

**Solid State Welding for Improving Joint
Integrity of Aluminum Silos**

BY

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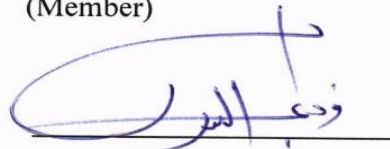
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Dedication

*To My Parents, My Wife and My Colleagues
with love.*

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All praise is due to almighty ALLAH, the most compassionate the most merciful who gave me the strength, knowledge and patience to complete this work.

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ABSTRACT (ENGLISH)

Full Name : Mohammed Menahi Alotaibi

**Thesis Title : Solid State Welding for Improving Joint Integrity of
Aluminum Silos**

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Aluminum alloys are used recently in construction of Silos, however welding of Aluminum is a challenge and may produce defects which lead to weld Failure. Here we review the common factors that lead to aluminum weld failure in silo, faulty erection, limits of design, improper maintenance, etc. This work will also investigate Aluminum welding defects and explore the friction stir welding technology to suggest best solution to eliminate welding defect of aluminum. In this work, Friction stir welding (FSW) between 3 mm thick AA 5052-32 aluminum alloy plates was investigated. Taguchi design of experiment has been implemented to reduce the number of trials of friction stir weld experiments, 18 welded joints were produced by varying tool traverse speed of 20, 40 & 60 mm/min and by varying rotating speeds from 700, 1000 & 1200 rpm. The welded joints were characterized by its appearances, microstructural and mechanical properties at room temperature. From the appearances of the welded joints at all rotational speeds produced sound welded joints with smooth surface. Rotational speed found to have the most significant influence on the overall joint properties, it was found at 1200 RPM the highest tensile strength was achieved. This work will also investigate Aluminum welding defects and explore the friction stir welding technology to suggest best solution to eliminate welding defect of aluminum.

ABSTRACT (ARABIC)

ملخص الرسالة

الاسم الكامل : محمد مناحي العتيبي

عنوان الرسالة : اللحام التحريكي الاحتكاكي لتحسين مفاصل الألومنيوم في الصوامع

التخصص : هندسة المواد

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تُستخدم سبائك الألومنيوم مؤخرًا في بناء الصوامع ، إلا أن لحام الألومنيوم يمثل تحديًا وقد ينتج عنه عيوب تؤدي إلى فشل اللحام. يمكن أن تفشل الصوامع مما يتسبب في خسائر الإنتاج وتكلفة الصيانة وقد يؤدي إلى وفيات. لا توجد إحصائيات محددة ولكن الصومعة تتعطل بمعدل كبير. يعد تصميم وإنشاء وتشغيل وصيانة الصوامع من الأسباب الرئيسية وراء فشل الصومعة. نراجع هنا العوامل الشائعة التي تؤدي إلى فشل لحام الألومنيوم في الصومعة ، والتي تشمل التركيب الخاطئ ، وحدود التصميم ، والصيانة غير الملائمة ، وما إلى ذلك. هذا العمل أيضًا سيبحث في عيوب لحام الألومنيوم ويستكشف تقنية اللحام بالضربة الاحتكاكية لاقتراح انسب الحلول للتخلص من عيب اللحام من الألومنيوم. في هذا العمل ، تمت دراسة لحام التقلاب الاحتكاكي بين صفائح ألومنيوم 5052 بمسك 3 ملم. تم تنفيذ تصميم تاغوشي للتجربة لتقليل عدد تجارب اللحام الاحتكاكي ، وتم إنتاج 18 وصلة ملحومة عن طريق تغيير سرعة اجتياز الأداة من 20 و 40 و 60 مم / دقيقة وبسرعات دوران مختلفة من 700 و 1000 و 1200 دورة في الدقيقة . تم تقييم الوصلات الملحومة بناءً على مظهرها وبنيتها الدقيقة وخصائصها الميكانيكية في درجة حرارة الغرفة. من مظاهر الوصلات الملحومة في جميع سرعات الدوران ، تم إنتاج وصلات ملحومة سليمة ذات سطح أملس. وجد أن سرعة الدوران لها التأثير الأكثر أهمية على الخصائص الكلية للمفصل ، فقد تم تحقيق أعلى مقاومة شد عند 1200 دورة في الدقيقة

CHAPTER 1

INTRODUCTION

1.1 Background

Due to its properties, Aluminum and Aluminum alloys are used as material of construction for many applications including silos for a variety of reasons, including the weight ratio to high strength, low cost, recycle ability, thermal and electrical conductivity and other attractive features [1-2]. However, there are great challenges when welding 5000 aluminum series alloys using fusion welding processes, which produce welding porosity that eventually lead to failure [3-4].

Report [5-7] have shown that, failure rate of silo is very high comparing to other industrial equipment. Sometimes Silo failures are serious which involve full collapse of the structure and may leading to fatalities. In other cases, the failure does not result in safety or operational hazard, only deformation or distortion to the silo body. Prior research suggests that, the cost of silo failure is considerably high, it involves the cost of lost production and the work necessary to restore the damaged silo back to the design condition. This has been discussed by a great number of authors in literature. [5-7].

This thesis will discuss the solid handling unit and the way of solid transfer. Silo design will be explained in more details. After that, possible causes of failure from literature will be discussed. Later on, comparison between Aluminum welding techniques will be discussed in more details. The main objective of this work is to understand Aluminum welding defects by fusion welding techniques and explore different techniques to suggest

best solution to eliminate welding defect of aluminum.

1.2 Applications

Silos are used as bulk storage by industry in the world. To avoid confusion in the terms used for storage equipment, the term silo is used in this work to describe the bulk solids storage vessel regardless of the size. Silos, most of the time are used to store the final product that going to be shipped, however they sometimes used as a part of the manufacturing process to store the raw incoming material or in-between products.

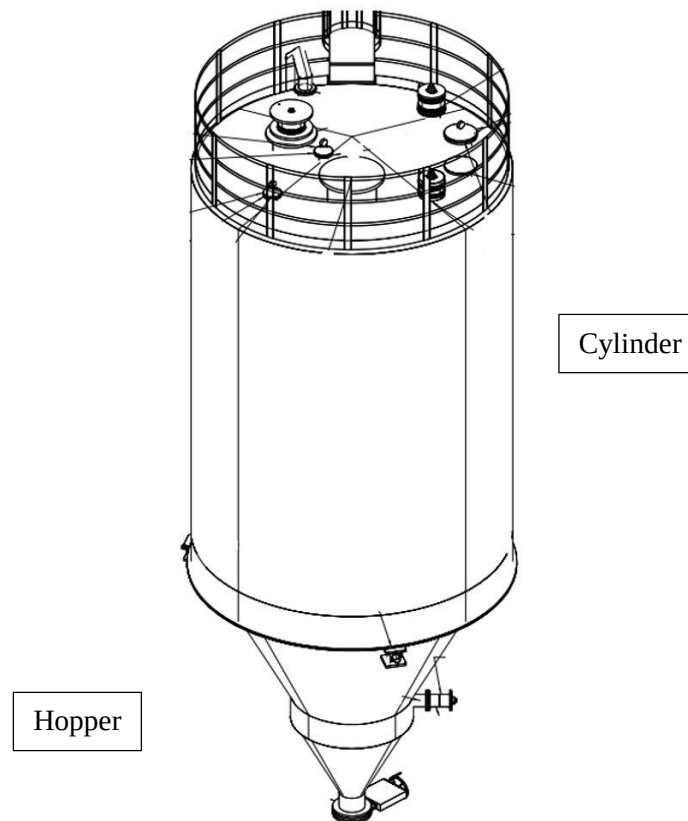


Figure 1: Silo body [8]

In all cases, the main function is to provide space or contain to adjust the change in production rate, as well as the change in the amount or rate of received or outward cargos.

There is another function for the silo not common but still important, which is to blend the product therein. [5-6] The majority of silos are built on mat or piled foundations. Silos may be elevated and supported by frames or reinforced concrete columns in some cases. The type and property of the filled material are usually taken into account while designing a silo. The load-bearing system of this construction is distinct from that of typical building structures. As a result, these Silos are constructed and assessed as unique buildings.

1.3 Objective

Having understood the potential defects that may be formed by fusion welding techniques for Aluminum, and with the recent development in the field of friction stir welding technology, the core objective of this thesis is to explore friction stir welding technique for welding aluminum and produce better weld joint.

The detailed objectives of this work are:

- Design and execute friction stir welding experiments on aluminum alloy 5052-H32 for different combinations of process parameters.
- Test and evaluate the new welded joints mechanical and metallurgical properties.
- Come up with optimized welding process parameters.
- Compare the developed joint with fusion welding.

1.4 Motivation for research

Aluminum welding using fusion weld is considered great challenges when welding 5000 aluminum series alloys. Aluminum has high thermal conductivity which is considered one of the main challenges for aluminum welding. The formation of an oxide layer and the high coefficient of thermal expansion also contribute to the challenges associated with welded joints. Finally, and the most important, hydrogen is highly soluble in molten state, which increase the probability to contaminate with the weld. So, to produce a good weld with aluminum alloys, welding parameters must be selected carefully. Therefore, the new development of friction stir weld makes it attractive to explore this technique in welding the 5000 Aluminum alloys.

1.5 Methodology

In this work, experimental techniques will be used to achieve the objectives of the thesis. Utilizing Friction stir welding machine to weld similar plates of material AA 5052-H32. In this work, the following parameters as shown in table1 will be changed: welding speed, rotational speed and tilt angles. The other parameters, such as pin shape, sample thickness and axial force will be fixed.

Table 1: welding process parameters.

Parameter		Unit		Levels			DOF
Tool rotational speed	A	RPM	700	1000	1200		3
Welding speed	B	mm/min	20	40	60		3
Tilt angle degree	C	degree	1	1.5	2		3

L9 orthogonal array will be utilized to reduce the number of trials by using a particular orthogonal array design to examine the full process parameter space with a minimal number of tests. This approach also identifies the most important parameters in overall performance.

Table 2: Orthogonal array for Different process parameters combinations.

Taguchi, p=3, L=4			
Run	A	B	C
1	700	20	1
2	700	40	1.5
3	700	60	2
4	1000	20	1.5
5	1000	40	2
6	1000	60	1
7	1200	20	2
8	1200	40	1
9	1200	60	1.5

To find the best welding parameters, 18 butt weld joints will be produced which represents 9 welding process parameters. Metallurgical, mechanical, and SEM/EDS techniques are used to assess the weldment's quality. This means each welded joint will be tested by tensile testing machine to find the tensile strength. In addition, the metallurgy of one sample from each weld process will be evaluated by SEM/EDS. Other testing such x-ray and hardness will be performed to gather more information that may help in the optimization step. Taguchi L9 orthogonal design of experiments will be implemented to optimize the process parameters. After getting the best parameters, new joint will be welded and tested. The result will be compared to the current sample using the fusion weld technique

CHAPTER 2

Literature Review

This chapter covers technical literature review to understand how silos are functioning and how they may fail. After that discusses the aluminum alloys and weldability of aluminum alloys. Finally, discuss friction stir welding process with emphasizes on welding similar alloys of aluminum 5052 grade.

2.1 Solid handling

Solid handling unit is considered one of the major units of production plant, where the final product in the solid form is stored and transferred [8]. This unit usually is composed of storage containers called silo or hoppers and conveying lines. Transferring the solid product after production is done by several means, including: pneumatic methods; bucket elevators, belt conveyors; and screw conveyors, this literature focuses on pneumatic conveyors [8-9]. Pneumatic conveying is defined as the method that use pressurized gas to move solid particles thru the pipelines. As the name implies, a pneumatic system makes use of the pressure of air or gas. This technique is used in industries to transport bulk goods by using air or gas pressure. [8-10] It is important to understand pneumatic conveying approach, several papers [8-12] suggest that two methods for this approach are exist, either lean phase or dense phase. In the lean Phase systems, the bulk is moved by the mass flow where the particles are suspended in the air stream with faster velocity and higher pressures. While dense phase, with conveying gas velocities ranging from 6 to 18 m/s and conveying pressures exceeding 1 Barg.

The material particles can still be in suspension at higher conveying velocities, but at lower velocities, the material will be mostly in contact with the conveying pipe and will flow in waves or plugs. [8-12]



Figure 2: Bulk Solid Handling Systems [13].

2.2 Silo and silo design

According to [8] a silo body can be separated into two main parts: hopper and cylinder figure 1. The cylinder part is the part of the silo with vertical sidewalls and a fixed cross sectional area all over its height. On the other hand, the cross-sectional area of a hopper changes as moving down its vertical access. The geometry of hopper is usually converging, which means the top cross sectional area is larger than at the bottom.

