EXPERIMENTAL INVESTIGATION USING BEST TOOL PARAMETERS ON MICRO FRICTION STIR WELDING OF DISSIMILAR ALLOYS (Al6061-Al5251)

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THIS THESIS IS SUBMITTED IN THE PARTIAL FULLFILMENT OF THE REQUIREMENT FOR THE DEGREE OF MS IN DESIGN AND MANUFACTURING ENGINEERING

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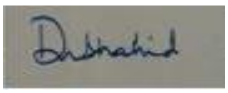

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DEPARTMENT OF DESIGN AND MANUFACTURING ENGINEERING (SMME)

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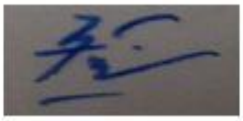
This thesis is submitted to the department of Design and Manufacturing Engineering in partial fulfillment of the requirements for the award of degree of Master of Science in Design and Manufacturing Engineering from NUST-12, Islamabad.



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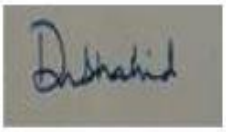

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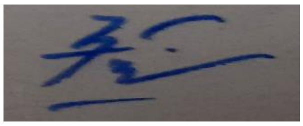
I declare that the presented research work titled "Experimental investigation using best tool parameters on micro friction stir welding of dissimilar alloys (Al6061-Al5251) is my own work. This research work has not been reported or submitted elsewhere for assessment. Moreover, all the experimental results are obtained after extensive experimentation by the author himself and relevant references are provided for supporting purpose.



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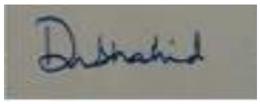

Supervisor Signature

Dedicated to my beloved parents whose incredible efforts and support led me to this wonderful accomplishment

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In the name of ALLAH, The Most Gracious, The Most Merciful. Peace and blessings of Allah be upon his last Prophet Muhammad (SAW).

I am profusely grateful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout my entire career.

Primarily, I express my gratitude and respect to my supervisor for his help throughout my research work and also as he has taught me two subjects named Computer Integrated Manufacturing and Quality and Reliability Management during my course work. I can certainly say that I haven't learned any other engineering subjects in such depth as these two which he has taught. His valuable comments and direction led me to complete my research work in time.

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ABSTRACT

A term micro friction stir welding is introduced when dealing with joining of base materials having thickness less than 2mm. This study investigates the effect of square shaped pin profile and welding parameters with mild steel as fixture back plate material on the welded joints formed with dissimilar alloys. Using AA 6061-O and AA 5251-H22 base material of different thicknesses, three different welding parameters namely rotational speed, traverse speed and coupons position have been taken into consideration. The welding joint is created in square butt joint configuration at rotational speed 1675 rpm, 2850 rpm and traverse speed at 60 mm/min and 80 mm/min by keeping the rotation of tool anti clockwise throughout the experiment. Both mechanical testing i.e. tensile and hardness etc. and microstructure analysis have been performed after T-6 thermal treatment to tensile samples. The results showed that the optimal parameters are 2850 rpm and 60 mm/min on which maximum tensile strength recorded as 104 MPa when 5251-H22 is at advancing side whereas highest average micro hardness value recorded in NZ is 84.41HV. In NZ micro hardness trend increased by increasing rotational speed and decreased by increasing traverse speed for both advancing side (AS) and retreating side (RS). However, micro-hardness of NZ is found greater than the hardness of base material (6061-O & 5251-H22).

Keywords: FSW . Thin sheet . Taguchi . ANOVA . AA 6061-O . AA 5251-H22

CHAPTER 01: INTRODUCTION

1.1 Background

Friction stir welding (FSW) is a solid-state welding technique introduced and developed at TWI Cambridge, UK by Wayne Thomas in 1991. Solid state welding implies that work pieces are joined together without reaching to their melting point. The work piece is allowed to clamp on a specially designed fixture to avoid any lateral movement during FSW. The FSW tool comprising of shoulder and a pin extended from it while rotating is drilled into the joining line between two work pieces. The pin is confined in a work piece until shoulder comes in contact with the surface of work piece and due to insertion and rotation of tool, friction and deformation is created in a work piece and material of work piece becomes soft. The frictional and deformational heat created by shoulder and pin causes the soft material to flow from front end of the tool to the back end as the tool stirring action proceeds. While tool traverses along the joint line, leaving the cool weld behind, and as a result of this action a solid joint is formed. [1]

FSW tool either rotates in a clock wise direction or in anti-clock wise direction that will determine the advancing side and retreating side of the weld. If the tool rotation is same as the traverse direction then the side will be termed as advancing side but if the tool rotation is opposite to the traverse direction then that respective side will be termed as retreating side. The orientation of welding sides during FSW process is very critical as there occurs variations in thermal conditions and it has been observed that advancing side experiences elevated temperature as compared to the retreating side of the weld. A pictorial representation of FSW can be viewed in Figure 1.

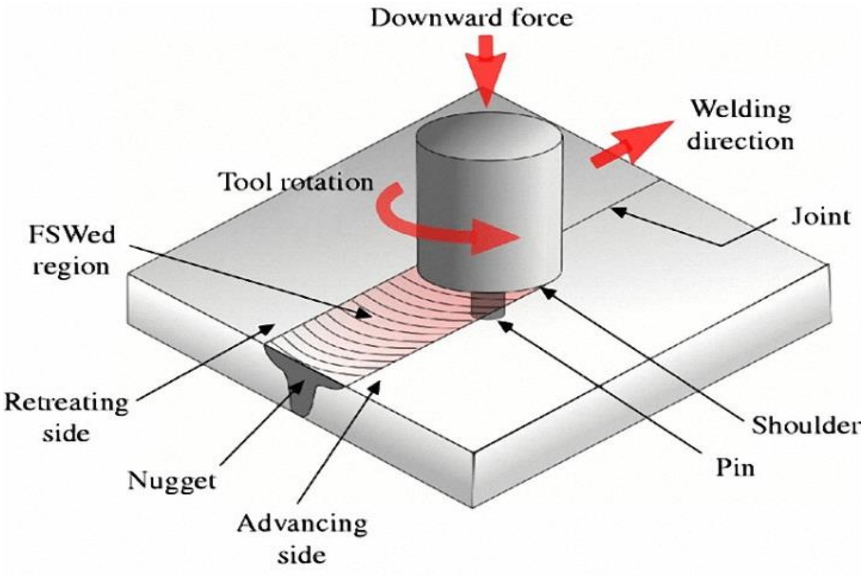


Figure 1: ***FSW Process [1]***

FSW machine was first developed by ESAB1 welding and cutting products in Laxa, Sweden. It can be performed either on milling machine or FSW machine. Friction stir welding can join material ranging from thin section to large thicknesses with good quality weld. This welding technique is employed in several industries such as Aerospace, Automotive, ship building etc. where reduction in weight is the major concern. It has been observed that friction stir welding is used for joining alloys possessing low melting points i.e. Aluminum, copper and brass etc. and this technique requires high heat resistant tools for joining alloys with high melting points. [2]

1.1.1 Friction Welding and Types

It is a type of solid-state welding in which heat is generated through friction due to relative motion between the mating surfaces of the part. High magnitude of force is exerted until the process is finished, allowing the material to be plasticized by the friction between mating surfaces. It was first introduced in 1956 by Soviet Union and the most renowned manufacturers for developing friction welding machines were Caterpillar, American Manufacturing Foundry, Rockwell International etc. [3]

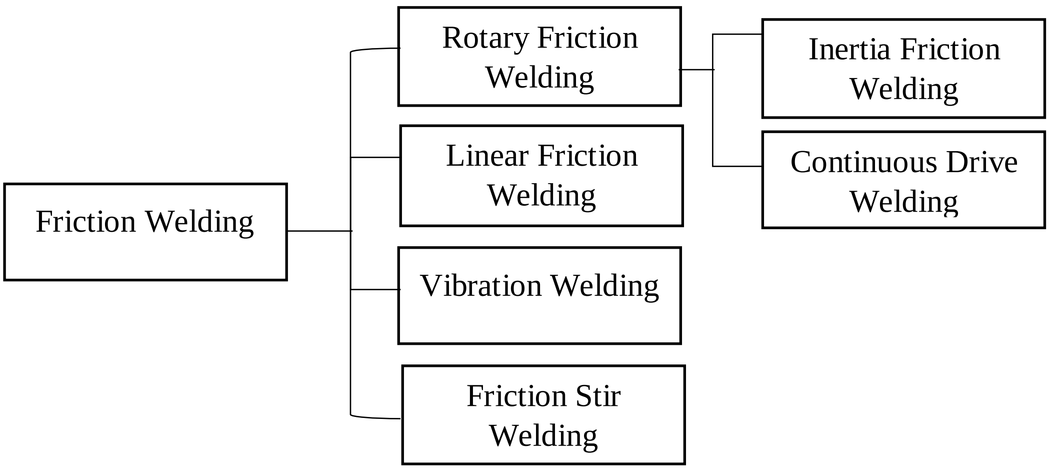


***Figure 2:* FSW Types**

1.1.2 Rotary Friction Welding

In this type of welding, the work piece mounted on a chuck is rotated while the other work piece remains stationary. A stationary part receives small amount of force to have a contact with the rotating part in order to clean them through burnishing process. The rotating part is allowed to push against stationary part with high rpm and more pressure is applied on a stationary part causes friction between both parts. This phenomenon proceeds while achieving a high temperature during welding displaces the deformed material and form as flash. On reaching the welding temperature, the rotor becomes stationary and more force is exerted until the required time is elapsed. This can be viewed in Figure 3.

It is further sub divided into **Inertia friction welding** and **Continuous friction welding**. Inertia friction welding uses two flywheels i.e. engine flywheel and shaft flywheel for stopping the rotation of rotor. In the first step, the shaft flywheel and engine flywheel are disengaged on achieving the desired welding temperature and then shaft flywheel stops automatically because moment of inertia is low. Continuous friction welding uses band brake to stop the rotation of rotor on achieving desired welding temperature.

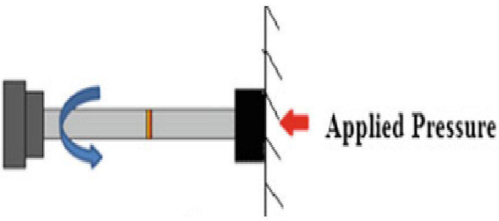


Figure 3: Rotary Friction Welding

1.1.3 Linear Friction Welding

This is another type in which one part clamped in a chuck oscillates and squeezed against the opposite part that remains stationary. Due to the relative motion between the matting components, friction is created which produces heat and causes the plasticized material to force out as flash and desired weld is achieved and is shown in Figure 4. Good quality of joint can be formed in linear friction welding due to its low operating speed than rotary type of welding. Major applications are jet engine blades, car frame etc.

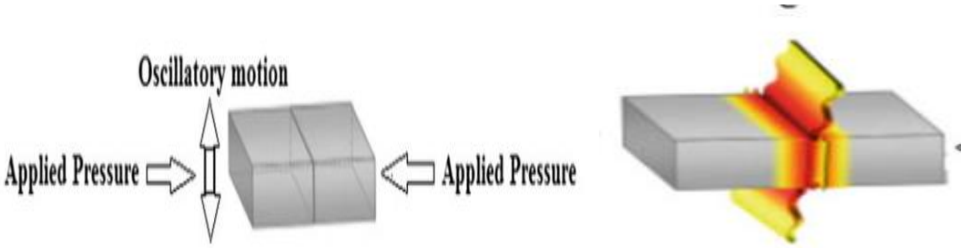


Figure 4: (a) Linear friction weld (b) flash

1.1.4 Vibration Welding

In vibration welding process two parts are allowed to mate each other at high pressure. A vibration force is applied externally to rub the matting parts with each other so that friction and heat is generated at their interface. Due to intermixing of plasticized material and application of pressure force a strong bond is formed between the two parts as shown in Figure 5.

