgical Quarterly*, Vol. 51, No. 3, 2012, pp. 250-261.
- [50] S. Hirasawa, H. Badarinarayan, K. Okamoto, T. Tomimura and T. Kawanami, "Analysis of Effect of Tool Geometry on Plastic Flow During Friction Stir Spot Welding Using Particle Method", *Journal of Materials Processing Technology*, Vol. 210, No. 11, 2010, pp. 1455-1463.
- [51] H. Badarinarayan, Y. Shi, X. Li and K. Okamoto, "Effect of Tool Geometry on Hook Formation and Static Strength of Friction Stir Spot Welded Aluminum 5754-O Sheets", *International Journal of Machine Tools and Manufacture*, Vol. 49, No. 11, 2009, pp. 814-823.
- [52] K. Elangovan and V. Balasubramanian, "Influences of Tool Pin Profile and Tool Shoulder Diameter on the Formation of Friction Stir Processing Zone in AA6061 Aluminum Alloy", *Materials & Design*, Vol. 29, No. 2, 2008, pp. 362-373.
- [53] Q. Atiah, S. Al-Rubaii and Z. Al-Tahir, "Determination of Optimum Tool Design for FSW AA2024-T351", *Engineering & Technology Journal*, Vol. 32 Part (A), No. 11, 2014.
- [54] Gene Mathers, *The welding of aluminum and its alloys*, Woodhead & crc Cambridge England 2002,

- [55] Aluminum Standards and Data, Aluminum Association, New York, 1976, p. 15.
- [56] The Materials Information Society, ASM handbook: Heat Treating. Ohio:ASM International, 1991.
- [57] Jastrzebski Z.D., *The Nature and Properties of Engineering Materials*. New York: John Wiley & Sons, Inc., 1959.
- [58] Smallman R.E. and Bishop R.J., *Metals and Materials Science, Processes, Applications*. London: Butterworth-Heinemann, 1995.
- [59] Chee Fai Tan*, and Mohamad R. Said, Effect of Hardness Test on Precipitation Hardening Aluminium Alloy 6061-T6, *Chiang Mai J. Sci.* 2009; 36(3) : 276-286.
- [60] A.K. Gupta , D.J. Lloyd , S.A. Court , Precipitation hardening processes in an Al-0.4%Mg-1.3%Si-0.25%Fe aluminum alloy, *Materials Science and Engineering A301* (2001) 140-146
- [61] Robert E. Sanders, Jr. (2001). "Technology Innovation in Aluminum Products". *JOM*. 53 (2): 25. Bibcode:2001JOM....53b..21S. doi:10.1007/s11837-0010115-7.
- [62] Barnwal, V. K., Raghavan, R., Tewari, A., Narasimhan, K., & Mishra, S. K. (2017). Effect of microstructure and texture on forming behaviour of AA-6061 aluminium alloy sheet. *Materials Science and Engineering: A*, 679, 56-65.
- [63] Shen Z, Chen Y, Haghshenas M, Gerlich AP (2015) Role of welding parameters on interfacial bonding in dissimilar steel/ aluminum friction stir welds. *Eng Sci Technol Int J* 18:270-277
- [64] Dehghani M, Amadeh A, Akbari Mousavi SAA (2013) Investigations on the effects of friction stir welding parameters on intermetallic and defect formation in joining aluminum alloy to mild steel. *Mater Des* 49:433-441
- [65] Mofid MA, Abdollah-zadeh A, Malek GF (2012) The effect of water cooling during dissimilar friction stir welding of Al alloy to Mg alloy. *Mater Des* 36:161-167