Usually the silo outlet is connected to a feeder to control the discharge of the silo. The feeder function is for controlling the feed and for measuring the discharge amount. [8] Bulk material, geometric, and structural factors all are important factor in the design of bulk solids storage silos. Bulk solids' frictional and cohesive characteristics differ from one solid

to another, and these qualities have a significant impact on material behavior, therefore it is very critical to consider bulk material features. Flow abnormalities such Arching or ratholing, and the flow pattern are all potential challenges when evaluating the geometric design of a silo. The tendency of Arching or ratholing to happen in a bulk material is mostly determined by its cohesiveness, while the internal friction will determine the flow pattern upon discharge. [8] Among all design parameters (bulk material, geometric, and structural), the silo loads portion is the most difficult part of the silo design. However, the silo's integrity may be jeopardized if the loads and structural design are not done correctly. Understanding the flow pattern inside the silo is crucial for the design, however there are still several papers [7-9] and flow experts frequently disagree about the predicting of the flow. This is especially in prediction of a flow channel will emerge in a funnel flow silo, as well as other characteristics.

2.3 Causes of Silo Failures

The literature review [14-21] shows that Silo failures can be caused by a variety of factors, including design flaws, construction flaws, usage flaws, maintenance flaws, or a combination of these factors.

Several studies [15-18] suggest that, Silo design requires a high level of expertise. The flow behavior inside the silo is very important, for example the development of Ratholing is a problem, and this limits the working volume of a silo while also jeopardizing quality control. This also can impose vibration which may eventually lead to fatigue failure. Sometimes the silos contain internal inserts, which create unequal stresses. Moreover, Silos vibrate due to self-induced vibrations. This can be a cyclic vibration with a high frequency

but low amplitude, or irregular vibration with a low frequency but high amplitude that causes shocks. Structure failures have been reported as a result of the latter. Some papers suggest that the failure of silo can be due to mistakes during the construction of the silo and its supporting structure. Starting with poor quality craftsmanship. Secondly, the introduction of poorly planned, or even illegal, alterations in construction time in order to hasten the job or cut charges is another source of construction issues. Sometimes Incorrect Material will be used for different reasons this will cause deviate from design specifications then eventually to silo failures.

Normally structures are designed for a certain application. But because of incorrect usage, the service life of the structure reduces. For example, if different material is placed in a silo than the materials for which it has been designed, this can lead to some problems, the reason is related to the flow properties. Previous studies have shown that changing the material will change the flow pattern as well. As result dynamic loads will be developed due to collapsing arches or ratholes, self-induced vibrations or explosions, which may be a reason for failures. Some authors have also suggested that, silo failure could be due to lack of Maintenance. Maintenance helps keeping a structure healthy for a longer service life. Some of the problems due to improper maintenances are corrosion, erosion, and Lack of routine inspection.

2.4 Aluminum and aluminum alloys

Aluminum and aluminum alloys are considered to be the main construction materials for numerous applications due to their properties. [1-2] According to the statistics [22-24] aluminum production getting more than other metals. For example, Figure 3 shows global

commercial production around 41 million tons of aluminum, 16 million tons of copper, 4 million tons of lead, and just about 0.3 million tons of tin in 2010.

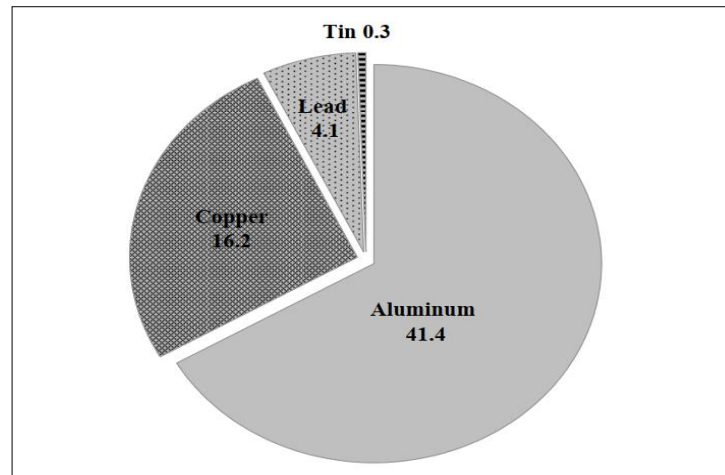


Figure 3: Global commercial production of Aluminum and other non-ferrous metal. [22]

Aluminum alloys can be classified in different manner, according to the fabrication, they are categorized into cast alloys and wrought alloys. These two types can be further classified according to the chemical structure and temper label to families of alloys. [23] Pure Aluminum is relatively weak comparing to other metals such Iron and Copper. According to literature [23], Table 3 shows comparison between metals regarding their physical properties. Aluminum has the least value in yield stress and ultimate tensile stress.

Table 3: comparison of mechanical properties between Al, Fe and Cu. [23]

	Density (g/cm ³)	Melting Point °C	Boiling Point °C	Heat Capacity (J/mol/K)	Electrical Resistivity (nwm)	Thermal Conductivity (W/m/K)	Thermal Expansion (Um/m/K)	Young's Modulus (GPa)	Yield Stress (MPa)	Ultimate tensile strength (Mpa)	Vickers Hardness (HV)
Al	2.7	660	2519	24.2	28.2	237	23.1	70	15-20	40-50	167
Fe	7.9	1538	2862	25.1	96.1	80	11.8	211	80-100	350	608
Cu	8.9	1084	2562	24.4	16.8	401	16.5	130	33	210	369

Therefore, Aluminum is usually alloyed with other elements to improve its strength. Copper, manganese, magnesium, silicon, lithium, and zinc are the primary alloying elements. To attain specified qualities, small amounts of zirconium, nickel, titanium, chromium, and scandium can be added. Undesired impurities known as residual elements may be present in trace amounts. Which have no effects on mechanical properties. [23-25]

The following table summarizes the effect of the important alloying element:

Table 4: The effect of alloying elements on Aluminum. [24]

Element	Effect
Magnesium (Mg)	Improve both strength and work hardening ability.
Manganese (Mn)	Improve both strength and work hardening ability.
Copper (Cu)	Improve both strength and work hardening ability. Reduces weldability, ductility and corrosion resistance.
Silicon (Si)	Improve both strength and ductility.
Zinc (Zn)	Improve both strength and work hardening ability.
Iron (Fe)	Improve strength of pure aluminum.
Chromium (Cr)	Improve stress corrosion resistance.
Nickel (Ni)	Improves strength at high temperature
Titanium (Ti)	A grain-refining element.
Zirconium (Zr)	A grain-refining element.

2.5 The Weldability of Aluminum

Welding is considered one of the most essential manufacture processes utilized in the aluminum alloy sector as part of the fabrication process. According to the literature, Tungsten Inert Gas and Metal Inert Gas are the most often utilized joining methods for aluminum alloys. These welding techniques produce sound weld joint with optimum mechanical properties. [1-4]

However, there are great challenges when welding 5000 aluminum series alloys using fusion welding processes. Aluminum has high thermal conductivity which is considered one of the main challenges for aluminum welding. The formation of an oxide layer and the high coefficient of thermal expansion also contribute to the challenges associated with welded joints. Finally, and the most important is the high solubility of hydrogen in the molten state. To produce a good weld with aluminum alloys, welding parameters must be selected carefully. [3-4]

Compared to fusion welding processes, A number of authors have recognized Friction Stir Welding process as alternative in welding aluminum alloys. This is a solid state joining process in which the welded material does not melt and recast. As a result, when alloys are friction stir welded, the phase transitions that occur during the weld's cooling are of the solid state type. Because there is no parent metal melting, the novel FSW welding technique appears to have various advantages over fusion welding. In comparison to fusion welding methods, there is little or no porosity or other fusion-related flaws. [27-30]

To better understand why aluminum welding is considered a challenge, the following section, compare between Aluminum and steel, discussing the core physical and chemical features: [25]

The melting points for both metals and their oxides are different. For Iron, the iron oxides melt below the iron melting point, while for aluminum the oxide melts above aluminum's melting point. This has significant consequences for the welding process, because it is necessary to remove the formed oxide layer, to obtain the desired joint. This film for Aluminum is coherent and durable, compared to iron oxide. Hence, aluminum alloys gain exceptional corrosion resistance.

The thermal expansion coefficient for Aluminum is double that of steel, during welding this can be the cause for buckling and deformation. The thermal conductivity coefficient for Aluminum is six times that of steel. This means, the heat source used to weld aluminum must be significantly further intense and focused than the one used to weld steel. This is true for thick portions, where excessive heat loss during the fusion welding process might result in fusion flaws.

The specific heat of aluminum is double that of steel. Unlike steel, the color of Aluminum does not change as the temperature increases during welding, which makes it difficult for the welder to control the welding. Another challenge for welding aluminum by technique utilizing the electrical resistance is the electrical conductivity which is six times greater compared to steel.

There is advantage for being aluminum non-magnetic, the arc blow that sometimes happen with welding steel is no longer a concern for Aluminum. Both Aluminum and steel are ductile while Aluminum has modulus of elasticity three times that of steel which mean

three times stiffer than steel on the other hand they can absorb more energy on impact loading. Compared to steel, aluminum does not change its crystal structure by heat treatment, which give no effect for the cooling rate on Aluminum hardness.

Aluminum retains its notch toughness as the temperature drops because it has a face-centered cubic crystal structure. In fact, some of the alloys improve in tensile strength and ductility as the temperature drops, with EW-5083 (Al Mg 4.5Mn) showing a 60 percent increase in elongation after being in service at 200 °C for a period of time. This crystal structure also means that formability is excellent, allowing objects to be made via extrusion, deep drawing, and high energy rate shaping.

2.5.1 Common Aluminum Welding Defects:

The following defects and flaws are the main factors for Aluminum weld failures:

- Gas porosity.
- Solidification (hot) cracking.
- Oxide inclusions and oxide filming.
- Reduced strength in the weld and HAZ.

This Section discuss the following problems, i.e. porosity and hot cracking

2.5.1.1 Porosity:

Several papers [24-25] show that, Aluminum welding is highly susceptible to porosity. Porosity is caused by trapped gases in the weld especially hydrogen gas. While in the molten condition, the weld metal absorbs a large amount of hydrogen. It then seeks to eject

the hydrogen when it solidifies. However, if the solidification of the weld happens quickly, the hydrogen is unable to escape and remains trapped within the weld, forming microscopic pores. The size of Porosity can vary from small microporosity to coarse pores with diameters of 3 or 4 mm.

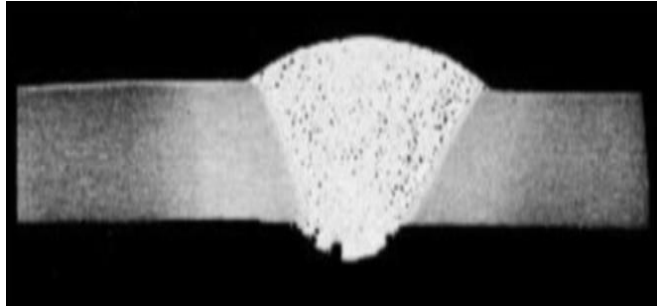


Figure 4. Porosity in Aluminum weld [25]

For aluminum, hydrogen is the main gas causing porosity, this is due to the large solubility in molten metal, as it is shown figure. 4. This demonstrates a loss in solubility by 20 times as solidification occurs, a drop in solubility that makes producing a porosity-free weld in aluminum extremely challenging.

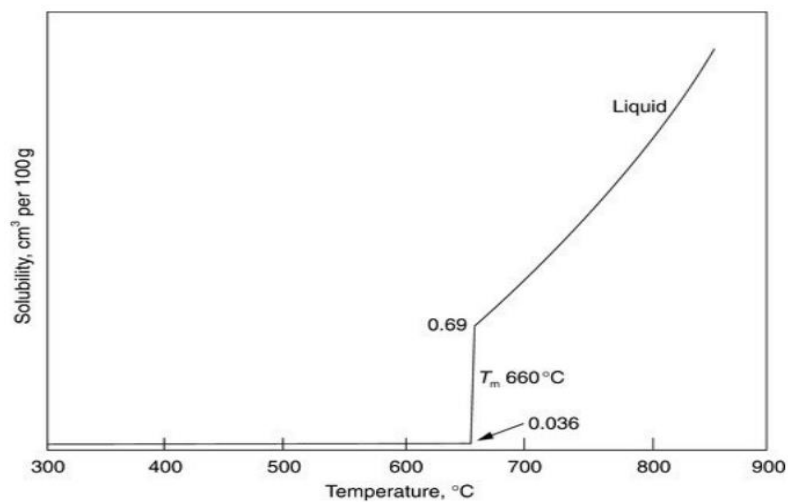


Figure 5: Solubility of hydrogen in aluminum [25]

The following welding parameters (filler metal, arc current, welding position, heat input, travel speed and alloy composition) are considered the main that affect the porosity existence in the weld. [25]

- Autogenous welds have the least porosity. Because of contamination from the wire, porosity levels tend to rise when filler metal is utilized. Because of the hydrogen contamination of the wire, in summary for this factor it is found TIG process has lower porosity than MIG process among the traditional fusion welding methods.
- It is found that, the rate of hydrogen absorption is increased if the temperature of the weld pool rises, this can happen if the arc current rises.
- Reducing the travel speed can provide a similar effect. As the arc voltage and/or arc length are increased, the molten metal is exposed to more pollution, and porosity rises as a result.
- By altering the solubility of hydrogen, there is a favorable effect for the alloy composition on the amount of porosity, magnesium, in specific. For example, At 6% Mg, magnesium is expected to increase hydrogen solubility and limit hydrogen absorption by as much as twofold. The effects of copper and silicon are diametrically opposed. A conclusion that can be derived from this is that when porosity is present, using Al-Mg filler can help to alleviate the issue. Of course, this requires that the filler metal in question is suitable for the application.