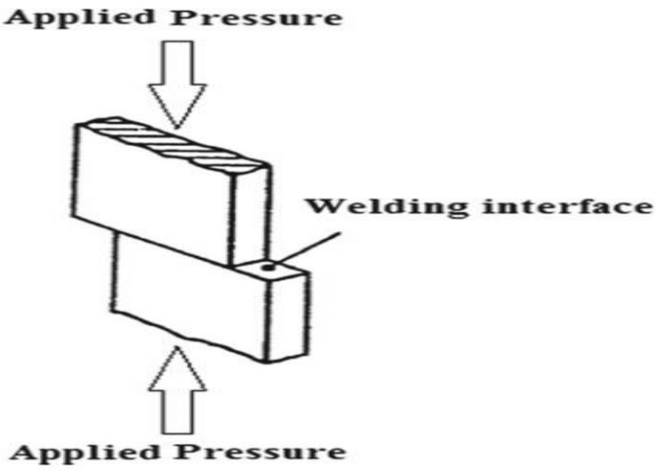


Figure 5: ***Vibration Welding***

1.2 Problem Statement

FSW is a technique which has been performed extensively on wrought Aluminum alloys in a literature specifically for 6XXX and 5XXX series. Each grade of aluminum alloys has particular applications and varies in terms of their thermo-physical and mechanical properties. It has been observed that there is less emphasis towards FSW of dissimilar alloys of aluminum. Though it requires special apparatus with skilled workers but they have wide applications in various manufacturing industries. This study will be performed on AA 5251-H22 and AA 6061-O with thickness 1.6mm and 1.4mm respectively. These alloys are available in the market with required specifications and they have good welding characteristics.

1.3 Aims and Objectives

The major purpose of current study is to carry out welding of alloys Al6061-O and Al5251-H22 with best tool parameters found in the previous literature through FSW technique. The objectives of the research study are as:

1) Fabrication of FSW tool and welding coupons.
2) To analyze the impact of selected welding parameters (rotational speed, welding speed, plunge depth, coupon position, tool geometry) on final weld quality.
3) To analyze mechanical properties (tensile and hardness) of welded section by making a comparison with the base material.
4) To investigate the microscopic structure of welded section, HAZ and comparison with the base material.

1.4 Research Motivation

The motivation behind selecting friction stir welding of aluminum alloys as topic of research is due to following reasons;

1) The aluminum joining process is quite challenging for the industry as it cannot be joined with traditional welding processes i.e. Arc and gas welding etc.
2) It is a green technology and it takes advantage over other welding processes because of its effective mechanical properties.
3) It is used for materials having low melting point and also an energy saving technique.
4) It is a great demand for industries seeking for fabrication of light weight products.

1.5 Chapter 1 Summary

This chapter provides overview of current research study and answers the queries about selecting Friction stir welding of Aluminum alloys as topic of research and its significance in various industries. In order to develop better understanding about the said research work, this chapter begins from background, highlights problem statement, aims and objectives and motivation behind carrying out this research work. All the headings explained in this chapter have been briefly outlined below;

Background: The discussion on basic introduction of FSW, phenomenon of FSW and sources used to carry out FSW, types of friction welding are included under background heading.

Problem Statement: A statement is written after going through the literature review which focuses on the emphasis for conducting research work on FSW of dissimilar alloys and its characteristics.

Aims and Objectives: This heading illustrates about setting aims and objectives prior approaching to experimentation for the ongoing study.

Research Motivation: This heading justifies potential of conducting further research and explore applications of this technology.

CHAPTER 02: LITERATURE REVIEW

2.1 Brief Description

This chapter offers a comprehensive overview of previous studies conducted on FSW process. FSW can be performed either on FSW machine, Vertical milling machine or CNC milling machine depending upon rotational velocity and feed rate. The configuration of welding coupons is mostly done in butt joint or lap joint. In butt joint configuration, the plates to be joined are clamped together facing each other and at the intersection of the plates, The FSW tool with a revolving pin and shoulder is plunged until the tool's shoulder contacts the plates. This tool rotates for a certain time period, known as dwell stage. Due to this action, heat is generated and material is converted from solid state to plastic condition. After this stage, the rotating tool thus moving the soften material along with the pin in a weld direction where shoulder acts as a forging element and form a weld bead between the two plates. On the other hand, In Lap joint configuration, one of the plate overlaps with the other plate to form a weld. A strong thermally insulating backing plate is inserted at the bottom of work piece to provide a smooth surface for welding, avoiding any lateral movement and loss of heat.

2.2 Process Parameters

The process parameters are very crucial for performing successful welding. Many researchers worked on parametric improvement of FSW process and these parameters include Rotational speed, Traverse speed, Plunge depth, Tilt angle, Tool geometry and position of base material. The inappropriate selection of welding parameters causes defects in a weldment. These parameters vary depending upon the nature of material to be welded. These input parameters have greater effect on the joint strength and microstructure properties of the weldment and base material as well.

2.2.1 Rotational and Traverse Speed

Both the Rotational speed and Feed rate should be controlled to achieve desired properties in a weldment. If rotational speed is increased by decreasing the feed rate, this would result in the formation of hot weld and it is necessary that material in the vicinity of the tool must be soft so that breakage of tool and void defects may be avoided.

2.2.2 Tilt angle

Tool is tilted at certain angle to avoid from the defects arising from the downward forces. It must be positioned between 2° to 4°.

2.2.3 Plunge depth

This parameter ensures full penetration of tool inside the weldment and achieving the downward pressure to avoid machine deflection from the predefined position.

2.2.4 Tool design

The other parameter that affects the joint quality formed by FSW process is design of tool. The geometry of the FSW tool must hold two characteristics i.e. design must be kept simple to reduce its cost and it must be capable of producing stirring effect to provide ease to the flow of soften material. The material of the tool must have high wear resistance, good surface finish and low conduction of heat. The tool used for FSW process is comprised of shoulder and pin and its geometry contributes major role in the formation of weld and flow of material which actually affects post weld mechanical properties and formation of defect.

2.2.5 Tool Shoulder

The shoulder of the tool generates frictional heat and high amount of heat generation is associated with the large diameter of the shoulder. The shoulder part provides heat through large compressive forces and more rotational speed causing the material to plasticize and contain beneath it. The tool diameter determines width of SZ and TMAZ. The material gets heated because of tool shoulder and stirred by the rotation of tool. The compressive stress and large diameter produce more heat which reduces voids and pores in the consolidated weld but weld quality also becomes degraded due to excessive heat generation i.e. loss of cold work, dissolution of strengthening precipitate etc. It has also been seen that small diameter leads to improper mixing in SZ due to less frictional heat. Therefore, an optimal shoulder diameter must be selected that could promote efficient heat generation, proper mixing of material and torque reduction. The amount of heat generation and mixing of material also depend upon the shoulder features represented below in a Figure 6.

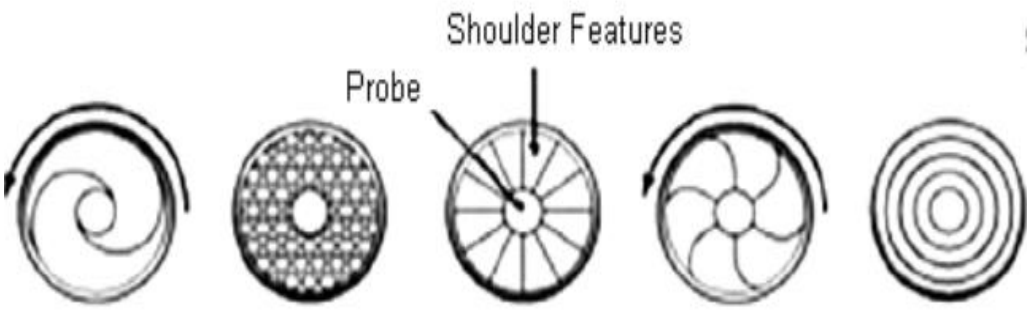


Figure 6: ***Shoulder Features***

2.2.6 Tool Probe

The shape of probe and size are very important in FSW process. The function of probe is to drill work piece, create plastic deformation and move the material from front end to the rear end as well as in vertical direction with thread features. The diameter and length of probe is defined as per the thickness of work piece and probe diameter must be 1/3 of shoulder dia. The length of probe is designed in such a way that it ensures full penetration inside the work piece but not touches the backing plate. Some probes have thread features and some even come with more complex features mentioned in a Figure 7. Each profile plays different function in terms of movement of material. Cylindrical and Tapered cylindrical profile just move the material around the pin but threaded feature on cylindrical profile moves around as well as move in vertical direction also. Square, cam and hexagonal profiles are considered best for their pulsating action as their faces are flat. This pulsating action is the cause of efficient mixing and results in the formation of sound weld joint. With the passage of time these profiles tend to wear out and acquire the conical shape other than cylindrical profile. Therefore, an optimal shape must be selected against large number of experiments which cannot only sustain its shape but also provide better movement of material.

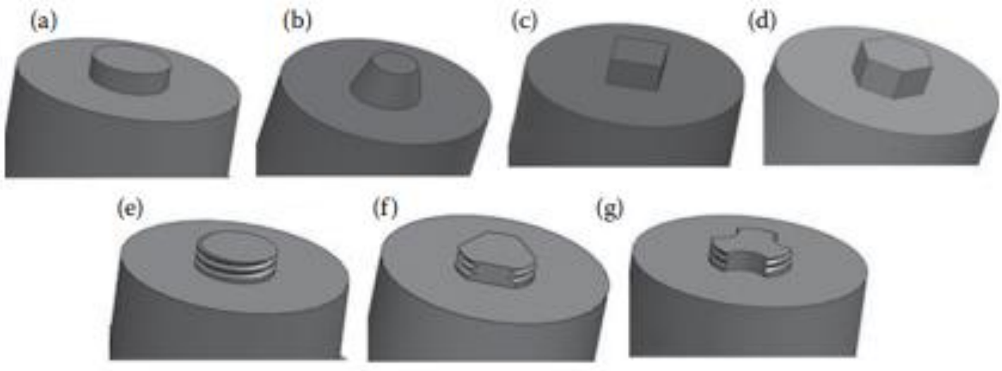


Figure 7: Pin Shapes

The design of thread on the probe depends on the direction of spindle rotation. As threading on a probe pushes material downward, if spindle is rotating in a clock-wise direction then it requires left handed pitch thread.

2.3 Microstructure Zones in FSW

FSW greatly affects the micro structure of weldment formed and this section can be analyzed through metallurgical microscopes. The amount of change in microstructure depends on the position of weld, type of alloy and welding parameters. When we aim to enhance the quality of the joint, we deal with the variables that may give best possible micro structure results. In order to analyze weld micro structure, it is classified into four unique regions as shown in Figure 8 below.

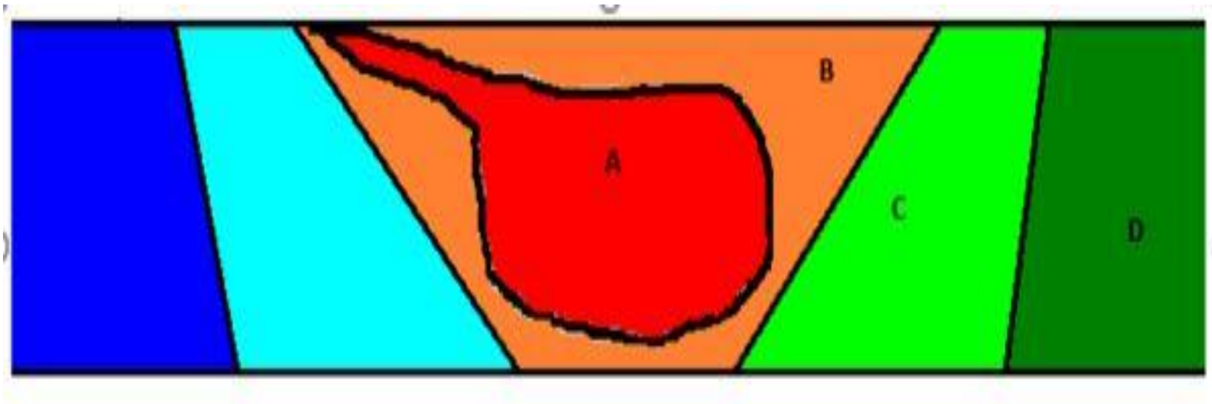


Figure 8: FSW Microstructure zones [3]

2.3.1 Nugget Zone

This region is fully occupied by the pin and experiences high temperature and large plastic deformation. Due to this phenomenon, recrystallization takes place which is dynamic in nature and also termed as dynamic recrystallization. This zone is only separate in case of Aluminum.