- [66] Murr LE, Pizaña C (2007) Dynamic recrystallization: the dynamic deformation regime. *Metall Mater Trans A* 38(A):2611–2628
- [67] McNelley TR, Swaminathan S, Su JQ (2008) Recrystallization mechanisms during friction stir welding/processing of aluminum alloys. *Scr Mater* 58:349–354
- [68] Q. Zheng, X. Feng, Y. Shen, G. Huang, P. Zhao, Dissimilar friction stir welding of 6061 Al to 316 stainless steel using Zn as a filler metal, *Journal of Alloys and Compounds* (2016), doi: 10.1016/j.jallcom.2016.06.092.
- [69] Sirvan Zandsalimi, Akbar Heidarzadeh and Tohid Saeid Dissimilar friction-stir welding of 430 stainless steel and 6061 aluminum alloy: Microstructure and mechanical properties of the joints, *J Materials: Design and Applications*,0(0), 2018,
- [70] Chen, Y.-C., Bakavos, D., Gholinia, A. & Prangnell, P. B., 2012. HAZ development and accelerated post-weld natural ageing in ultrasonic spot welding aluminium 6111-T4 automotive sheet. *Acta Materialia*, Volume 60, p. 2816–2828.
- [71] Bakavos , D. & Prangnell, P. B., 2009. Effect of reduced or zero pin length and anvil insulation on friction stir spot welding thin gauge 6111 automotive sheet. *Science and Technology of Welding and Joining*, 14(5), pp. 443-456.
- [72] Sato, Y. S. et al., 2010. Effect of interfacial microstructure on lap shear strength of friction stir spot weld of aluminium alloy to magnesium alloy. *Science and Technology of Welding and Joining*, 15(4), pp. 319-324.



جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة بابل
كلية هندسة المواد
قسم هندسة المعادن

توصيف اللحام النقطي الاحتكاكي للمعادن المختلفة

رسالة

مقدمة الى كلية هندسة المواد / جامعة بابل وهي جزء من متطلبات نيل شهادة
الماجستير في هندسة المواد / المعادن

من قبل

ريام حسن هادي زاير

باشراف

أ.د احمد عودة جاسم الربيعي

أ.م.د باسم محيسن محمد الزبيدي

1443هـ

2021 م

الخلاصة :

في هذا البحث تم استخدام اللحام النقطي بالاحتكاك (FSSW) وهي عملية ربط المواد الصلبة والفولاذ منخفض الكربون سمك 1.0 مم A16061 ببعضها البعض . تم ربط معدنين مختلفين FSSW باستخدام أداة قياسية (تتكون من كتف ودبوس) بقطر 10 مم .

الهدف من هذا البحث هو تحسين أداء الوصلات المتباينة عن طريق إضافة طبقة بينية تحتوي على Zr ودراسة متغيرات اللحام على هذا الأداء . لذلك تم استخدام ثلاث سرعات دورانية (1200، 1600، 2000) دورة في الدقيقة وثلاث أوقات للحام (1.0 ، 2.0 ، 3.0 ثانية) .

تتم عملية اللحام لعينة غير مطلية بالزركونيوم ومقارنتها بعينات أخرى مطلية بسماكات مختلفة (0.001 – 0.005) . تم استخدام هذا الطلاء للتخلص من مشكلة تكوين المركبات المعدنية .

تم إجراء العديد من التجارب الأولية لتحقيق أفضل معايير عمليات اللحام .

أظهرت العينات الملحومة بطبقة داخلية تحتوي على إضافات Zr تحسناً ملحوظاً في مقاومة الشد مقارنة بالعينات الأصلية (ملحوظة بدون أي طبقة داخلية). على سبيل المثال، عند استخدام معدل دوران 1600 دورة في الدقيقة ، ووقت لحام 3.0 ثانية، وإضافة طبقة بينية 0.005 جم Zr ، كانت قوة كسر المفصل حوالي 1.8 كيلو نيوتن مقارنة بـ 0.5 كيلو نيوتن فقط لمفصل تم تحضيره باستخدام نفس متغيرات اللحام ولكن بدون إضافة Zr ومع ذلك لا تزال العينات تظهر كسراً هشاً أثناء اختبار الشد والقص مع وضع الكسر البيئي .