Finally, It is important to understand the sources of hydrogen; this section will discuss the possible sources for hydrogen that may cause porosity. There are several sources for

Hydrogen in the fusion welding approach including, weld consumables, gas shield, gas hose and the hydrogen available the metal itself.

Welding consumables are considered the main sources for Hydrogen where the Moisture is an inherent element of the flux, during welding the moisture will decompose in the arc and produce Hydrogen which will eventually cause the porosity. On welding techniques that use gas shielded, the gas is considered one source of moisture. Sometimes, the gas hoses themselves are considered source of contamination. Lastly, hydrogen impurity exist inside the aluminum alloy can be source of porosity. It is clear that, this condition hardly to happen in wrought products but while welding cast product. Therefore, it is recommended to avoid welding metal contains more than 2ppm hydrogen.

2.5.1.2 Solidification Cracking:

Aluminum alloys are prone to cracking due to their high thermal expansion and significant shrinkage after solidification. These cracks usually appear near the weld's central line. It's usually caused by using the wrong combination of filler and parent metal, having poor joint shape, or welding under high constraint. Additionally, element such as phosphorus and sulfur are also important because they separate during solidification. Hence, it's critical to clean the weld region of any oil or grease contamination before welding. Copper, tin, lead, and zinc, and metals with a low melting point, should be avoided. The use of a non-matching, crack-resistant filler, such as those from the 4XXX and 5XXX series alloys, can lessen the likelihood of solidification cracking. [30-31]

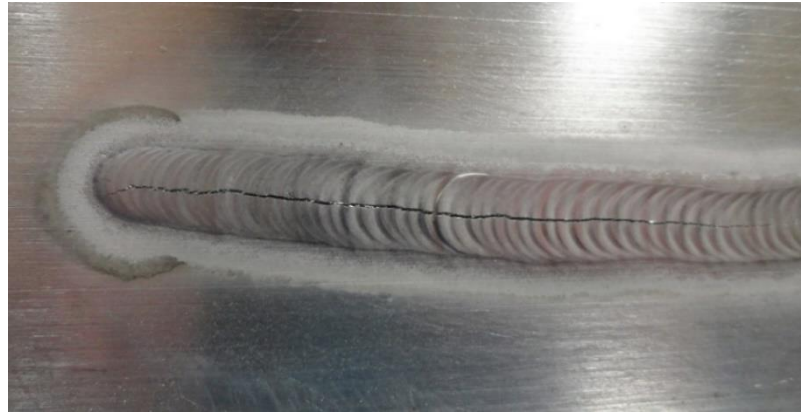


Figure 6 : Solidification Cracking on Aluminum weld [31]

An overview of recent literature comparing fusion welding and solid state welding methods for aluminum alloys is included in this section. In terms of mechanical and metallurgical qualities, several articles suggest and effectively demonstrate that solid state welding is superior to fusion welding. [27-33]

For example, Navyashree et al, investigated two distinct welding techniques for the joining of commercial aluminum panels with dimensions of 150X50X6mm: tungsten inert gas and friction stir welding. The results demonstrated that a friction weld's microstructure differed from that of tungsten inert gas welded sections. The tensile strength of the weld joint in friction stir welding is higher than that of tungsten inert gas welding. Friction stir welding has a hardness test than both tungsten inert gas and the parent material. A smooth surface finish can be achieved utilizing friction stir welding with a tool having a smooth pin, according to the study's findings. The microstructure is examined, and the heat affected zone (HAZ) is found to be well fused and free of nonmetallic defects. [32]

Another study by Ashwani Kumar et al., compared the effect of heat input and the weld efficiency for different welding methods (MIG ,TIG and FSW) on welding aluminum alloy of grade AA6061. The findings revealed that the joint efficiency for the joint using FSW is higher by 19.4% compared to TIG weld joint and by 35.5% compared to MIG. [24].

2.6 Friction stir welding technique

The welding of aluminum and its alloys has been challenging topic and leading to premature failures of the welded parts by fusion welding. This has been improved by the invention of the Friction stir welding, several papers reported the improved quality of aluminum welding by this technique. In this process, two parts are joined by the effect of heat produced by friction between the rotating tool and the workpiece. [34]

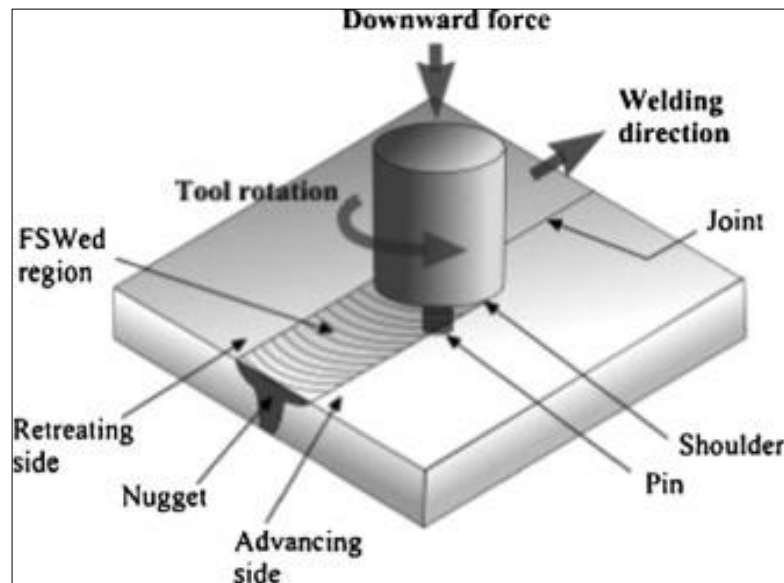


Figure 7: Friction stir weld parameters [34]

This section explores the literature to understand the influence of several factors on the weld quality and strength of joint for aluminum alloys by friction stir welding. Several

papers [35-37] showed that, there are four factors which affect the FSW process: Rotational speed (rpm), Axial force (N), Welding speed (mm/s) , and Material thickness (mm).

According to (Pasquale Cavaliere [35]), during FSW process there are some factors which consider main factors can be controlled and affecting the produced joint, they include, the tool's rotating speed, traverse speed, axial force applied by the tool shoulder to the workpiece, angle at which the tool and workpiece are in contact, tool geometry, and revolutionary pitch.

Raza Moshwan [36] and his team tried to investigate the influence of the tool rotational speed on the mechanical and microstructural characteristics of 3 mm thick friction stir-welded AA 5052 alloy plates'. Several welded joints were produced in their study using a fixed tool speed of 120 mm/min and varied rotational speeds between 800 and 3000 rpm. The appearance, microstructural, and mechanical characteristics of the welded joints were evaluated at room temperature. It was clear from the appearance of the welded joints that all of the joints were free of defects at all rotational speeds with a smooth surface, with the exception of the joint welded at rotating speed of 3000 rpm. It was because of the excessive rotational speed that the welding zone's material flow was not sufficient. When compared to the strength of the base material, all tool rotational speeds generated lower yield and ultimate tensile strengths. As the tool's rotating speed climbed from 800 rpm to 1000 rpm, the tensile strength grew to a maximum value. Tensile strength slowly decreased as rotating speed was raised over 1000 rpm. From 1500 rpm to 3000 rpm, this pattern was clearly visible in every joint. The greatest tensile strength of the joint produced at 1000 RPM was 132 MPa, or 74% of the strength of the base material.

Similar study by Yong-Jai [37], investigated the impact of rotational speed on the mechanical, microstructural, and surface characteristics of a friction stir-welded joint made of 5052 aluminum alloy. A5052 aluminum alloy plate has the following measurements: 30 mm wide, 160 mm long, and 2 mm thick. The tool for FSW has a 10 mm shoulder diameter. The probe measured 1.7 mm in height and 4 mm in diameter. The rotational speed varied between 500 rpm to 3000 rpm, while the welding speed fixed at 100 mm/min and the tilt angle was 3°. The findings demonstrated that all welded joint produced defect-free welds at all tool rotation speeds. The welds show remarkably smooth surface morphologies, especially at 1 000, 2 000, and 3 000 r/min. In the friction-stir-welded zone, onion ring structure can be seen clearly at 500, 1000, and 2000 r/min (SZ). As the tool rotation speed is raised, the onion ring structure region also gets broader. As the tool rotation speed is decreased, the grain size in the SZ, which is smaller than that in the base metal, also decreases. The SZ shows higher average hardness than the base metal at all tool rotation rates. The average hardness of the SZ increases to a level that is approximately 33% higher than that of, particularly at 500 r/min. The friction stir welded plates' tensile strength is comparable to base metal at 500, 1000, and 2000 revolutions per minute (about 204 MPa). The FSWed plates' elongation is roughly 22% less than that of the base metal. However, it is evident that at 1000 r/min, the maximum elongation of roughly 21% is attained.

Anant Kumar [38] and his colleague studied the mechanical properties of the Friction stir welding of 5052 aluminum alloy joint when they changed the welding speed and the rotational speed, welding speed at three levels 30, 40 & 50 mm/min, the rotational speed varied 1300, 1400 and 1500 RPM. In this study, they used aluminum 5052 H32 plates with

dimensions of 200 x 85 x 2 mm. FSW process by using cylindrical shape tool pin with length of 1.8 mm , pin diameter of 4 mm and shoulder diameter of 14 mm while the material for the pin was H13 die steel. The results showed that the optimum welding parameters are achieved at 1400 rpm and 40 mm/min, where the maximum tensile strength and hardness was 187.5 MPa and 48 respectively.

Similar study by Kumbhar [39] and his team but with a fixed tilting angle at 3, looked into how mechanical properties are affected when changing welding speed and rotational speed, at 1120 and 1400 rpm and for various traverse speeds ranging from 60 mm/min, 80 mm/min and 100 mm/min. Two aluminum 5052 plates have been welded by friction stir welding (FSW), with plate dimensions of 300 mm x 50 mm x 5 mm. During the experiment the tilt angle was fixed at three degrees. They used steel tool with a cylindrical geometry and dimensions of 4.8 mm pin length, 6 mm pin diameter, and 25 mm shoulder diameter. The results showed that, higher ultimate tensile stress (UTS) values when welding at 1120 rpm for all welding speeds (60, 80 and 100 mm/min) in the range 260–265 MPa, while lower ultimate tensile stress (UTS) values around 200 Mpa when welding at 1400 rpm.

Another contribution by Chi-Hui Chien [40], where four level of variables were investigated to find the optimum process parameters for welding Aluminum 5083 plates by FSW, Tool tilt angle of (1/2/3/4°), rotation speed of (550/1100/1250/1800 rpm), transverse speed (53/90/143/180 mm/min), and pin tool length (2.5/2.7/2.9/3.1 mm). Butt joints were produced by FSW using two aluminum plates 5083 with dimensions as 160 mm x 3.0 mm × 50 mm. The results showed that, among the four parameters the pin tool length was the most significant FSW process parameter. While the tilt angle has the least effect.

Moreover, the best condition and combination of parameters was achieved at rotational speed of 1800 rpm, transverse speed at 180 mm/min, tool tilt angle at 1° , and pin tool length at 2.9 mm.

S. Jayaprakash [41] and his colleagues investigated the influence of the welding parameters on welding dissimilar aluminum alloy (AA5083 and AA7068). The investigation factors included the main parameters (tool type, welding speed, a rotational speed, plate thickness and axial force). They used three different types of tools including triangular tool, taper cylindrical tool, and straight cylindrical tool. In their experiment, different plate thickness (5, 6, 7 and 8mm) have been used. They varied the welding speed to be 30, 40, 50, and 60 mm/min, while also varying the rotating speed to be 800, 1000, 1200, and 1400 rpm, and the axial force to be 3, 4, 5, and 6 KN. The result showed that, the welding speed and rotational speed are considered the main parameters that affect the overall quality of the produced joint. While there was no major effect for the tool shape on the tensile strength. Straight cylindrical tool providing ultimate tensile strength of 275 MPa, a triangular tool producing 286 MPa, and a cylindrical taper tool producing 267 MPa. The highest tensile strength was achieved as 290 MPa using the following parameters: rotational speed of 1400 rpm, welding speed of 40 mm/min, axial force of 5 kN, and plate thickness of 5 mm. Another important finding the results showed that all of the tools provided the maximum tensile strength at 1200 rpm, 30 mm/min welding speed, and 3 kN axial force.