2.3.2 Thermo-Mechanically Affected Zone

This region is extremely closed to the weld line and lies just below the shoulder of the tool experiences deformation as well as heat. Both the deformation and heat generation affect size of grains which are a bit larger than the Stir zone.

2.3.3 Heat Affected Zone

This region is located close to the weld line and undergoes thermal cycle as well. The heat effect occurs on grains but grains are not deformed plastically here.

2.3.4 Parent material/Unaffected Zone

This zone exists away from the weld line. Though, there occurs possible temperature changes in the zone but the parent material exhibits the same mechanical properties and microstructure as it had before the welding process. That’s the reason, it is known as uneffaced zone.

2.4 Defects in FSW

It has been observed that the problems encountered during FSW may occur due to inappropriate heat generation and poor choice of welding parameters. Some of the major problems are mentioned below:

2.4.1 Incomplete root penetration

This defect occurs due to several causes like improper tool design, misalignment in tool position and local variations in thickness of plate. In case of improper tool design, a region remains unstirred due to incomplete tool pin penetration at the bottom of plate. Under the subjection of load, an appropriate pin length and plunge depth are required for the thorough mixing till the weld root which are adjusted according to the thickness of coupons so that touching of tool pin with the back plate may be avoided. Therefore, an optimal pin length and plunge depth must be selected to overcome this defect.

2.4.2 Voids

This defect usually occurs on the AS of the weldment. The reason behind the occurrence of this defect is because of deficient downward pressure and high Traverse speed. The material cools earlier before it can fill the region deformed by the pin. Therefore, optimal diameter and welding speed must be selected to overcome this type of defect.

2.4.3 Kissing Bond

This defect may arise due to poor cleaning of work piece surfaces and wrong choice of parameters for tool design. Due to this an oxide layer is formed through the weldment and insufficient deformation takes place. Apart from this lack of material deposition due to high flow stress and inadequate heat generation lead to discontinuity in bonding which may cause defect of kissing bond.

2.4.4 Tunneling

Tunneling may be formed due to rotational speed, traverse speed and inappropriate welding conditions. It has been reported that low heat input results high flow stresses causing deficiency in the stirring of material in tool pin surroundings which restricts the consolidation of material on trailing side of the pin and forms a tunnel defect. Deficient downward pressure decreases weldment temperature causing base metal's flow stress to increase and consequently inappropriate material movement and plastic deformation also resulting in a tunnel defect. This defect can be eliminated through appropriate heat generation and distribution on the respective sides of that joint and proper consolidation of soften material. It is a major reason of stress concentration and reduction in cross-sectional area.

2.5 Merits and Demerits of FSW Process

Table 1: Merits and Demerits

Merits	Demerits
Better mechanical properties and absence of fumes formation	Requires complex set up for welding
Used for both similar and dissimilar materials	Presence of end hole when tool is withdrawn
No solidification cracking and low distortion	Capital cost is high
Parent material's chemistry is retained	Limited to few types of welded joints
No shielding gas and filler material required	Not applicable to super alloys

2.6 Benchmark Articles Summary

Wondu et al. conducted research on FSW of dissimilar 6061-T6 and 5052-H32 with 6mm thickness. He considered RS, TS and pin profiles as FSW parameters to optimize properties of the weldment i.e. metallurgical and mechanical. He found that Tensile strength and Hardness are maximum at 1400 rpm and 40 mm/min. The results showed that square pin profile exhibited good microstructure properties and has major contribution in making sound weldment as compared to tool RS and TS. [4]

Baghdadi et al. studied improvement in dissimilar FSW Al5083 and Al6061 joint. He investigated PWHT effect on mechanical properties of dissimilar joints formed at rotational speed (800, 1000, 1200, 1400) and traverse speed (100, 200, 300, 400) with samples thickness 4mm each. He concluded that ultimate tensile strength due to T6 thermal treatment had raised from 181MPa to 270MPa which constitutes 93% efficiency of the weldment and hardness properties improved from 55HV to 95HV. [5]

Yasir et al. considered AA5052-H32 for the study with 1.2mm thick sheet. All the parameters of tool have been defined according to the thickness of the sheet. He investigated the impact of rotational speed, traverse speed and pin shapes to achieve high strength and defect free joint and optimized these said parameters with respect to tensile strength of the joint using Taguchi method. He found that the optimal parameters were 3250 rpm, 200 mm/min with square shaped pin. [6]

Yue et al. studied friction stir welding of al-clad AA2024-T4 in butt joint configuration. The welding parameters were tool rotational speed, tool traverse speed, tilt angle and plunge depth. The investigation showed that between 400 to 1000 rpm and 50 to 150 mm/min, a joint is formed free from defects. The maximum tensile strength of 399.5MPa was achieved at 1000 rpm and 150 mm/min. The hardness of SZ is 6% less than the base metal. [7]

Shashank et al. carried out research to investigate the impact of welding parameters on mechanical and microstructure properties considering AA6063 as base metal possessing thickness of 3mm. The rotational speed of 700 rpm,1000 rpm,1500 rpm and welding speed of 60 mm/min and 100 mm/min have been taken into account. The maximum Tensile strength is achieved at 700 rpm and 60 mm/min. At 1500 rpm low tensile strength is obtained due to high temperature and stirring action. By reducing rotational speed hardness increases due to refinement of grain size. At 1000 rpm SZ hardness is lower than the base metal. Microstructural study reveals that by enhancing tool rotational speed, grain size increases. The grain size formed in SZ are equiaxed while those of HAZ and TMAZ are partially crystallized or less uniform. At 700 rpm and 60 mm/min defect free joints are formed. [8]

Nejad et al. studied Al 2024-T4 plate and weld is made with the help of cylindrical outer and concave end surface shoulder having tapered threaded and unthreaded probes. The investigated parameters are rotational speed, traverse speed and plunge depth and it is aimed to optimize these parameters to achieve best quality welds with both tools. For tool 'A' rotational speed btw 840 rpm to 1300 rpm and welding speed btw 115 mm/min to 145 mm/min whereas for tool B rotational speed btw 300 rpm to 500 rpm and welding speed btw 40 mm/min to 55 mm/min yields optimal welds. For featured tool B, the rotational speed of 500 rpm, plunge depth of 2.7mm and traverse speed of 55 mm/min whereas for unfeatured tool A rotation speed of 1300, plunge depth of 2.9mm and traverse speed of 115 results in finest grains in SZ, elongation, maximum tensile strength and micro-hardness values etc. [9]

Akbari et al. studied mechanical and microstructural properties of dissimilar AA5251 and AA5083 having thickness of 4mm each. It has been concluded that at 1000 rpm and 115 mm/min, tensile strength of joint is maximum. By increasing rotational speed from 800 to 1250 hardness in all regions of the weld decreases. There is no void defect on conditions at 1000 rpm, 1250 rpm with 115 mm/min, 85 mm/min. [10]

Doley et al. studied FSW of thin sheets AA5052 and AA6061 with different thicknesses of 1mm and 1.5mm respectively. He analyzed the effect of traverse speed by keeping the rotational speed constant. The results showed that UTS of 1.5mm thickness welded joint is 22% and average elongation is 47% more than 1mm thick sheet. The average micro hardness was found to be more than 5052-H32 alloy at SZ and less than 6061-T6 alloy. [11]

Koilraj et al. discussed FSW of Al 2219-T87 and Al 5083-H321 plates and optimization of process parameters using Taguchi L16 orthogonal technique. The process parameters took into an account are rotational speed, welding speed, tool geometry (CS, CT, TH, TT) and ratio of D/d. To produce a joint having maximum tensile strength. The ratio of D/d is important for determining the soundness of weld as shown by ANOVA. In microstructure analysis a comparison has been made between these two alloys in terms of presence of second-phase particles. It is observed that base material of 2219 is harder than base material of 5083 when compared with their respective nugget zone. The results show that AA2219 is significantly stronger than AA 5083. The joint specimen exhibited low strength than Al5083 alloy specimen. It is concluded that the optimal tool geometry is cylindrical threaded at 700 rpm, 15 mm/min and D/d=3 respectively. [12]

Sattari et al. conducted research on friction stir welding of ultra-thin sheet AA5083. He employed spindle rotation speed, feed rate and speed ratio as welding parameter to investigate the effect of selected parameter on mechanical properties of the weldment. To avoid the tool damage, it was heat treated to achieve 52HRC. The major dimensions of tool were 6mm and 2mm for shoulder diameter and pin diameter whereas pin height was taken as 0.65mm. Tool steel H-13 was selected as tool material. This study showed that welding speed range between 18.58 mm/min to 34.84 mm/min exhibited best welding results in terms of mechanical and failure properties. It was also concluded that defects free joints were obtained between temperature ranges 430°C to 510°C. The average hardness declines along the weld line if more heat is supplied. [13]

Cerri et al. investigated behavior of thin FSW sheet of aluminum alloy at warm and room temperature and microstructure as well. It is shown that at both room temperature and warm temperature thin friction stir welded joints demonstrated the capability to bear tensile stress but their ductility was poor and unaffected by temperature and strain rate. TEM investigations show that 2024-T3 BM had a higher strength than 6082-T6 BM due to precipitation and growth of ‘S’ type phases and that PFZ were observed in the joints. It is shown that micro-void size, distribution and coalescence vary depending upon the void nucleation mechanism. [14]

Kumar et al. considered the impact of FSW tool on weld formation and material flow pattern using Al 7020-T6 Alloy as base material. It has been noticed, As FSW tool interaction increases, the defect size reduces and tool interaction also increases with the axial load. This axial load and tool interaction are responsible for heat generation. The results show that there are two modes of material flow regimes namely “pin-driven flow” and “shoulder-driven flow”. The pin-driven flow is layer by layer stacking of material in the weld line and shoulder-driver material flows from retreating side and forges against the advancing side base material. The design of shoulder should be selected so that the maximum amount of material ejected by the pin from the weld cavity can be reflected back whereas the dimensions of pin may be chosen such that the maximum amount of transferred material is retained in the weld cavity. The formation of onion rings is due to the merging of pin-driven and shoulder-driven material flow and onion ring pattern arises from differential etching contrast. This etching contrast arises due to the difference in degree of deformation or difference in energy stored between the layers. [15]

MV Sezhian et al. studied thick plate of AA 6082 and AA 7075 using M35 Tool steel as tool material for making FSW butt joint. This study opted L8 orthogonal array for conducting experimentation. The results showed that the optimal parameters on which maximum tensile strength, hardness and bending strength obtained were 2300 rpm, 40 mm/min and 30 mm/min. [16]

2.7 Research Gap

Many research studies have been done for both similar and dissimilar alloys of aluminum. Some of the benchmark papers as mentioned before have been reviewed in this regard which are more relevant with this ongoing research work. While going through the comprehensive literature, following number of conclusions were made;

1. There are fewer research studies conducted on friction stir welding (FSW) of aluminum alloys and more work need to be done due to its high demand in industries where weight reduction is the main goal in product manufacturing.
2. Many authors focused much on optimization of the welding parameters (RS, WS, Tool geometry) and concluded their studies by pointing out best parameters on which finer quality of weld they obtained.