M. Shunmugasundaram and his team welded dissimilar aluminum alloys 6063 and 5052 using FSW. To develop the number of welding tests, the experimental procedure Taguchi

L9 orthogonal was employed to find the optimized process parameters. In their project, three parameters were considered: tool rotational speed, welding speed, and tilt angle. Based on the literature, hexagonal shape tool pin profile was selected with a 20 mm shoulder diameter, 5.5 mm pin length and 6 mm and 6 pin diameters. The best welding quality and maximize the tensile strength was at the following parameters the tool rotational speed of 850 rpm, the welding speed of 20 mm/min, and the tilt angle of 2. The result shows that the welding speed is more influential than the feed and tilt angle to join these dissimilar joints. [42]

Table 5: summary of literature of aa 5052 friction stir welding work

Author	Factors	thickness	Material.	welding speed	Rotating speed	findings
Raza Moshwan	tool rotational speed	3 mm	5052	120mm/min	800-300RPM	• 1000 RPM GREATEST TNSILE STREGHT. • Best joint from 800-1000. • Failed joints more than 1500 rpm
Yong-Jai	rotational speed	2 mm	5052	100mm/min	500-3000 rpm	1000 rpm the optimum parameter
Anant Kumar	welding& rotational speed	2mm	5052 h32	30 / 40 &50 mm/ min	1300-1500 rpm	The optimum welding parameters are achieved at 1400 rpm and 40 mm/min
Kubmhar	welding& rotational speed	5 mm	5052	60/80/100 mm/min	1120-1400 rpm	• Higher ultimate tensile stress around 260 MPa when welding at 1120 rpm. • Lower ultimate tensile stress around 200 Mpa when welding at 1400 rpm

CHAPTER 3

Experimental Work

3.1 Sample presentation

As received AA 5052-H32 sheets laser cut to $100 \times 50 \times 3$ mm size have been used in this study. Two sheets were but joint using FSW at 45° with respect to roll direction as illustrated in Figure 8. The chemical composition of investigated alloy is presented in Table 6 while mechanical properties are listed in Table 7.

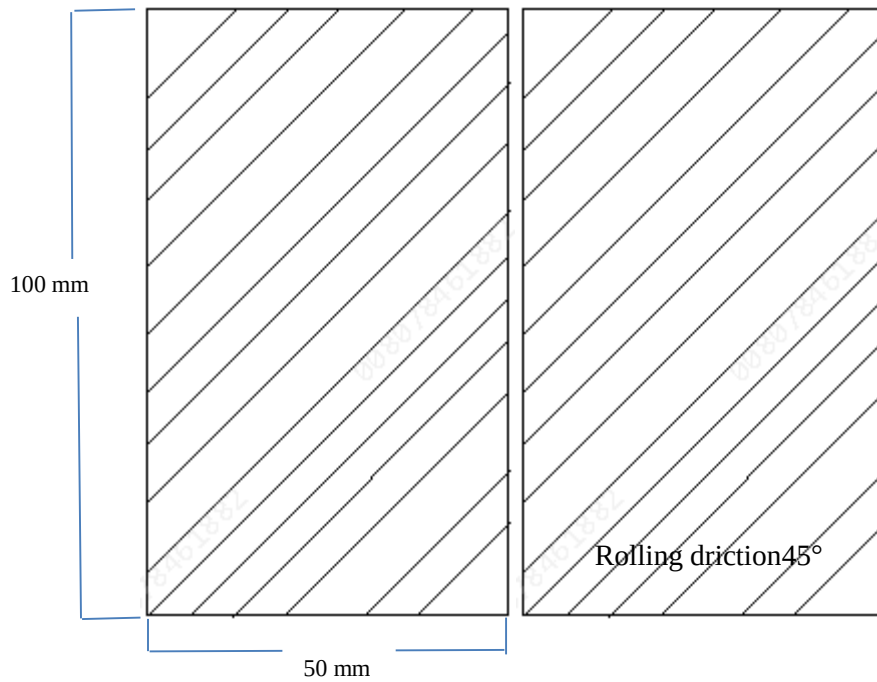


Figure 8: sketch of Aluminum plates showing rolling direction.

Table 6: Chemical composition of Al 5052 H-32

Weight %	Mg	Fe	Si	Cr	Zn	Mn	Al
5052 H-2	2.5	0.1	0.15	0.15	0.05	0.01	Remaining

Table 7: Mechanical properties of Al 5052 H-32

	Poisson	Tensile	Yield	Hardness	%
Density	ratio	strength Mpa	Strength Mpa	Vickers	Elongation
				HV	
2.68	0.33	228	193	68-75	10

3.2 Design of the experiment and Selection of Orthogonal Array (OA)

Taguchi L9 orthogonal design of experiments was implemented to optimize the process parameters. Nine sets of selected process parameters (rotational speed, traverse speed, and tilt angle) as listed in table 8 have been selected to find the best set of parameters. Each set of process parameters been repeated twice.

Table 8: Taguchi L9 orthogonal

Run	A Rotational speed	B Traverse speed	C Tilt angle
1	700	20	1
2	700	40	1.5
3	700	60	2
4	1000	20	1.5
5	1000	40	2
6	1000	60	1
7	1200	20	2
8	1200	40	1
9	1200	60	1.5

3.3 Friction Stir Welding Experiments

18 butt welds joints were produced using Friction stir welding technique, each joint is about two plates, each plate is 3 mm thick plates of measuring 100 mm and 50 mm. The plates were welded along their length using the fully instrumented RM-1 FSW machine shown in figure 9. To fabricate FSW joints, a square butt joint configuration; with zero gap, as shown in figure 10 has been prepared. The joints were welded using single pass welding procedure with a fixed tool geometry and dwell time of 4 seconds for all runs.

In FSW fixtures are mandatory to securely hold the workpiece during the welding process. As shown in figure 10, the fixture has been developed, fabricated, and appropriately mounted clamps were used to securely hold the workpiece on the backing plate, moreover, 6 mm thick steel bar was used beneath the clamp to distribute the clamping pressure over the workpiece.



Figure 9: RM-1 FSW Machine.

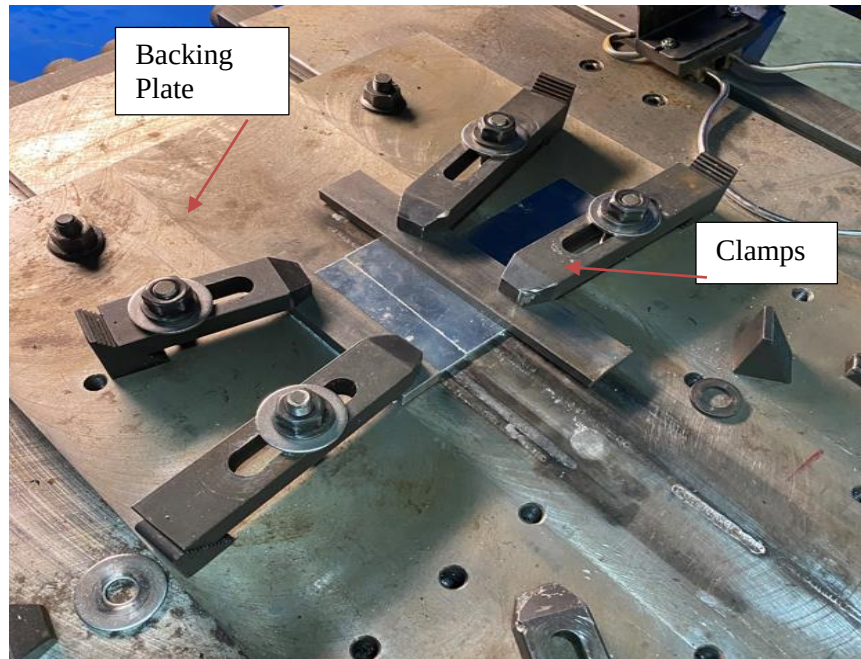


Figure 10: FSW work piece fixture.

The FSW tool used during this study was made of H13 tool steel material. Tool shoulder diameter 12 mm, shoulder was scrolled Pin length 2.7 mm, tool pin shape left hand thread as shown in figure 11.

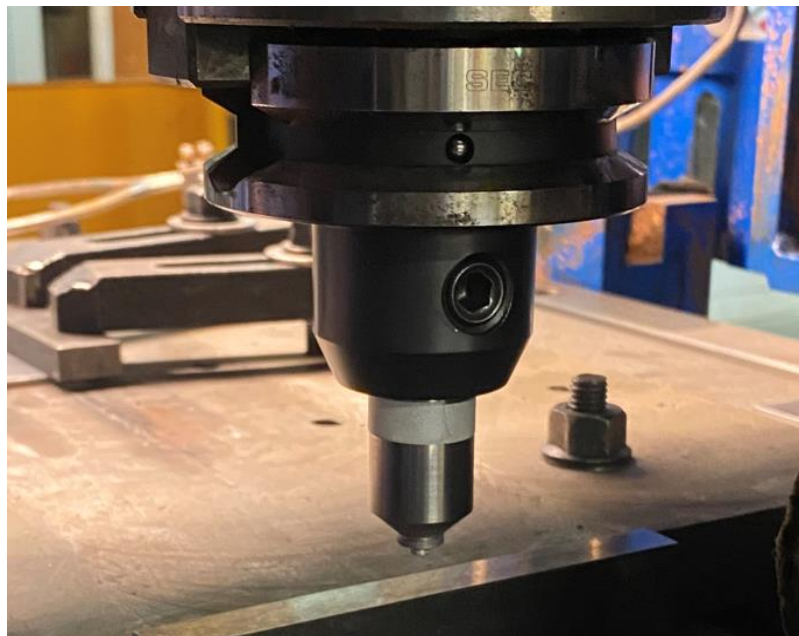


Figure 11: FSW tool geometry.

In order to start welding the plates by FSW, the work piece must be clamped firmly to the bench through backing plate. After that, the process parameters are inserted in the control unit. When all the parameters and axis orientation are adjusted then the welding can start by the tool penetration. With a specific combination of rotational and travel speeds, the rotating pin is driven into the work piece and moved along the desired path. As the pin is rotating frictional heat is produced, which is caused by the rotating shoulder's relative motion to the sheet being processed. The produced heat must be adequate to soften and plasticize the material around the rotating tool. Consequently, material will flow from the advancing side to the retreating side, with the effect of forging force from the shoulder the plates are welded.



Figure 12: starting of the FSW process.

3.4 Sample Preparations and Characterizations:

After carrying out the welding, standard metallographic specimens perpendicular to weld seam were extracted for metallographic observations the effect of welding condition on microstructure and hardness. The samples were mounted using the hot mounting as shown in figure 13 to allow them to be handled easily. After that, they have been ground, starting from 200 grit courser paper until finer 4000 grit paper. Finally, each sample has been polished using Polishing disc covered with soft cloth impregnated with abrasive diamond particles and an oily lubricant.

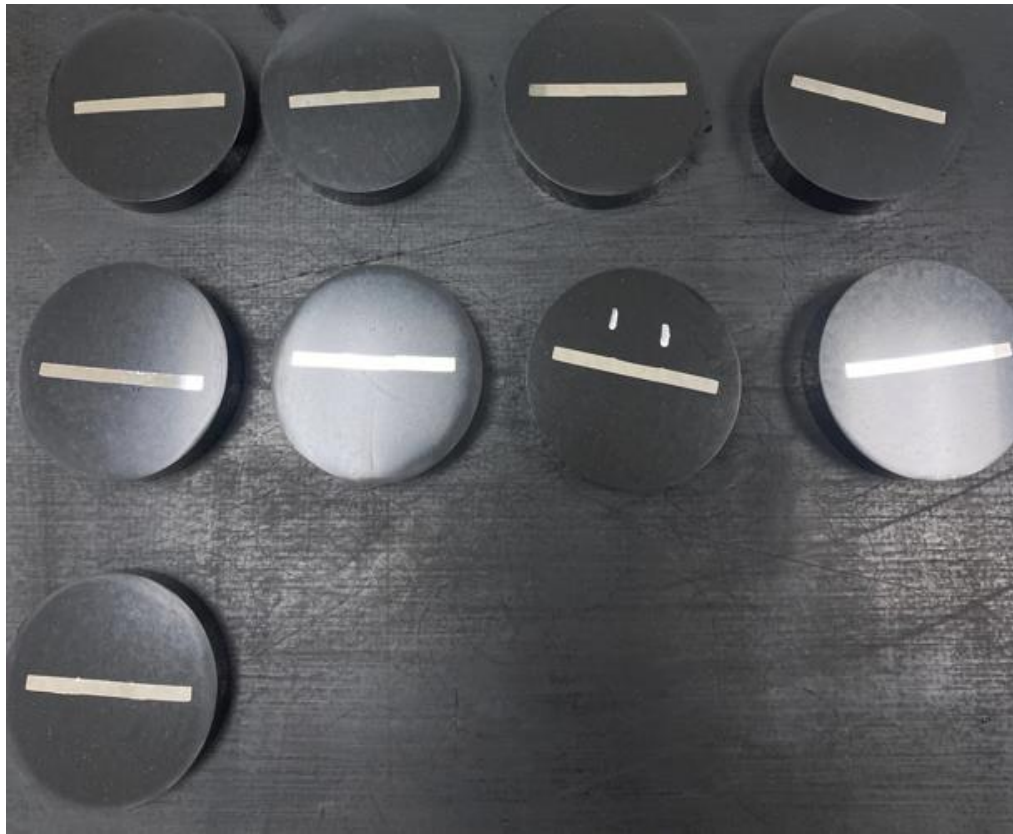


Figure 13: Mounted sample for each run.