3. It was observed that many authors considered 6XXX and 5XXX series aluminum alloys for both similar and dissimilar combinations in their research because they are extensively applied in aerospace, automotive, shipbuilding and chemical industry.

On the behalf of these findings, ‘Experimental investigation using best tool parameters on FSW of dissimilar alloys (Al6061-Al5251)’ as topic of research has been finalized for this research work.

2.8 Chapter 2 Summary

This section of Thesis provides an overview about past studies carried out on Friction stir welding of Aluminum Alloys. This includes detail of process parameters, categories of weld zones for FSW of Aluminum Alloys, Defects occur during FSW process, Merits and Demerits, Research articles summary and Research gap which provide a solid foundation to develop a methodology for this ongoing research work.

CHAPTER 03: METHODOLOGY

3.1 Flow Chart

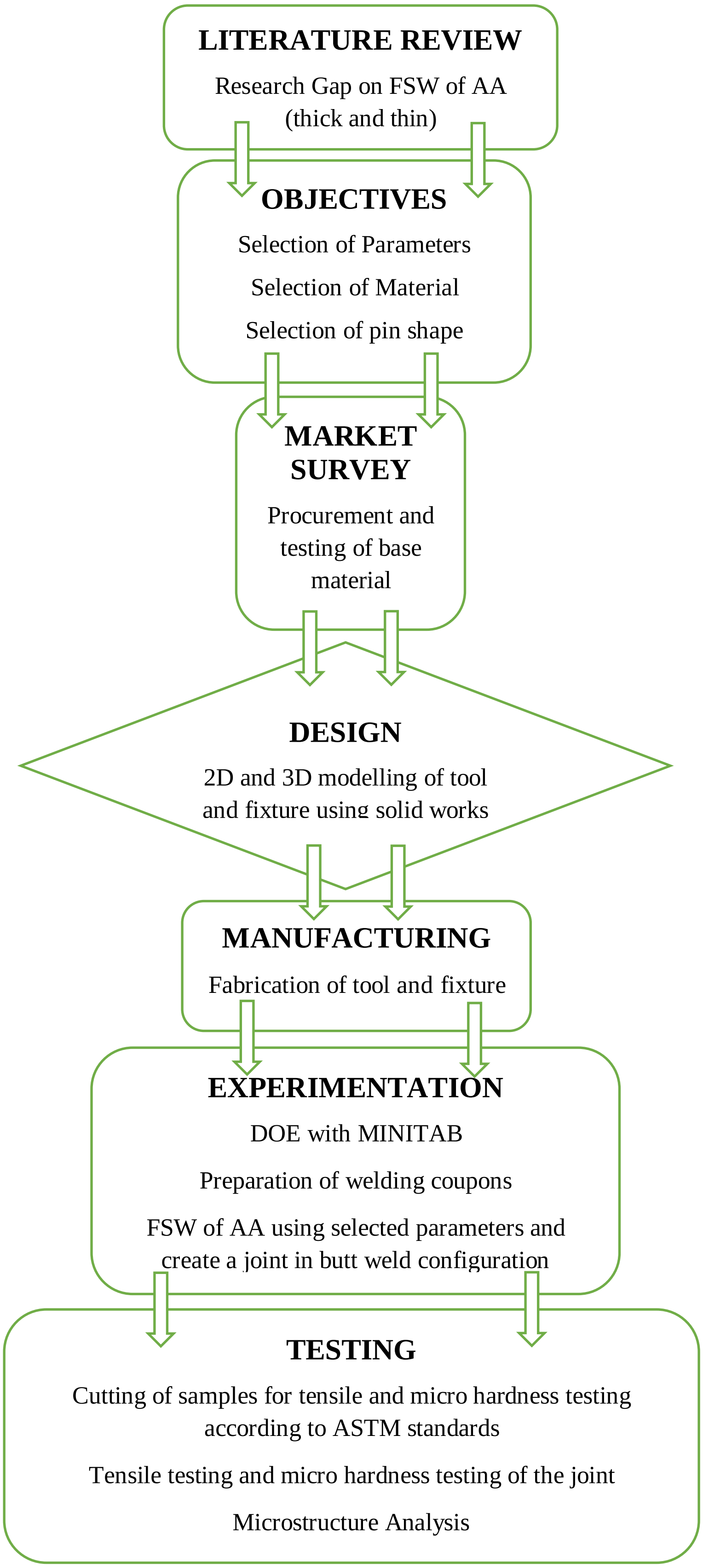


Figure 9: Methodology

The methodology opted in this research work has been shown in the form of flow chart in Figure 9. This chapter discusses each module of the flow chart in detail as follows:

3.2 Procurement and Testing of Base Materials

While conducting a literature review, two things kept in mind which are very crucial for every researcher when going for procurement of alloys i.e. availability of material in a local market and type of aluminum alloys mostly considered in previous studies with wide applications in industry etc. It was quite challenging to procure aluminum alloys for the research work as these alloys termed as silver sheet in a local market and only few technical vendors had a knowledge about specific graded alloy sheets. The base materials used in this study are heat treated AA 6061-O and strain hardened AA 5251-H22. Both these alloys belong to the wrought category of aluminum. The first digit of the alloy indicates type of alloy, second digit indicates modification whereas third and fourth digits specify their place in that particular series [J.R. Davis].

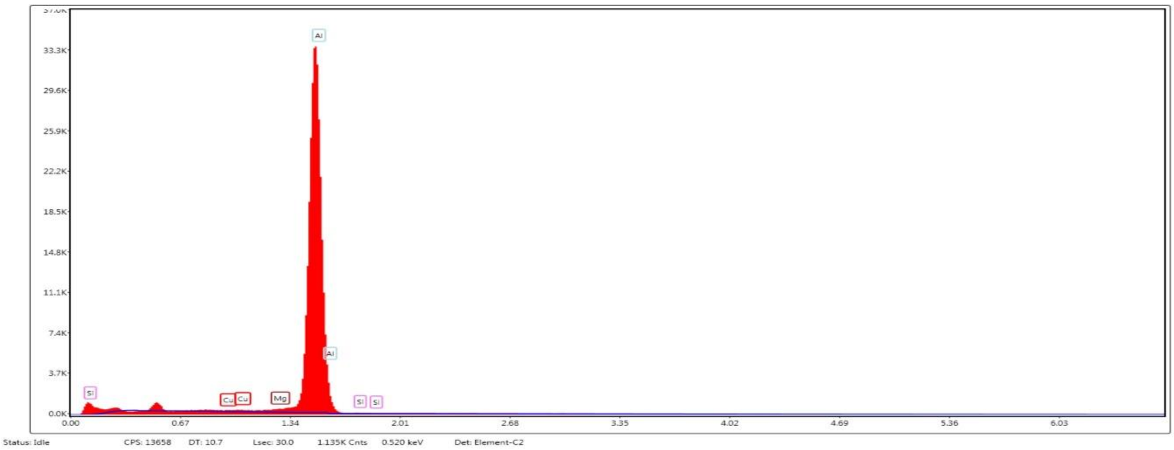


***Figure 10:** EDX Spectrum of 6061-O*

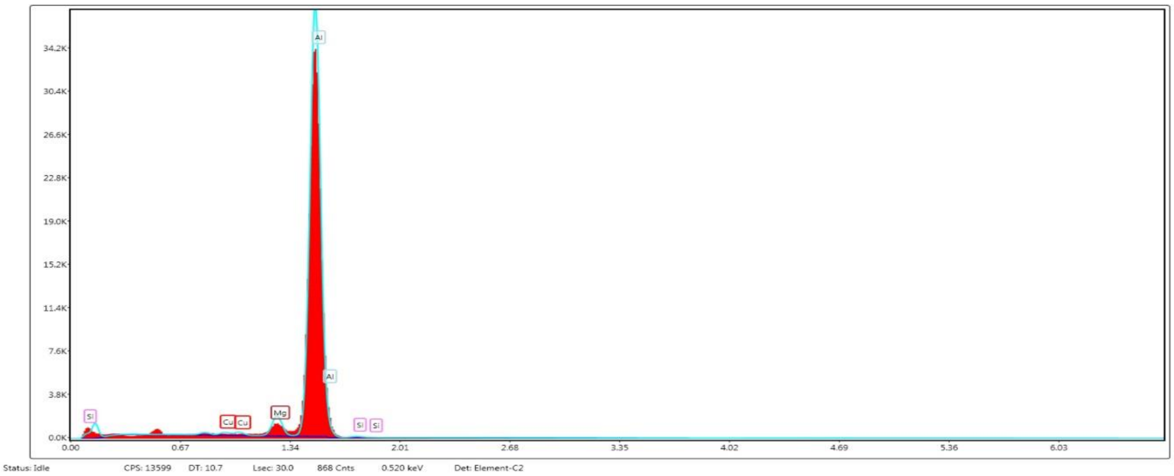


Figure 11: ***EDX Spectrum 5251-H22***

After successful procurement, these alloys were tested through EDX-ray technique in order to get elemental composition of each alloy. The chemical compositions of both alloys is given in a Table 2 along with EDX-ray spectrum as shown in Figure 10 & 11.

Table 2: ***Chemical Composition of 6061-O and 5251-H22***

Alloy	Mg	Cu	Si	Al
6061-O	1.57	0.57	0.42	97.44
5251-H22	3.49	0.66	0.38	95.47

3.3 Design of tool and fixture

The FSW tool and fixture being used in the current study are modeled using solid works. Tool and fixture are modeled by keeping in mind their required features and design specifications to perform the intended function. Both the tool and fixture are modeled using first angle of projection. The 3D isometric view of tool and fixture can be viewed in a Figure 12.

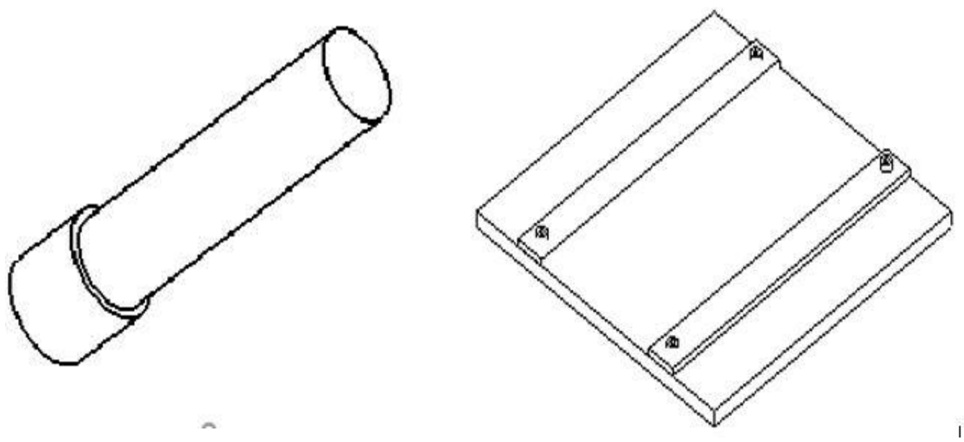


Figure 12: ***Isometric View of Tool and Fixture***

Wondu et al conducted research on aluminum alloys 6061-T6 and 5052-H32 and investigated the impact of different pin shapes on the joint formed between the two dissimilar base material used. It was concluded that the square shaped profile played critical role in enhancing the properties of weldment rather than any other parameter. The experiments were conducted on 6mm thick sheets. [4]

Yasir et al. designed tools and fixture for FSW process of Aluminum alloy 5052. He selected HSS material for the specialized tools and Bakelite/MS as Fixture material. The dimensions for all three types of tools remained same as: shoulder diameter= 7.5mm, pin diameter= 2.5mm, and pin height= 0.85mm for welding 1mm thick sheet. The optimal results found with square shaped pin with 2.5mm each side length. [6]

Elangovan et al. considered five different types of pin profiles which also included square profile for thick similar sheets of 6061-T6. It was observed that the tool with square shaped profile exhibited superior tensile properties and defect free joint. The tool material used in this study was High Carbon Steel. [16]

All the 2D drawings of fixture and tool along with dimensions are shown as following in Figure 13 and 14 respectively.