Moreover, in order to prepare for the tensile test, the welded joints and the parent material plates were sliced using power hacksaw. To achieve the required dimension of (ASTM E8M-04) guidelines American Society for Testing of Materials, CNC milling machine was utilized. Figure 14 shows the required dimension of the tensile specimen as per the guidelines. Tensile tests were carried out on an Instron universal tensile test machine figure 15 at rate of 2 mm/min ram speed by testing three different samples for each welding process set.

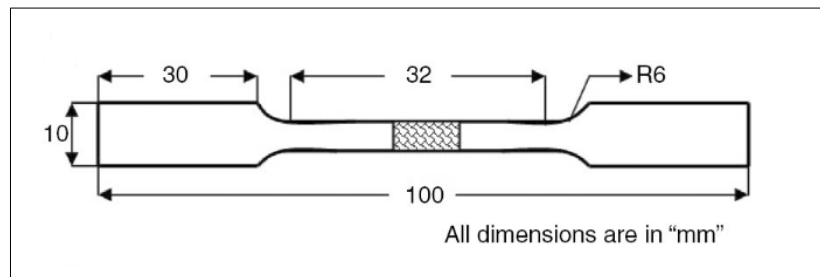


Figure 14:ASTM E8 tensile specimen dimensions.



Figure 15: Instron universal tensile test machine

CHAPTER 4

Results and Discussion

4.1 Surface appearance of the joints

This section shows the surface appearance of the joint for each run. In each figure 16(a-i), all zones, advancing side, retreating side, and base metal are marked SZ, AS, RS, and BM, respectively. No defects were identified in the weld region for any joints. Semicircular traces which are known as shoulder marks and they mainly affected by the ratio of tool traveling speed to rotational speed can be seen in the weld region for the FSW joint in all joints, however they are more visible at rotating speeds of 700 rpm.

It is found that, in the case of higher rotational speed and lower welding speed, the surface appearance of welded samples is quite good or smooth. In the case of a combination of lower rotational speed and higher welding speed, the weld surface morphology is poor, leading to a semicircular trace across the welded surface. In addition, another factor that impacts weld surface appearance is down force or downward force in Z-direction. Flash formation is moderate in all the joints, when the welding tool rotates and moves down a joint line, metal is dragged to the retreating side, where it accumulates, and that metal is flashed. Surface appearance of welded joints is as follow.



Figure 16a: Surface appearance joint #1

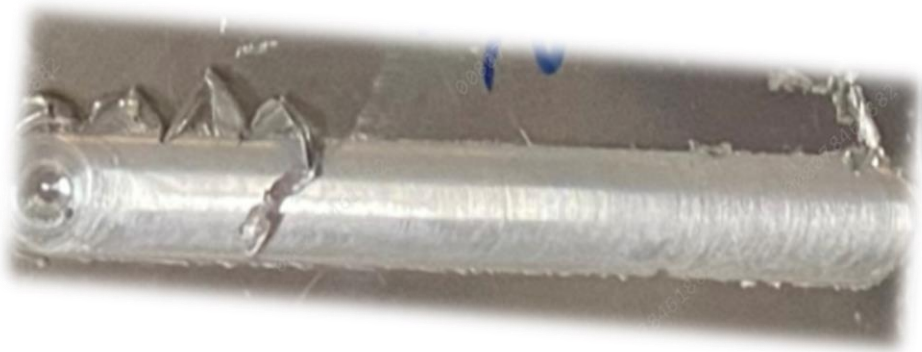


Figure 16b: Surface appearance joint #2



Figure 16c: Surface appearance joint #3

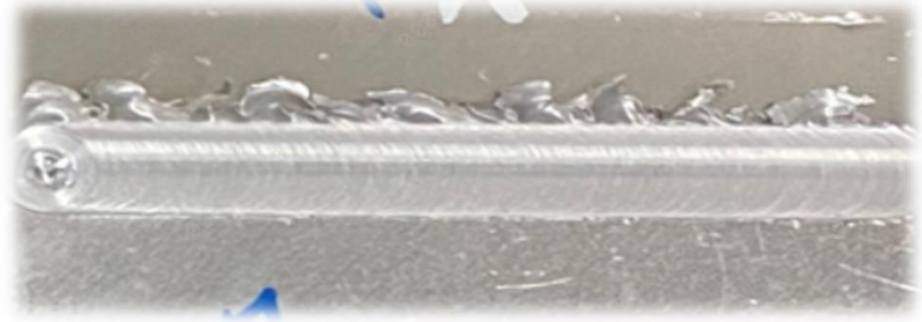


Figure 16d: Surface appearance joint #4



Figure 16e: Surface appearance joint #5



Figure 16f: Surface appearance joint #6



Figure 16g: Surface appearance joint #7

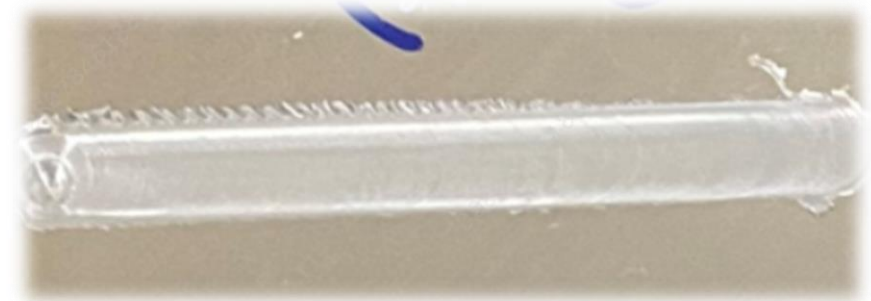


Figure 16h: Surface appearance joint #8



Figure 16i: Surface appearance joint #9

4.2 MACROSTRUCTURE ANALYSIS

The friction stir welded joints were evaluated by x-ray and shown in figure 17, all the joints are free from defects like porosity, slag inclusion, solidification cracks, etc. Although, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, kissing bond, Zig-Zag line and cracks, etc., due to improper flow of metal and insufficient consolidation of metal in the stirred zone, but here all the joints are free from these defects.

This important observation can prove that the selected combination of process parameters provided the enough heat input to plasticize the mating sheets and allow for stirring to happen to produce free of defect weld joint. Theoretically, voids or other defect may appear if the heat input is not enough or the material is too cold in the stir zone. On the other hand if the heat input is high this will affect the final weld properties.



Figure 17: X-ray results of welded joints

4.3 Microstructure Analysis:

4.3.1 SEM:

Scanning electron microscopy was used to examine the microstructure of the weldments. The SEM test was carried out for all the nine welded joints to find any defects. The microstructure of FSW joint can be divided into four zones, starting from the base metal (BM), the heat affected zone (HAZ), the stirred zone (SZ), and the thermomechanical affected zone (TMAZ).

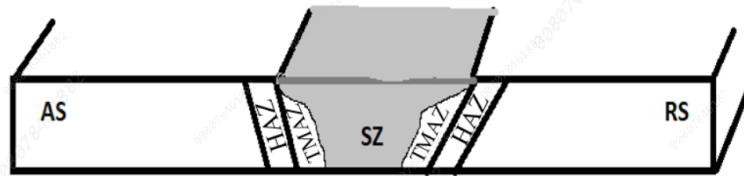


Figure 18: sketch for the microstructure zones.

A. Base metal or Unaffected material:

This is the material far from the welding zone, that has not been deformed and, although not gone through a thermal cycle, so the properties are not altered by the heat. For all the joints the SEM images show free of defect joints and the hardness is almost uniform in this zone with value of 75 VH, which is same as original plate.

B. Heat affected Zone (HAZ):

The heat affected zone usually is not affected by plastic deformation, however it is affected by the thermal cycle. Usually, the grain structure of the heat affected zone is comparable to that of base metals, however in this work we could not see the grain boundary due to the etching. The SEM images for all the joints show comparable topography between the HAZ and base metal.

C. Thermo-mechanically affected zone (TMAZ)

During FSW, this zone undergoes both temperature and deformation and it is characterized by a highly deformed structure, however due to insufficient deformation strain, recrystallization did not occur in this zone. This zone's microhardness was lower than the parent material's, which can be attributed to precipitate dissolution and growth during the joining process.

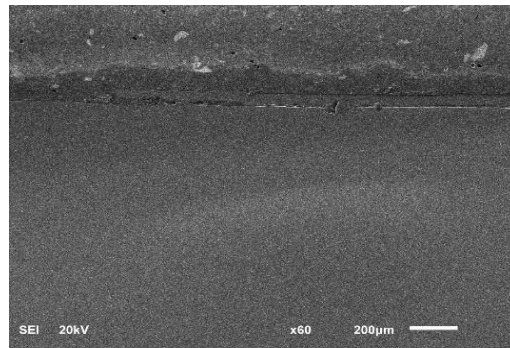
D. Weld nugget:

Recrystallization and texture development occur during the FSW process due to intense plastic deformation and high temperature exposure within the stirred zone. It is widely understood that dynamic recrystallization during FSW/FSP causes the nugget zone to produce fine, equiaxed grains.[42]

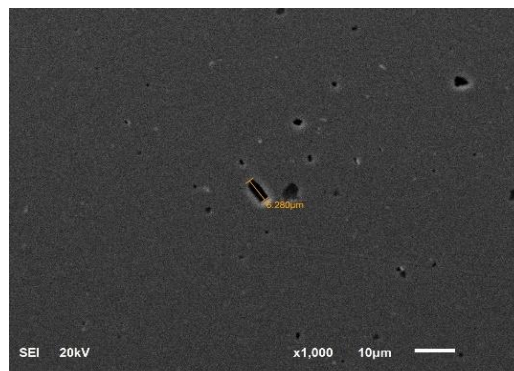
The grain size within the weld zone increases towards the top and drops with distance on either side of the weld-zone centerline, roughly corresponding to temperature difference within the weld zone.

The following pictures show the result of sem tests:

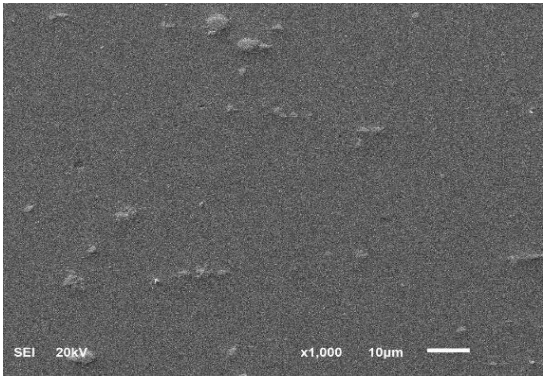
Joint #1



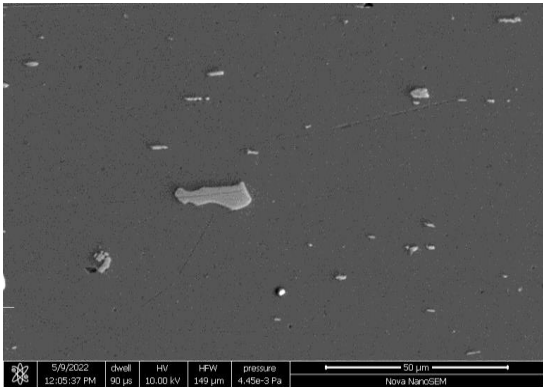
Joint #2



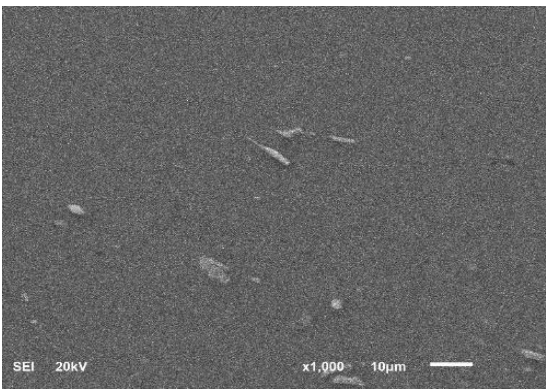
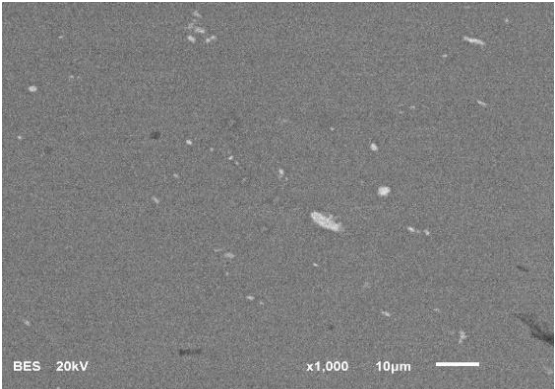
Joint #3



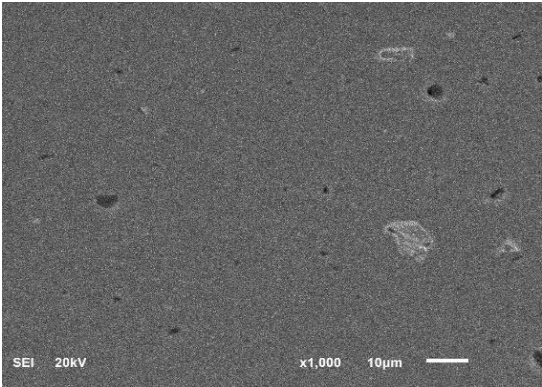
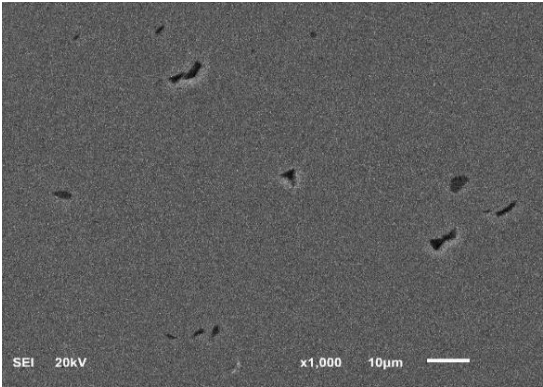
Joint #4



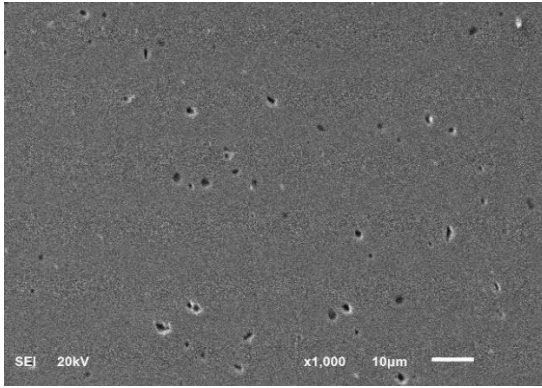
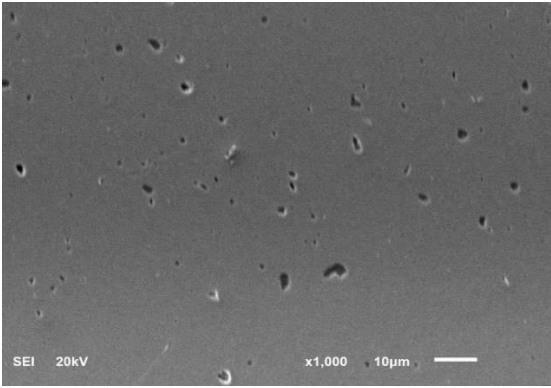
Joint #5



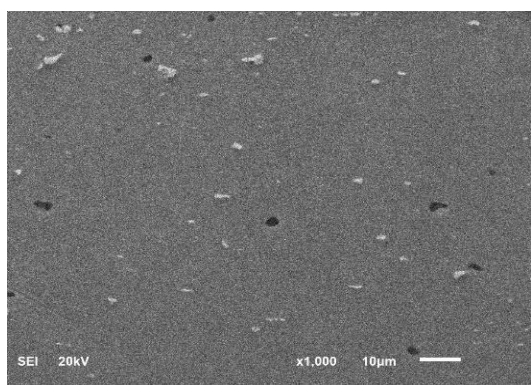
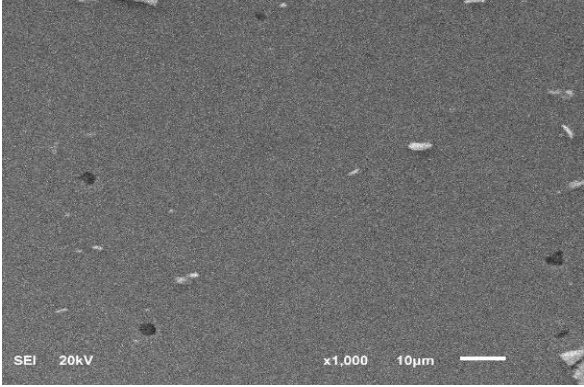
Joint #6



Joint #8



Joint# 9



4.3.2: Hardness:

The test's micro hardness is measured across the joint, and the findings are displayed in figure 19. Through a micro hardness tester, hardness is determined along the weld length in the stirring zone, TMAZ, HAZ, and base material. With conventional equipment, a 500-gram load was applied and dwell time 10 s.

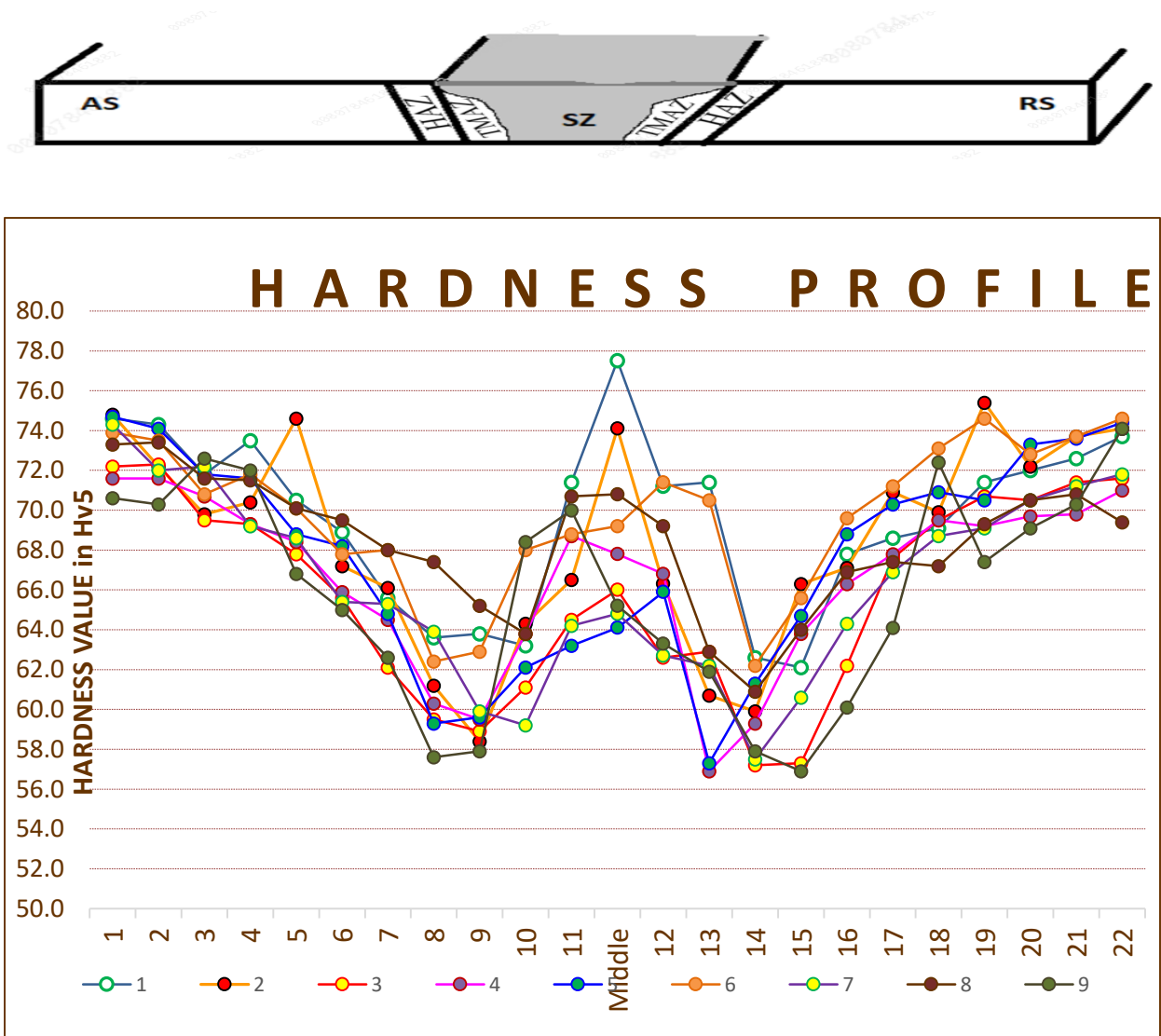
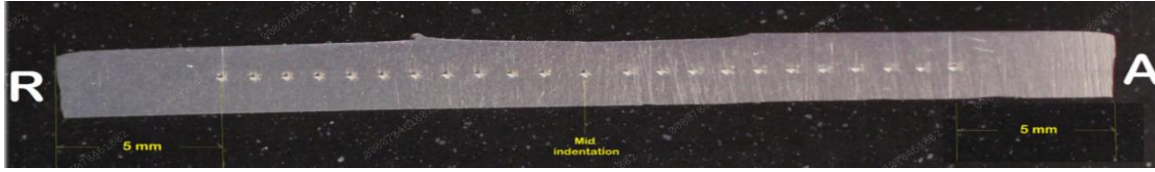


Figure 19: micro hardness



4.4 Tensile testing results:

This section discusses the results of tensile tests, the tensile strength of welded joint was examined to investigate the effect of process parameters of friction stir welding. Table 9 shows tensile test results for all joints, three tensile samples for each run have been tested. All samples showed a lower tensile strength than the original material. In addition, fracture occurred inside the weld line in all joints which is expected to be due to sheet thinning in the welding zone caused by the forging action of the tool. There are slight differences in the average tensile strength for all the experiments, however the highest value was achieved using 1200 rotational speed, travel speed of 40 mm/min and at tilt angle of 1.

Table 9: Tensile test result

Run	Rotational speed	Transverse speed	Tilt angle	Tensile test1	Tensile test2	Tensile test3	Avg
1	700	20	1	180.6	192	183.6	185.4
2	700	40	1.5	184.56	184.07	182.27	183.633
3	700	60	2	184.83	185.24	184.74	184.93
4	1000	20	1.5	172.74	190.98	177.15	180.29
5	1000	40	2	187.1	183.64	185.55	185.43
6	1000	60	1	185.54	181.646	184.57	183.92
7	1200	20	2	183.63	186.18	191.54	187.12
8	1200	40	1	188.8	191.14	185.1	188.346
9	1200	60	1.5	188.17	185.95	182.65	185.59

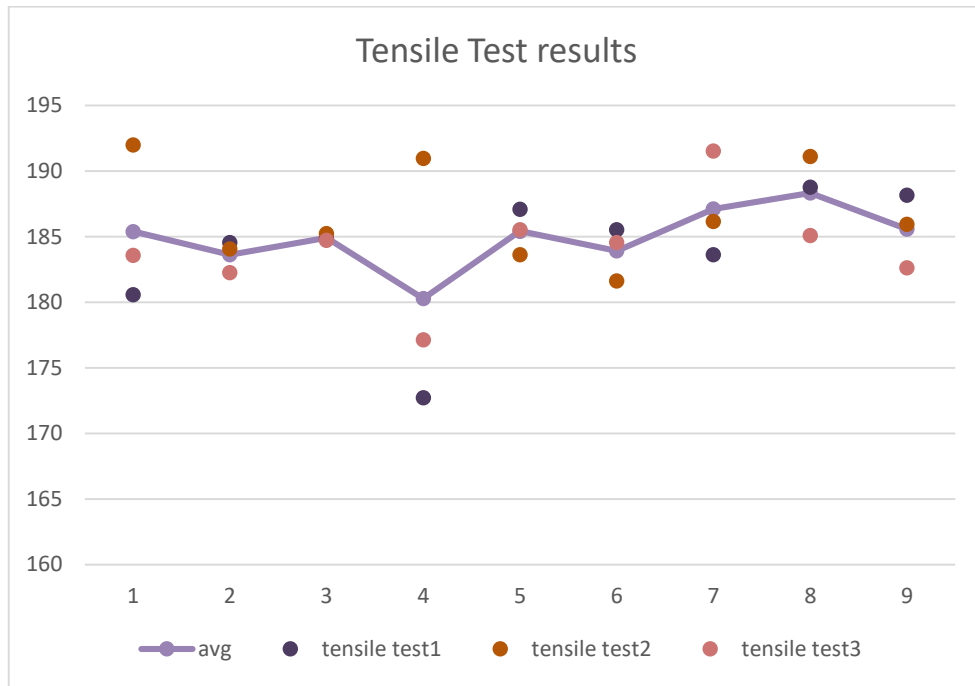


Figure 20: tensile test results

Table 10 Yield and Elongation results

Run	yield strength 1	yield strength 2	yield strength 3	avg	Elongation [%]	Elongation [%]	Elongation [%]	avg
1	105.6	116.27	106.76	109.5433	10.26	11.48	11.9	11.21333
2	107.85	105.84	106.69	106.7933	14.46	13.18	12.48	13.37333
3	93.59	94.2	100.09	95.96	14	12.82	12.73	13.18333
4	104.32	115.82	110.86	110.3333	11.11	11.89	12.1	11.7
5	108.38	111.49	101.39	107.0867	13.29	13.78	12.45	13.17333
6	103.26	105.1	103.14	103.8333	12.58	11.9	11.78	12.08667
7	102.28	103.3	113.32	106.3	14.39	13.46	14.59	14.14667
8	108.22	104.61	98.22	103.6833	12.18	14.23	14.73	13.71333
9	109.6	104.57	98.46	104.21	11.88	12.06	12.49	12.14333

The signal to noise ratio and mean were calculated from the experimental data. Tables 10 shows the average value of the S/N ratio for each experiment. In Table 11 there is not that much variation in the S/N ratio values. The bigger the S/N ratio, according to the objective function of maximizing tensile strength, the better the results.