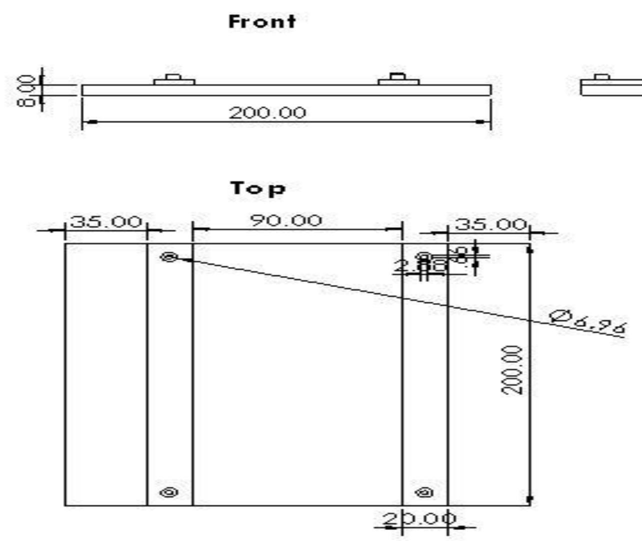


Figure 13: ***2D Orthographic views of Fixture***

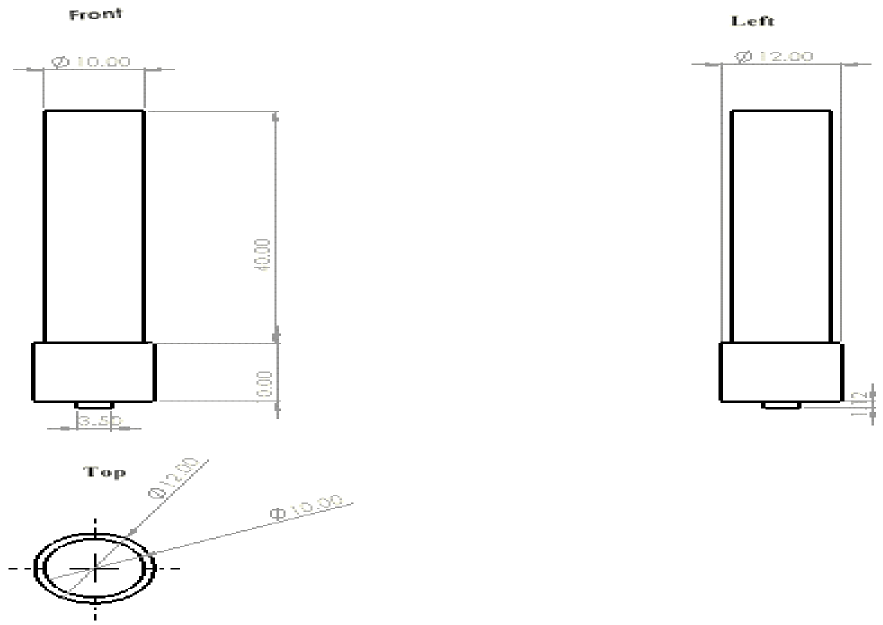


Figure 14: ***2D Orthographic views of Tool***

3.4 Fabrication of tool and fixture

The circular diameter and length of Tool steel H-13 rod used for fabrication of FSW tool were 15mm and 200mm shown in Figure 15. The diameter of shank is reduced to 10mm so that it can easily fit into the machine collet whereas shoulder and pin diameter kept as 12mm and 4mm as per design specification. The required diameter of the tool shank and shoulder is achieved through turning process on Centre Lathe machine. The square pin shape of the tool was formed on vertical milling machine which is 1.12mm in depth having each side length of 3.5mm respectively as shown in Figure 16. [17]

When it comes to the fabrication of fixture, the back plate and holding strips of mild steel were selected as material. The size of back plate is 200×200mm which must be hard enough to resist tool force. The strips are tightened with the back plate using Allen bolts. Both the back plate and holding strips were ground to ensure smoothness on their surfaces before using for FSW process.

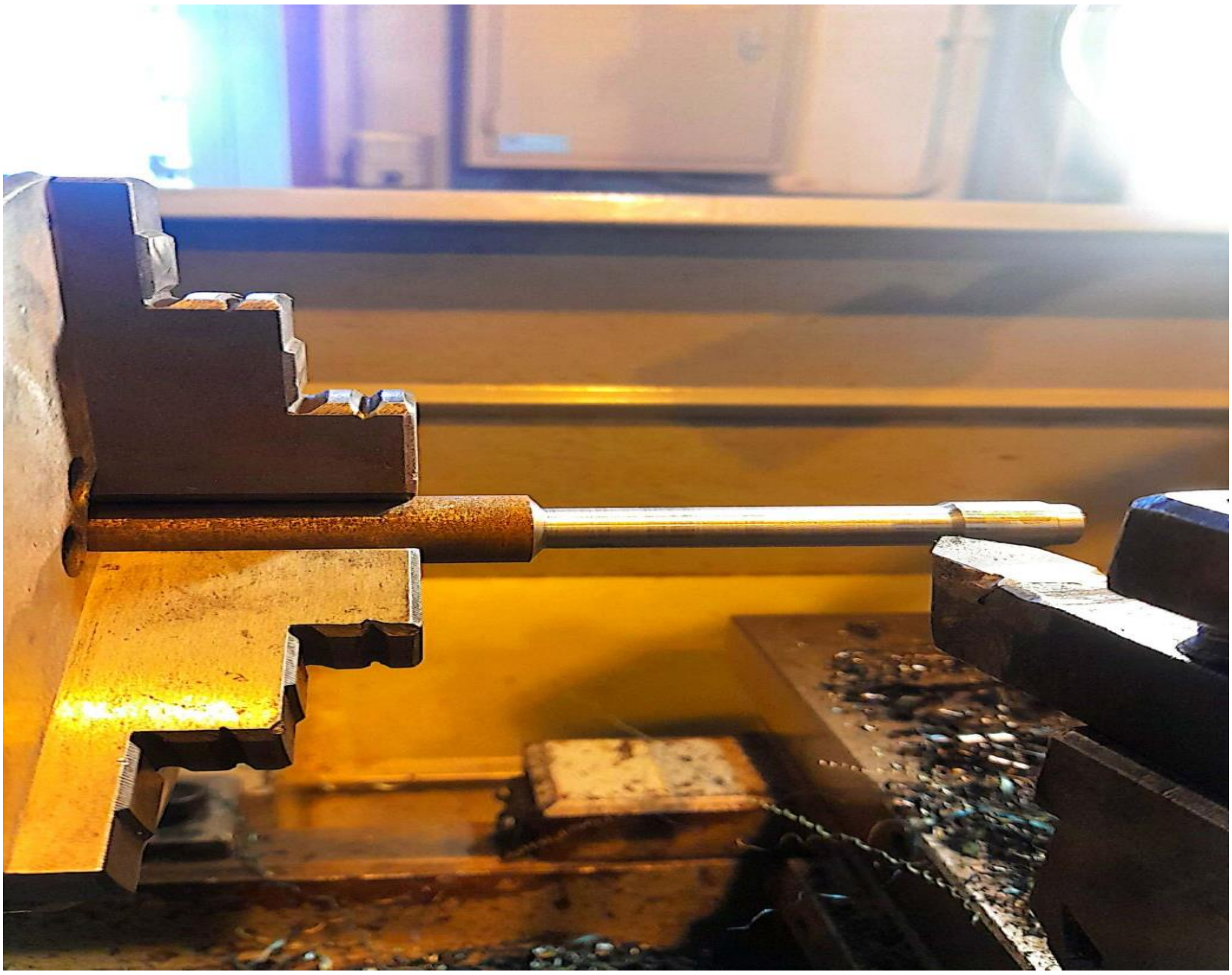


***Figure 15:* Tool steel H-13 rod Machining**

***Figure 16:* FSW Tool**

3.5 Experimentation

Experimentation is the most important phase of research work on the basis of which results have been compiled. It involves design of matrix, fabrication of coupons and FSW process execution on CNC milling machine.

3.5.1 DOE with Minitab

Design of Experiments is widely used in scientific experimentation and this study incorporates Minitab 18 for performing experiments which uses Taguchi technique. This is an organized way of performing experiments and investigating the response of selected parameters on the output variables. Hence in 1954, Dr. Genichi Taguchi suggested a statistical model, "Taguchi Design of Experiment" to improve the quality of product and process by reducing the variations.

Taguchi design matrix is created, which shows tool rotational velocity, traverse velocity and coupons position as input variables, also termed as factors. Each factor has two level therefore it will be 3 factors and 2 levels design matrix. Hence the design array L8 is suitable for eight experiments. The summary of Taguchi Design Matrix is listed in a Table 3 below;

Array L8 (2^3)

Factors 03

Runs 08

Table 3: Taguchi Design Matrix

Rotational Speed	Traverse Speed	Position
1675	60	AS
1675	60	RS
1675	80	AS
1675	80	RS
2850	60	AS
2850	60	RS
2850	80	AS
2850	80	RS

3.5.2 Fabrication of Coupons and FSW

All the experiments were performed on Vertical CNC milling machine in butt joint configuration. Before starting the experiments, rectangular shape coupons of 6061-O and 5251-H22 sheets, having dimensions 75×150mm with 1.4mm and 1.6mm thicknesses were cut using sheet metal shearing machine.

Table 4: Mechanical Properties

Base Material	Density	Poisson's ratio	Young's Modulus (MPa)	UTS (MPa)	Rockwell (HRC)	Micro-Vickers (HV)
6061-O	2.71E-09	0.33	69000	128.85	-	43.6
5251-H22	2.69E-09	0.33	70000	145.99	-	68.9
Tool Steel H-13	7.80E-09	0.3	210000	1369	51	-

Tool steel H-13 FSW tool was quenched in oil medium to achieve 51HRC. The mechanical properties of 6061-O, 5251-H22 and H-13 Tool steel are listed in a Table 4 above. The welding coupons were filed and ground with grinding paper to remove burrs and make their edges straight and smooth to ensure that there is zero gap between the joining plates. The FSW tool has to be fixed in the collet of machine whereas coupons are held tightly in a fixture to avoid movement during welding process. The plunge depth was taken 0.2mm for all the experiments. The direction of spindle rotation kept anti-clockwise throughout the experiments and every trial was performed thrice in order to get accurate results. During the experiments, infrared thermal camera was used to record the temperature in HAZ of the weldment. After successful welding execution, I-shaped samples were thermally treated to 535°C for 1 h and quenched in water. After quenching the samples were heated to 175°C for 8 h. The setup of FSW process is shown in a Figure 17 below:

***Figure 17:* (a) Vertical CNC Milling (b) FSW Set up**

3.6 Tensile Test

All the sub size I shaped samples for tensile testing were extracted in the middle of welded plates in perpendicular direction with the help of wire cut EDM. These samples were prepared as per the ASTM standard E8/E8M-04 [18]The description of sub size I sample is listed in a Table 5.