Tables 11 and 12 reveal the reactions of S/N ratios and means over tensile strength. Accordingly, the tool rotational speed has greatest impact on the tensile strength, while tilt angle has a greater influence on response than welding speed.

Calculation Steps for S/N ratio:

$$\text{Formula: } \eta_i = -10 \log [1/n \sum_{i=1}^n (1/y_i^2)]$$

Where: η_i = S/N ratio for i^{th} experiment.

y_i = Observed value for i^{th} experiment.

n = Total number of observed value for i^{th} experiment.

Table 11: Tensile strength of the specimen with S/N ratio

Run	Average tensile strength	S/N ratio
1	185.4	45.35
2	183.633	45.278
3	184.936	45.340
4	180.29	45.095
5	185.43	45.362
6	183.918	45.291
7	187.116	45.438
8	188.346	45.496
9	185.59	45.369

Calculation Steps for Average S/N Ratio:

1. For parameter of Rotational Speed:

$$SN_{RTj} = \frac{\text{Total signal-to-noise ratio, } \eta_i \text{ for parameter of Rotation speed at level } j}{3}$$

2. For parameter of Transverse speed:

$$SN_{RTj} = \frac{\text{Total signal-to-noise ratio, } \eta_i \text{ for parameter of transverse speed at level } j}{3}$$

3. For parameter of Tilt Angle:

$$SN_{RTj} = \frac{\text{Total signal-to-noise ratio, } \eta_i \text{ for parameter of tilt angle at level } j}{3}$$

4. Calculation Steps for S/N Ratio Difference:

Difference S/N ratio = Max S/N ratio – Min S/N ratio

Table 12: Response table for S/N ratios of Tensile strength

Level	rotational speed	S/N Ratio	
		Axial Speed	tilt angle
1	45.324	45.295	45.385
2	45.25	45.379	45.247
3	45.434	45.33	45.380
Difference	0.184	0.083	0.133
Rank	1	3	2

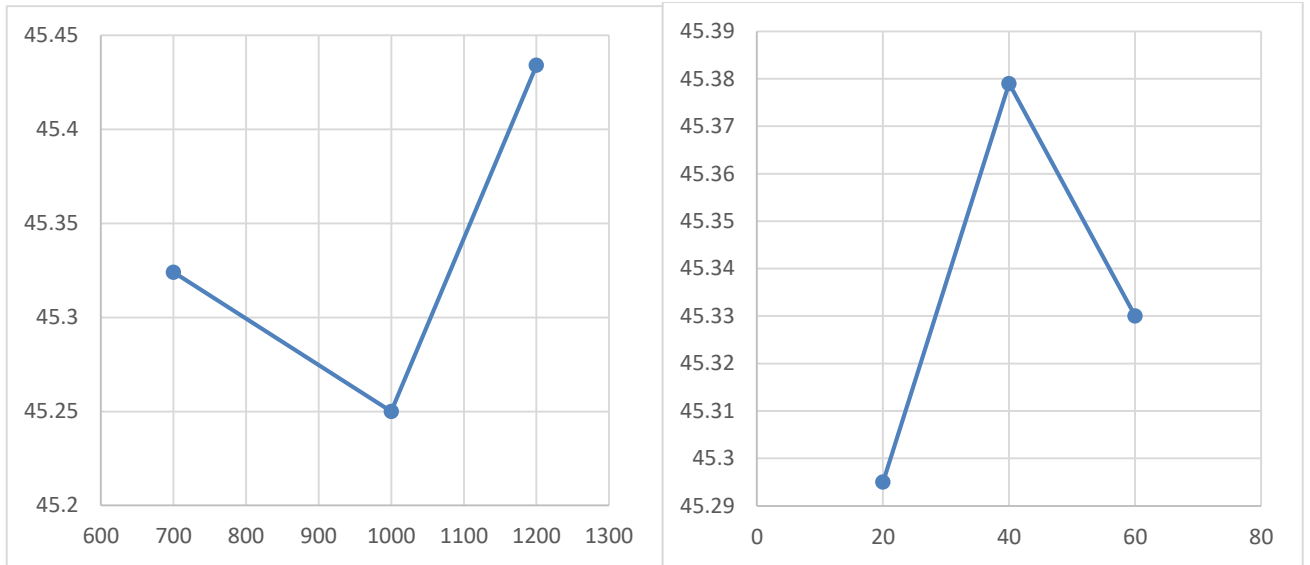


FIGURE 21: Main effects plot for S/N ratios of tensile strength

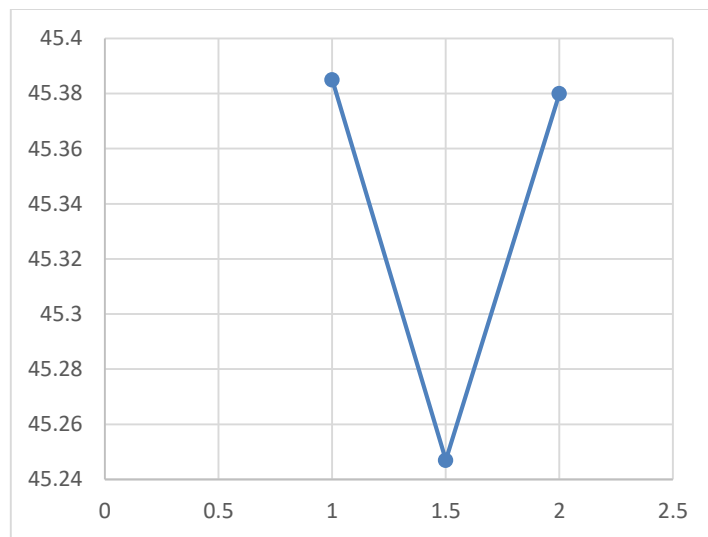


FIGURE 22: Main effects plot for S/N ratios of tensile strength

Calculation Steps for Mean Tensile Strength:

1. For parameter of Rotational Speeds

$$\text{Mean Tensile Strength at level } j = \frac{\text{Total } \bar{y}_i \text{ for parameter of Rotational speed at level } j}{3}$$

2. For parameter of axial speed:

$$\text{Mean Tensile Strength at level } j = \frac{\text{Total } \bar{y}_i \text{ for parameter of transverse speed at level } j}{3}$$

3. For parameter of Tilt angle:

$$\text{Mean Tensile Strength at level } j = \frac{\text{Total } \bar{y}_i \text{ for parameter of tilt angle at level } j}{3}$$

Table 13: Response Table for Means of Tensile strength

Level	Mean Tensile Strength (MPa)		
	Rotational Speed	Axial Speed	Tilt angle
1	184.66	184.27	185.88
2	183.21	185.8	183.17
3	187.02	184.8	185.827
Difference	3.81	1.53	2.71
Rank	1	3	2

Calculation Steps for Predicted Optimum performance:

$$\text{Formula: } Y_{\text{opt}} = T/N + (P_{\text{opt}} - T/N) + (T_{\text{opt}} - T/N) + (S_{\text{opt}} - T/N)$$

Where Y_{opt} = Predicted optimum performance

T = Total of observed values for all the experiment

N = Total number of observed values

P_{opt} , T_{opt} , S_{opt} = Average tensile strength resulted from rotational speed,
axial speed and tilt angle at optimum level

*Average tensile for each optimum parameter level is got from table 14

$$T/N = (1655.97+1680.85+1657.17) / 27 = 184.96$$

$$Y_{opt} = 184.96 + (187.02 - 184.96) + (185.8 - 184.96) + (185.88 - 184.96) = 188.78 \text{ MPa}$$

Table 14: Optimum Parameter Level and Results

	Rotational speed	Axial speed	Tilt Angle
Optimum Level	3	2	1
Average Tensile Strength (MPa)	187.02	185.8	185.88
Predicted Optimum Performance: 188.78 MPa			

Figures 21 and 22 show the response of each parameter; it is obvious that the tensile strength of the weldment increases as the tool rotating speed is raised. When welding speed is raised, however, the tensile strength briefly increases before rapidly falling. When welding speeds are between 20 and 40 mm/min, tensile strength improves. When welding speed is increased from 40 to 60 mm/min, tensile strength decreases.

The impact of tool tilt angle provided a mixed picture. Tensile strength decreased as the tool tilt angle increased, but it increased as the tilt angle climbed more. When the tool tilt angle is between 1 and 1.5, tensile strength decreases dramatically, but when the tool tilt angle is between 1.5 and 2.0, it rapidly increases. In my opinion, this is not because of the tilt angle.

GTAW joint (TIG) results:

Three joints have been welded by GTAW, using approved procedure and qualified welder. The joints have been tested by x-rax and tensile testing, the results revealed free of defect joints. The tensile strength and yield are listed in Table 15 and 16.

Table 15: Tensile strength of Gtaw welded joint

Joint	Tensile test1	Tensile test2	Tensile test3	Avg
Tig Weld	174.46	167.17	180.11	173.9

Table16: Yield stress of Gtaw welded joint

Joint	Yield Stress [MPa]	Yield Stress [MPa]	Yield Stress [MPa]	avg
Tig Weld	64.59	60.33	66.8	63.9

Figure 23 shows the hardness result of the GTAW joint, the hardness increased at the middle of the joint which reflect the effect of the fusion weld.

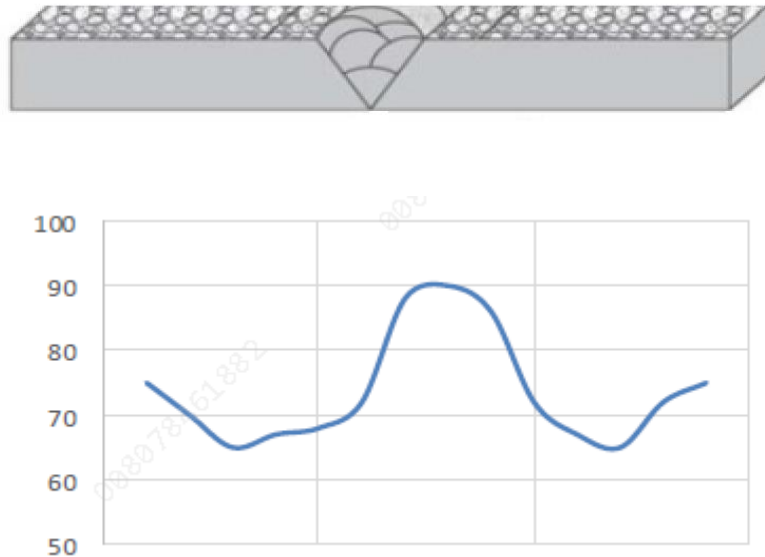


Figure 23: Hardness profile for the GTAW joint

4.5 Fatigue Strength Estimation:

Fatigue failure occurs when cyclic stresses are applied at levels below those required for permanent deformation of the material, and in some situations, considerably below the yield strength of the material. Under cyclic loads, laboratory fatigue tests are commonly used to assess the endurance or life span of engineered materials.

When compared to welds made using traditional fusion welding procedures, aluminum 2XXX [20], 5XXX [21,22], and 6XXX [21,23–25] series alloys connected using FSW have generally exhibited longer fatigue life and an enhanced endurance limit. When the fatigue behavior of defect-free FSW joints was compared to fusion weld design codes, similar findings were observed [20–22,26].