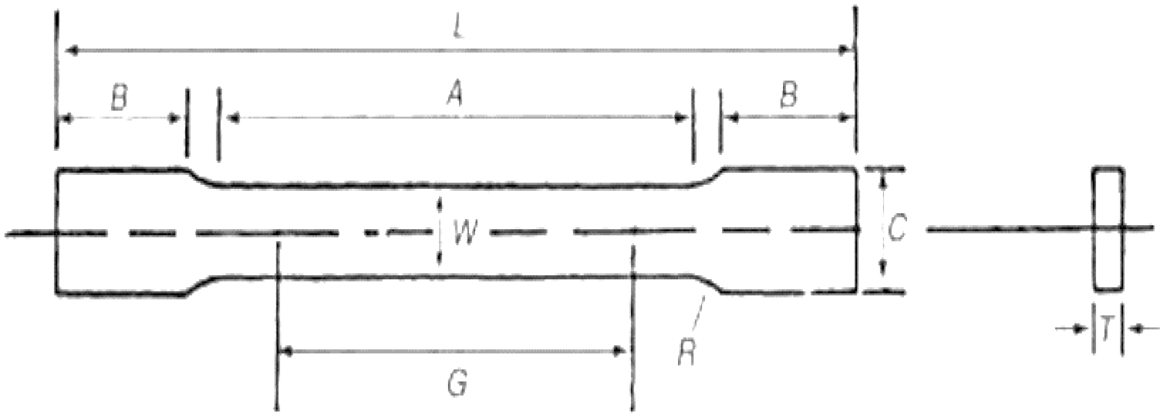


Figure 18: Dog bone shape for Tensile Test

Table 5: Sub size I sample dimensions

L	**100**
A	**32**
W	**06±0.1**
G	**25±0.1**
B	**30**
C	**10**
R	**6**
T	**1.6**

The Tensile tests were conducted on UTM at a rate of 3mm/min and measured ultimate tensile strength for the welded samples as well as base material. This can be viewed in Figure 19.

Figure 19: ***Universal Testing Machine***

3.7 Micro Hardness Test

In order to measure hardness, all the experiments were carried out on Micro Vickers Hardness Tester as per the ASTM standard E384-17 shown in Figure 20. The samples for hardness were also extracted perpendicular to weld direction. The samples were mounted, ground and polished before conducting the experiments. The experiments were performed three times on each sample i.e. middle of weld and HAZ on both AS and RS etc. and took the average of three

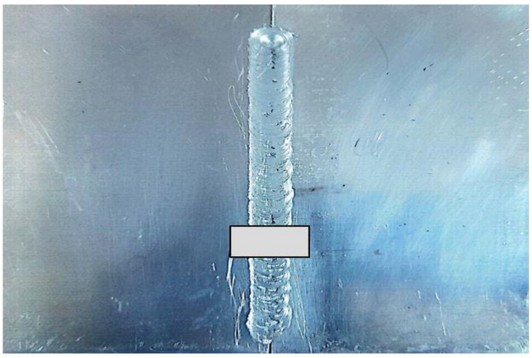


Figure 20: ***(a) Micro-Hardness Tester (b) Micro-Hardness Sample***

readings to get the required micro-hardness. All the experiments were performed by adjusting dwell time=10sec with 200g applied load.

3.8 Microscopic Analysis

Microscopic analysis plays vital role in determining the quality of the weldment and base material. In this regard samples were prepared in metallographic lab as shown in Figure 21. These samples were mounted, ground, polished and etched so that visibility of internal structure can be improved.

3.8.1 Mounting

The samples for microstructure analysis were extracted through wire cut EDM. The cross section of each sample was 15mm×5mm. Each sample was allowed to go through in a mounting hydro press for which the material selected for mounting was non-conductive Bakelite.

Preparation of mounting samples starts by adding Bakelite powder in hydro mounting press. In first cycle temperature and pressure are allowed to increase and in second cycle both the temperature and pressure gets dropped. On powering the hydro press, adjust initial temperature value to 180°C and pressure value to 270 bar which usually takes 4 minutes to achieve this state. After passing this time, machine sucks water for showering on heated sample and allowed it to cool. Due to this action temperature and pressure starts decreasing and this may take 40 minutes. Finally, temperature reaches to 39°C and pressure reaches to 2 bar and machine sounds a buzzer which means machine has to be stopped at that time.

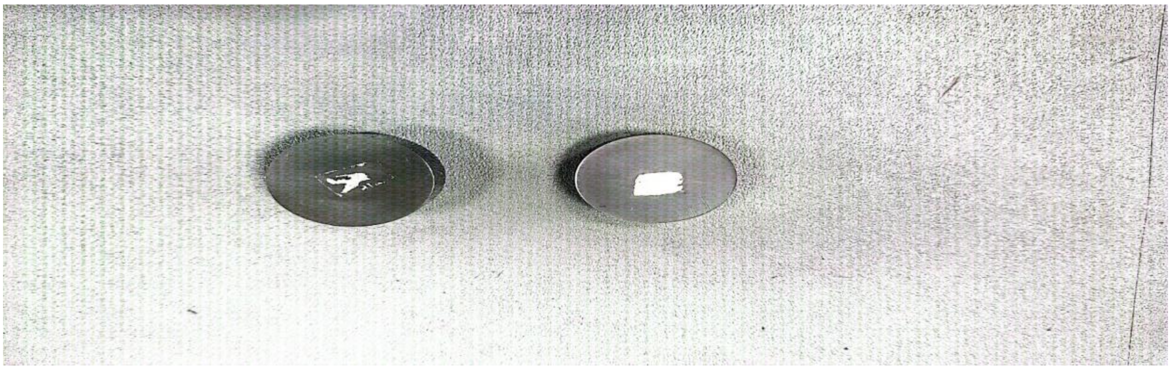


***Figure 21:* Mounted Samples**

3.8.2 Grinding and Polishing

After mounting, samples were fitted in a grinder and polisher equipment of Buehler Auto met 250 as shown in a Figure 22 below. The diameter of rotating bed plate on which grinding and polishing paper were gripped was of 250mm. The rotational speed of head plate and bed plate were adjusted to 100 RPM and 200RPM whereas rotation of both plates remained opposite. The emery papers used in grinding process with different grit sizes such as 240, 800, 1200, 2000 and 2400. During grinding, water is supplied through a small pipe with diameter= 3mm to ensure smooth grinding and avoiding from scratches. The grinding force and time for the operation were adjusted to 10N and 3min.

***Figure 22:* Grinder and Polisher Equipment**

Polishing was performed on the same equipment with the help of polishing pads/cloths and instead of water, alumina suspension of 1µm and 0.5µm is recommended with RMP-FNLA Polishing cloth. The ratio of suspension was kept 1:10. For polishing, set time= 5min, speed= 200rpm and force= 5N and make sure that both the plates are rotating in a same direction. The samples were ground and polished as per the ASTM standard E-311.

3.8.3 Etching

The etching process starts after polishing the samples surface. This process involves the reaction of samples surfaces with strong acids. Initially, the selection of suitable etching reagent for aluminum alloys was quite challenging and after comprehensive working on this subject, it was concluded that the most suitable etching reagent is Tuckers reagent. The chemical composition of Tuckers reagent is listed in a Table 6 below;

Table 6: Tucker's Reagent Composition

Chemical	Composition
HNO3	15ml
HF	15ml
HCL	45ml
Distilled Water	25ml

Before starting etching it is to ensure that contact surface is free from contaminants and impurities to avoid any chemical reaction. All the samples including base material were swabbed for 15 sec. This process of etching was performed as per the ASTM standard E407-07 (Standard practice for Micro etching Metals and Alloys).

3.9 Digital Microscopy

The digital microscope is specially opted for microscopic examinations as it doesn't only use for visualization but also for measurement purpose. In the field of metallurgy, it is used for determining surface roughness, angle measurement, particle size, distance between particles and shape of particles. In this investigation Olympus digital microscope DSX1000 as shown in Figure 23 has been used for analyzing the microstructure of etched samples. The magnification lens used with microscope was 400X for all the images. While performing microscopic analysis, grain size was measured in weldment and base material samples as well. This has been explained in the coming chapter.

Figure 23: Olympus Digital Microscope DSX100

3.10 Chapter 3 Summary

This chapter details about the experimental methodology opted in this research work. Due to a lack of vendor expertise, it was challenging to find aluminum alloys 6061-O and 5251-H22 locally for this research. The tool and fixture were designed in SolidWorks and manufactured to exact specifications. The FSW tool and fixture were fabricated using the procured material verified by EDX-ray analysis. On a CNC milling machine, trials were performed as per the Taguchi Design of Experiment (DOE) technique. Tensile and micro-hardness tests were then conducted in accordance with ASTM guidelines. After the samples were ground, polished, and etched, the Digital Microscope was used to examine the microstructure of the welded section and base material.

CHAPTER 04: RESULTS AND DISCUSSION

4.1 Tensile Strength

The purpose of performing tensile test in this study is to evaluate the joint strength of the weldment as well as base material. All the tests have been performed on Universal Testing Machine as per the Taguchi DOE matrix. There are three number of factors in an array and each factor consists of two levels. These factors are rotational speed, traverse speed and coupons position. The number of runs in a design matrix are 8 as L8 orthogonal array is selected for the experiments. The tensile tests were performed on each run and ultimately calculated their peak stress. Each experiment was repeated three times and subsequently calculated their mean for ultimate tensile strength. These experimental results were fed in Minitab 18 software for the sake of performing analysis on it.

The Taguchi analysis showing in Table 7 is performed on the basis of mean and SN ratio. This DOE created in Minitab 18 generated results in the form of SN ratio which shows the effect of noise factor on final response. Highest value of signal to noise ratio means that the final response is more robust on that particular factor. Here A5 is the sample on which high value of SN ratio is recorded and it is not defective. The criteria of determining the sample defective and not defective is based on the intensity of control factors.

***Table 7:* Taguchi L8 DOE with UTS and SNRA1**

Sr. No	Sample	Rotational Speed (rpm)	WS (mm/min)	Coupon Position (CP)	UTS (MPa)	SNRA1	Weld Quality
1	A1	1675	60	5251(AS)-6061(RS)	76.73	37.6993	Defective
2	A2	1675	60	5251(RS)-6061(AS)	71.14	37.0723	Defective
3	A3	1675	80	5251(AS)-6061(RS)	85.13	38.6017	Not Defective
4	A4	1675	80	5251(RS)-6061(AS)	79.55	38.0128	Not Defective
5	A5	2850	60	5251(AS)-6061(RS)	101.98	40.1703	Not Defective
6	A6	2850	60	5251(RS)-6061(AS)	98.69	39.8855	Not Defective
7	A7	2850	80	5251(AS)-6061(RS)	92.18	39.2927	Not Defective
8	A8	2850	80	5251(RS)-6061(AS)	74.59	37.4536	Defective

4.1.1 Signal to noise ratio

In this ongoing research work Taguchi method is applied which defines the criteria for measuring the performance of parameters as signal to noise ratio and highlights that level of factors playing critical role in enhancing SN ratio. The equation used for calculating signal to noise ratio is given as;

$$\eta j = -10 \log10((1*\sum(1/Yi^2))$$

where;

Y_I = quality characteristic of i^{th} test

4.1.2 Larger is better

This research study selected 'larger is better' criteria in order to determine the optimal parameters. This way, the response of output is recorded in terms of SN ratio and mean by incorporating the experimental data represented in Figure 24 and 25. The response tables for SN ratio and mean are given below;

Table 8: ***Response table for Signal to noise ratio***

Larger is better

Level	**RS (X)**	**WS (Y)**	**CP (Z)**
1	37.84	**38.70**	**38.94**
2	**39.20**	38.34	38.10
Delta	1.36	0.36	0.84
Rank	1	3	2

Table 9: Response Table for Mean

Level	RS (X)	WS (Y)	CP (Z)
1	78.14	**87.14**	**89.01**
2	**91.86**	82.86	80.99
Delta	13.72	4.27	8.01
Rank	1	3	2

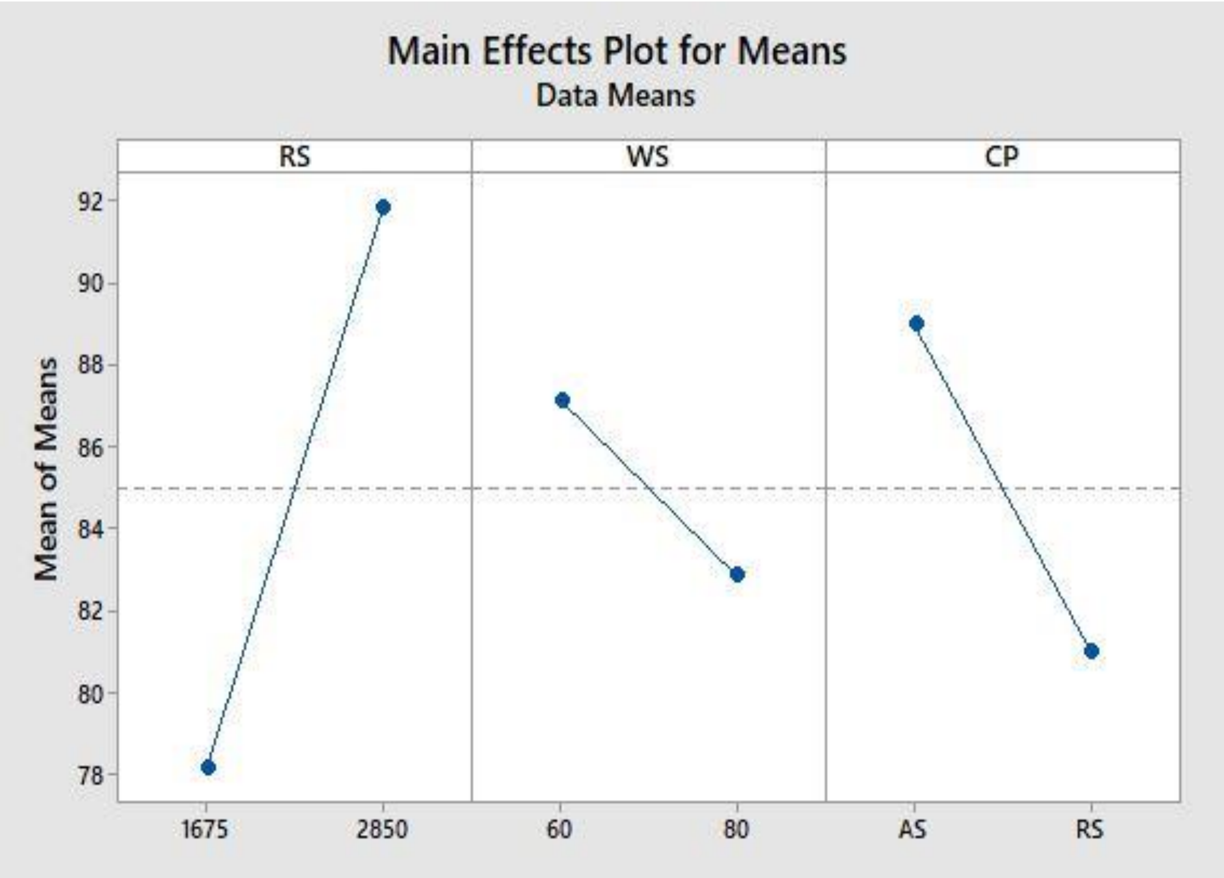


Figure 24: Mean for UTS

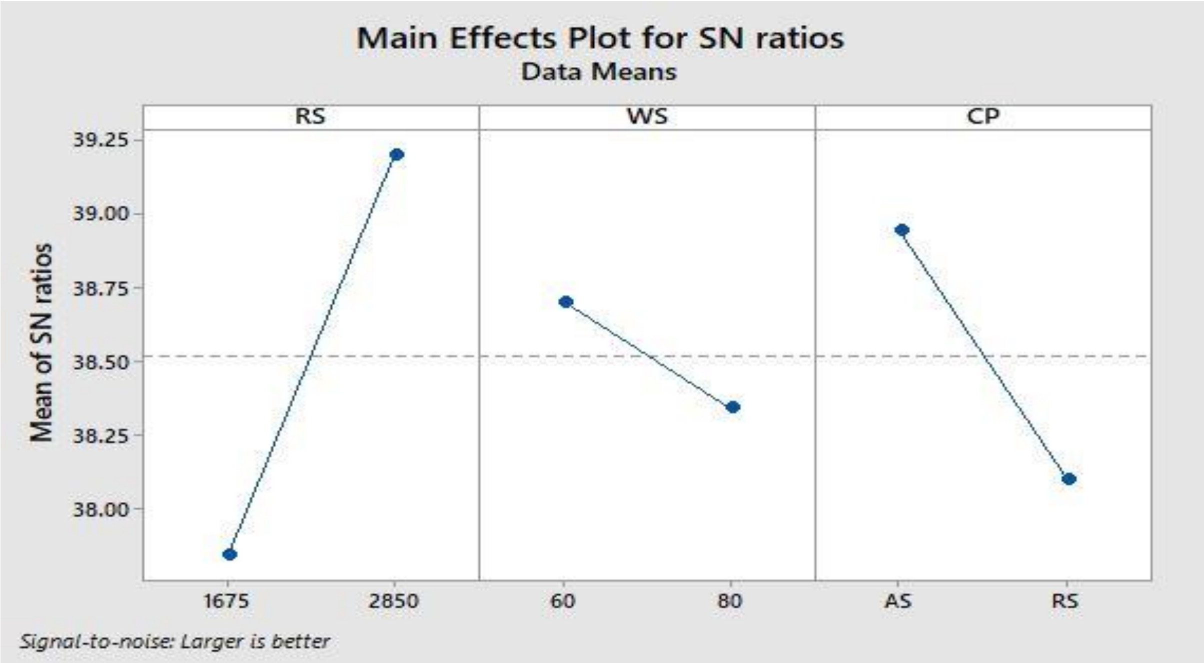


Figure 25: ***SN ratio for UTS***

The response Tables 8 & 9 are showing the calculated average values for signal to noise ratio and mean. The larger values are highlighted in both the tables. According to the data generated in a table, the optimal parameters for signal to noise ratio and mean were found as $X_2Y_1Z_1$.

4.1.3 ANOVA (Analysis of Variance)

ANOVA (Analysis of Variance) is basically a statistical tool implemented to evaluate the influence of input parameters on their corresponding responses. In order to check the influence of each parameter, this study takes into an account RS, WS and coupons position (both advancing and retreating side) specified by (CP) as control factors and UTS is treated as response. The largest value of F and SS will indicate that respective factor having major contribution towards generating higher value of response.

Table 10: ***ANOVA of means for UTS***

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
RS	1	**376.61**	**40.68%**	**376.61**	**376.61**	**3.92**	**0.119**
WS	1	36.51	3.94%	36.51	36.51	0.38	0.571
CP	1	128.40	13.87%	128.40	128.40	1.34	0.312
Error	4	384.35	41.51%	384.35	96.09	-	-
Total	7	925.87	100.00%	-	-	-	-

Table 10 is showing that rotational speed (RS) is a significant factor playing major role in enhancing the weld tensile strength because F and SS values are greater than rest of the factor values. Hence, the order of significance is rotational speed followed by coupons position and welding speed.

4.1.4 Strength Prediction and Confirmation Test

The optimal parameters on which maximum response was recorded were taken for calculation of UTS prediction value. The value generated by Taguchi predicted results was 98.01 MPa. In order to validate the predicted result value, I-shaped samples were prepared for conducting three tensile tests using the optimal parameters. The confirmation test average value was 104 MPa.

4.2 Discussion on Tensile Strength

Tensile testing of all the 8 samples and base material samples were performed in traverse direction because I-Sample was extracted perpendicular to the direction of welding. The experimental results showed that ultimate tensile stress for base materials 6061-O and 5251-H22 were 128.85MPa and 145.99MPa. These values are found greater than the ultimate tensile strength of those samples on which experiments have been performed. It is clear from the experimental results that the optimal parameters for the current study are 2850 rpm, 60 mm/min when 1.6mm thick 5251-H22 is at advancing side (AS).

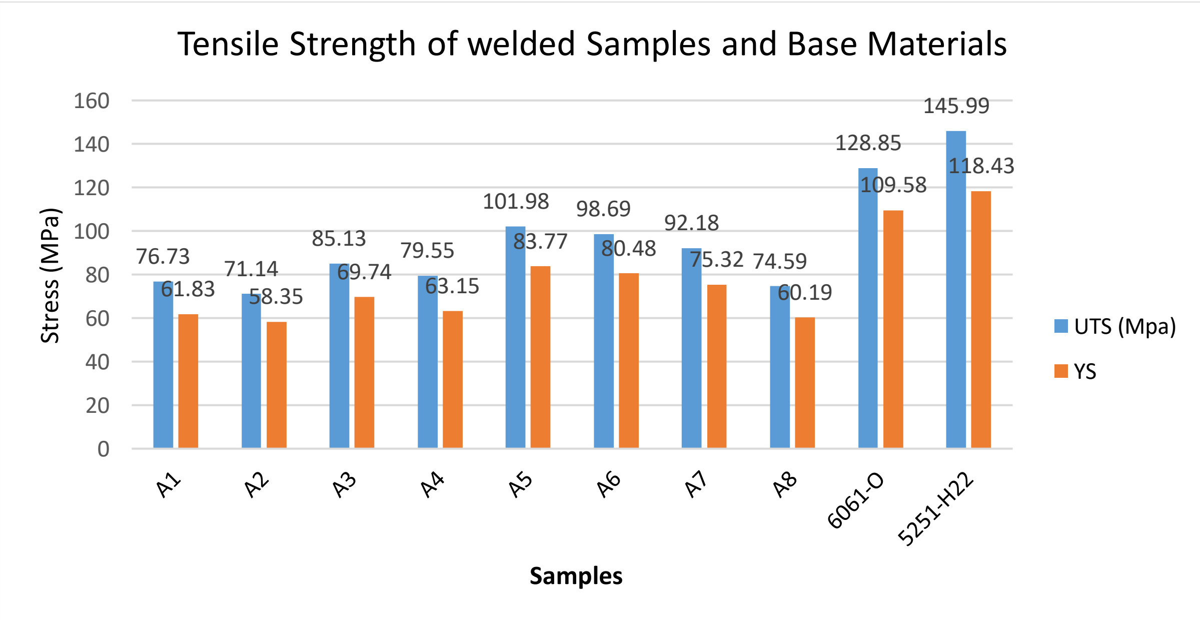


***Figure 26:** Bar chart for UTS and YS*

Stress strain data obtained from tensile curves have been plotted in the form of bar chart as shown in a Figure 26 where all the welded samples are denoted from A1-A8. According to the data all the samples are deformed plastically and high tensile stress is recorded on rotational speed 2850 rpm and welding speed 60 mm/min for sample A5. This is due to efficient generation of heat and flow of material inside weld line. It can be observed that there is low tensile strength recorded for samples A1, A2 on low rpm and traverse speed for both AS and RS and for sample A8 on high rpm when 6061-O is at AS. This is due to the absence of tilt angle, formation of flash and tunnel. Also, the depth of square pin is more closed to 6061-O thickness, therefore there is enough penetration and softening of material to the root of the weldment for 6061-O alloy rather than 5251-H22. The maximum strength achieved on optimal parameter constitutes 80.71% to the strength of 6061-O and 71.23% to the calculated strength of 5251-H22. It can also be noticed from the analysis that tensile strength values are recorded higher when 5251-H22 is placed at AS for all the parameters.