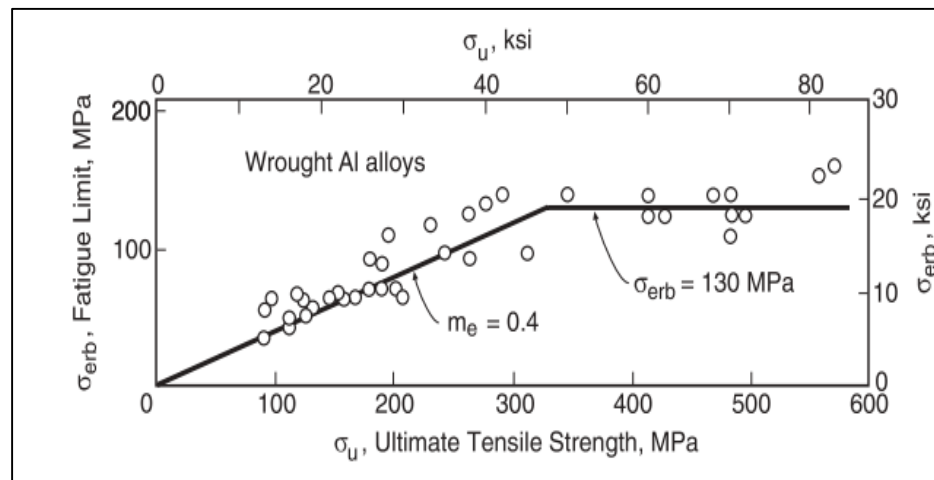


Figure 24; Fatigue strengths for various tempers of common wrought aluminum alloys. (Adapted from R. C. Juvinall , Stress , Strain , and Strength , 1967 ; [Juvinall 67] p . 215)

In this work, fatigue limit is estimated from figure 24, which shows the relation between the ultimate tensile strength and fatigue limit for various aluminum alloys including 5052.

According to the graph for ultimate tensile strength below 300 Mpa the fatigue limit can be calculated from the slope = $0.4 \times \text{Ultimate tensile strength}$.

Table 17: Endurance limit

Run	Avg Tensile Strength	Endurance limit
1	185.4	74.16
2	183.633	73.45
3	184.93	73.97
4	180.29	72.11
5	185.43	74.17
6	183.92	73.56
7	187.12	74.84
8	188.346	75.33
9	185.59	74.236

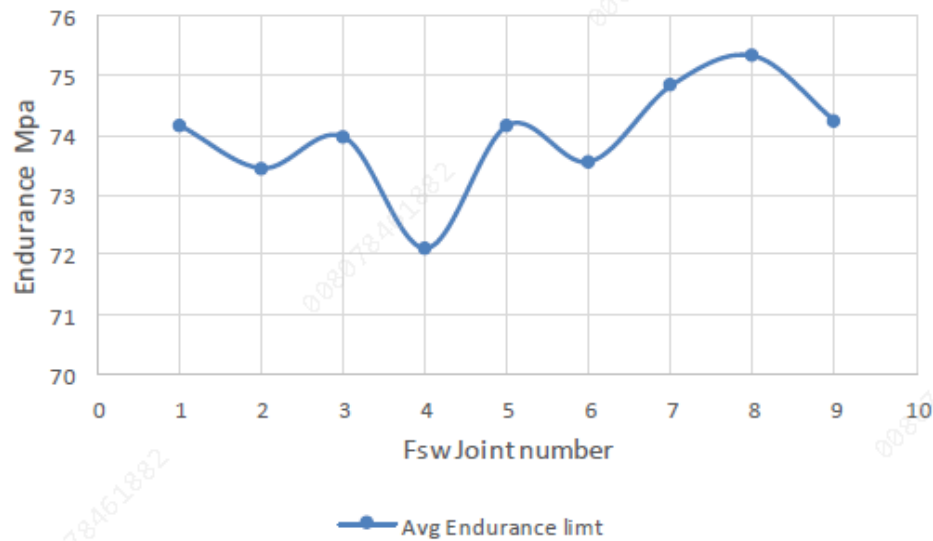


Figure 25: Endurance limit

4.6 Discussion:

In this work Taguchi design of experiment has been implemented to reduce the number of trials of friction stir weld experiments. The following parameters have been fixed: tool geometry and material, dwell time, work piece thickness and material. On the other hand, rotational speed, welding speed and tilt angle have been changed. This section discusses the result of welded joints and the influence of each process parameters on the mechanical properties. In addition, this section compares the result of friction welded joints with the joint that been welded by GTAW.

Rotational speed found to have the most significant influence on the overall joint properties, this align with the literature , it was found at 1200 RPM the highest tensile strength was achieved. Figures 21 and 22 show the response of each parameter; it is obvious that the tensile strength of the weldment increases as the tool rotating speed is raised. When welding speed is raised, however, the tensile strength briefly increases before rapidly falling. When welding speeds are between 20 and 40 mm/min, tensile strength improves. When welding speed is increased from 40 to 60 mm/min, tensile strength decreases.

The impact of tool tilt angle provided a mixed effect. Tensile strength decreased as the tool tilt angle increased, but it increased as the tilt angle climbed more. When the tool tilt angle is between 1 and 1.5, tensile strength decreases dramatically, but when the tool tilt angle is between 1.5 and 2.0, it rapidly increases. In my opinion, this is not because of the tilt angle.

Macrostructure analysis:

No surface defects were identified in the weld region for any joints, this indicate the proper

selection of process condition. However, at lower rotational speed, semicircular traces may be seen in the weld region. On the other hand, it is found that, in the case of higher rotational speed 1200 and lower welding speed, the surface appearance of welded samples is quite good or smooth, this is also matching the literature. [34 -40]

The macrostructure of all welded joints is free from the fusion welding defects like porosity, slag inclusion, solidification cracks, etc. This can be explained by the absence of high temperature, which is exist in fusion weld, Although, FSW joints are prone to other defects like pin hole, tunnel defect, piping defect, kissing bond, Zig-Zag line and cracks, etc., due to improper flow of metal and insufficient consolidation of metal in the FSP (weld nugget) region, but here all the joints are free from these defects.

Tensile strength analysis:

From the tensile testing results, all joints showed a lower tensile strength with maximum average at 188 Mpa than the original material which is 230 Mpa. In addition, fracture occurred inside the weld line in all joints see figure 26. Majority of the samples failed on the Advancing side, at TMAZ location, this can be related to high deformation on this area. All the samples reported lower hardness value at this zone than the other zones.

Figure 35 and 36 show the response of each parameter, it is clear that as the tool rotating speed is increased, the tensile strength of the weldment increases. However, when welding speed is increased, the tensile strength increases briefly before rapidly decreasing. Tensile strength improves when welding speeds are between 20 and 40 mm/min. Tensile strength falls as welding speed is increased from 40 mm/min to 60 mm/min. The influence of the

tool tilt angle showed different scenario, the tensile strength reduces as the tool tilt angle increases, but it increased when the tilt angle increased more. Tensile strength reduces significantly when the tool tilt angle is between 1 and 1.5, but it increases rapidly when the tool tilt angle is between 1.5 and 2.0.

There are slight differences in the average tensile strength for all the experiments, however the highest value was achieved using 1200 rotational speed, travel speed of 40 mm/min and at tilt angle of 1. It can be inferred from the results that the tool rotational speed is having influence on tensile properties of the FSW joints.

Chi-Hui Chien [40], achieved the best condition and combination of parameters at rotational speed of 1800 rpm, transverse speed at 180 mm/min, tool tilt angle at 1° , and pin tool length at 2.9 mm. In his experiment, there were two differences, first the tool pin length was varied and second was the material aa 5083. However there are agreement between both findings: the rotational speed has significant impact on the result, the tilt angle has least influence.



Figure 26: Fracture of tensile test.

Hardness analysis

In order to examine the variance in hardness at various welding regions, the Vickers microhardness was measured at a cross section perpendicular to the welding line. The corresponding microhardness profile graphs are displayed in Figure 28. Figure 27 depicts the general locations of the nugget, the base material, the advancing side interface (ASI), and the retreating side interface (RSI). According to the microhardness profile, the nugget's microhardness is just slightly higher than the base metal. As can be seen, the weld's microhardness is highest near the advancing side interface (ASI) than everywhere else. On the retreating side, the areas close to the HAZ and base material (BM) have a somewhat higher microhardness than those on the advancing side. In contrast to the sharp decline at the advancing side, the nugget's microhardness gradually decreases as it moves towards the retreating side.

4.6.2 Comparison between both techniques

The joint number 8 which showed optimum combination of properties and the best joint tensile strength at 188.346 Mpa was achieved at rotational speed of 1200 RPM, welding speed of 40 and tilt angle of 1. In addition, this joint was free from both macro and microstructure defects. The estimated fatigue endurance limit is about 75.33 MPa. While the average tensile strength of the joint that welded by GTAW is 173.9, and the estimated fatigue endurance limit is about 69.56 MPa.

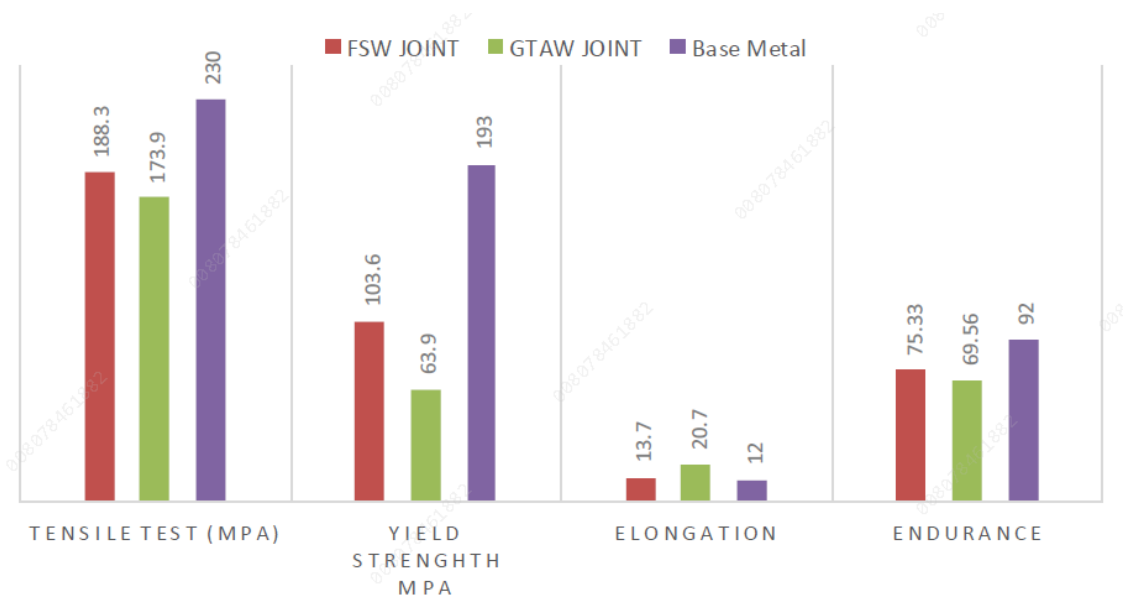


Figure 27: Comparison result between the Tig & FSW joints

CHAPTER 5

Conclusion

In this work, silo's applications and failures been discussed in detail to understand the failure moods of the silo. Aluminum as material of construction for the most of silos has been discussed in detail specifically for 5000 series which is the area of concern in this work. Aluminum welding is considered one of the challenges in the fabrication due to the potential defects that may be exist or produced by fusion welding techniques which eventually lead to structural failure, therefore this work explored the literature to investigate the aluminum welding and find out the best solution to eliminate the potential failures. According to the literature, it was found that Friction stir welding is one of the solution that eliminate or produce weldment free of defects, therefore the main objective of this work was to design and execute friction stir welding processing experiments on aluminum alloy 5052 for different combinations of process parameters. 18 butt weld joints been produced by friction stir weld technique. The welded joints were investigated using experimental approaches, and the friction stir welding conditions that resulted in sound weld quality were identified. Different welding speeds, rotational speed, and tilt angle were used to investigate the effect of FSW process parameters. All welds were friction stir butt joints with a consistent tool geometry. Microstructure analysis and tensile test been conducted to evaluate quality of the produced welds. It was found that the best tensile strength resulted at the rotational speed of 1200, welding speed of 40 and at tilt angle of 1. All the joints were free from and macro defects.

NOMENCLATURE

As	Advancing Side
BM	Base Metal
El %.	Elongation Percent
HAZ	Heat Affected Zone
HV	Vickers hardness
Mpa	Mega Pascal
n	Parameters takes into account the effect of strain hardening
N	Tool rotational speed (rpm)
q	Heat Flux (W/m^2)
Qp	Heat generation from the pin (W)
Qs	Heat generation from the shoulder (W)
Qt	Total heat generation from FSW tool (W)
Rp	Pin radius (mm)
Rs	Retreating side
Rsh	Shoulder radius (mm)
SZ	Stir Zone
T	Temperature (K)
TMAZ	Thermo Mechanical Affected Zone
Tmelt	Material solidus temperature (K)
V	Degrees of freedom
Vweld	Welding Speed (mm/sec)
Wt %.	Weight Percent
X	Mean of independent random sample

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