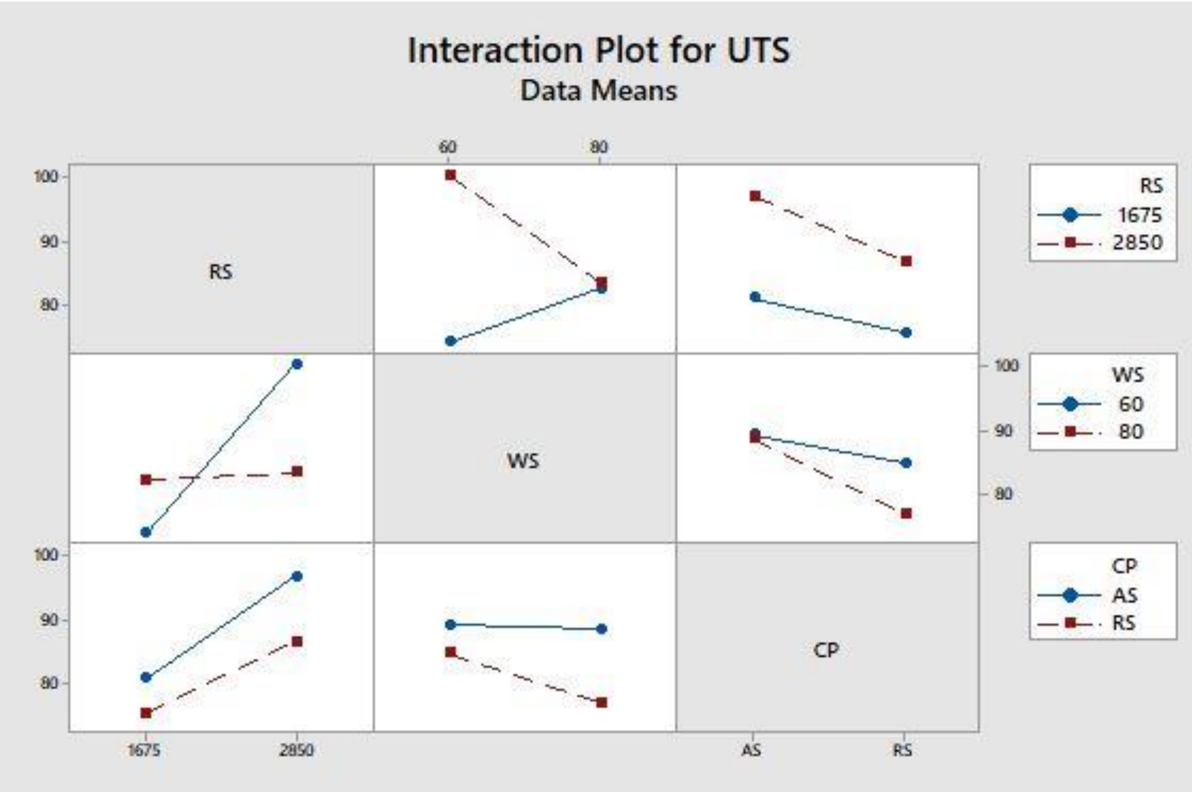


Figure 27: ***Combined effect of RS, WS and CP on UTS***

The combined effect of parameters on UTS showing in Figure 27 represents that by increasing RS and decreasing traverse speed the Tensile strength of samples is increasing. In comparison of welding speed and coupon position with rotational speed, it can be observed that 60mm/min and AS have more effect on UTS at 2850 rpm whereas rotational speed and coupon position versus welding speed 2850 rpm and AS are more dominant at 60 mm/min to increase the tensile strength. Therefore, it is clear from the graph that welded samples gained more strength on

2850 rpm and 60 mm/min and AS is dominating rather than RS for all the welded samples after rotational speed effect among three parameters.

4.3 Microstructure

Microstructure analysis is performed on digital microscope to examine the impact of FSW parameters on welded joints formed by dissimilar base materials. For this reason, the weld zone is classified into different regions named as NZ, HAZ and BM. The microscopic sample contained in a Bakelite mounting is investigated under digital microscope and value of grain size for all experiments have been recorded with 400X magnifying lens.

As per the analysis the average size of grain recorded in NZ is 8 µm. The average grain size recorded in HAZ is 18 µm. This is due to the generation of high heat and recrystallization phenomenon in NZ. The temperature generated in HAZ during experimentation was found lower than the temperature generated in NZ. As moving away from the weld line, this temperature drops causing increase in the size of grains. The size of grains recorded for base

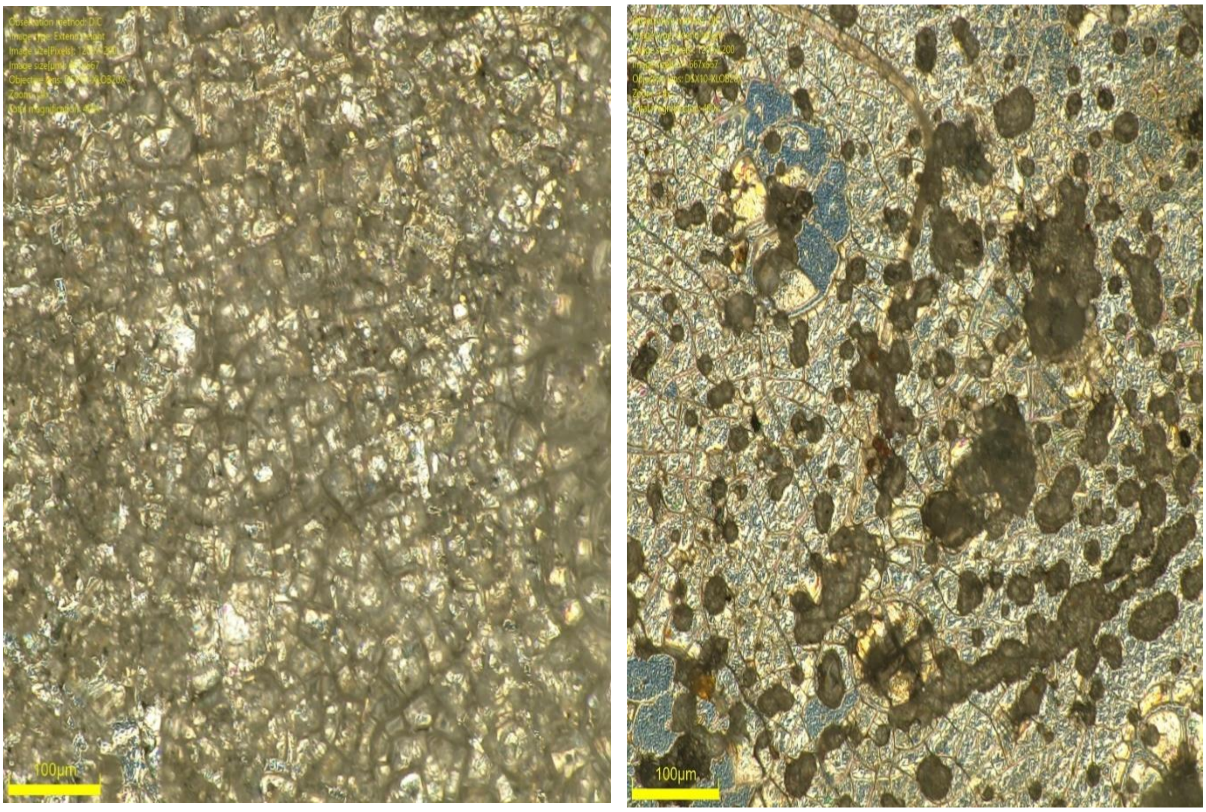
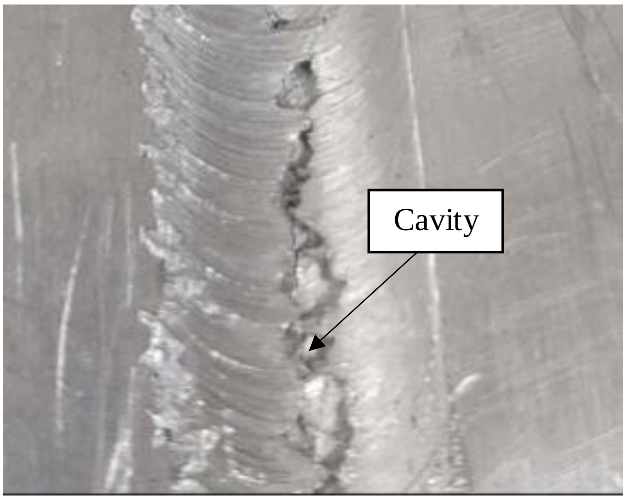


***Figure 28:* (a) Base Metal 5251 H-22 (b) Base Metal 6061-O**

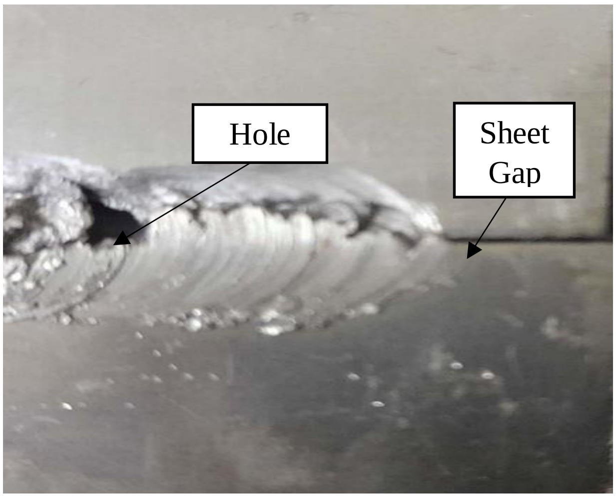
materials 6061-O and 5251-H22 are 39 µm and 32 µm respectively. The micrographs of base materials are shown in a Figure 28.

4.4 Discussion on Microstructure

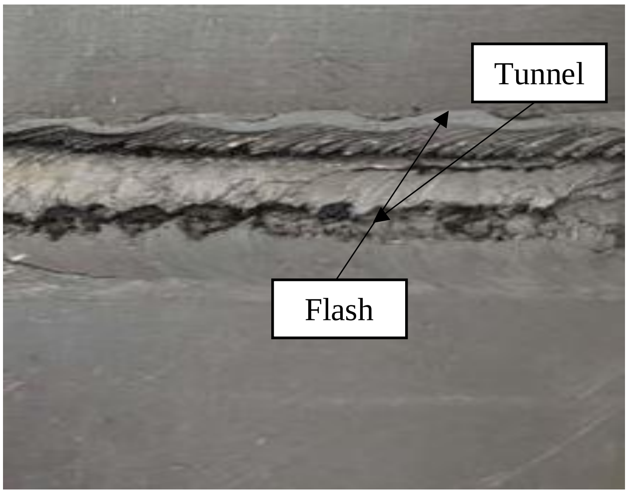
The square shaped tool probe produces smaller size grains and play major role in enhancing quality of welded joint in SZ due to its capability for high deformation and frequency (Yasir et al.). Therefore, the shape of tool probe remained fixed throughout the experiments. As the size of grains are smaller, fine and equiaxed in nugget zone (NZ) for all the samples other than base material (BM), Thus grain size varies with the amount of heat generated in a weldment and dependent on selected welding parameters. However, there are certain parameters on which defective joints were produced. This is due to formation of cavities, inappropriate heat generation and absence of tilt angle. In sample A1 and A2 cavities can be seen at low rotational and traverse speed which is a solid proof of improper consolidation of soft material in NZ because of low temperature generation.



A1



A2



A8

Figure 29: ***Defective samples***

In the same way flash and tunnel are caused due to high temperature and un trapped material as the tool force acted on one side in the absence of tilt angle for sample A8 when low strength alloy 6061-O is on AS. These are the samples welded at high rotational speed with high traverse speed and low rotational speed with low traverse speed and are found defective because of improper flow of material and high thermal effect. The images of defective joints are shown in Figure 29. On making a comparison between grain values for NZ and HAZ, it was found that 2850 rpm and 60 mm/min are the best parameters with higher thickness base material 5251-H22 at AS. The experimental investigation for microstructure showed that grain size decreases by increasing the tool RS and increases by increasing WS. The average micro hardness recorded in NZ and HAZ on 80mm/min is less than the average micro hardness recorded on 60 mm/min. The optimal micrographs obtained on the selected parameters for the samples are shown in a Figure 30.

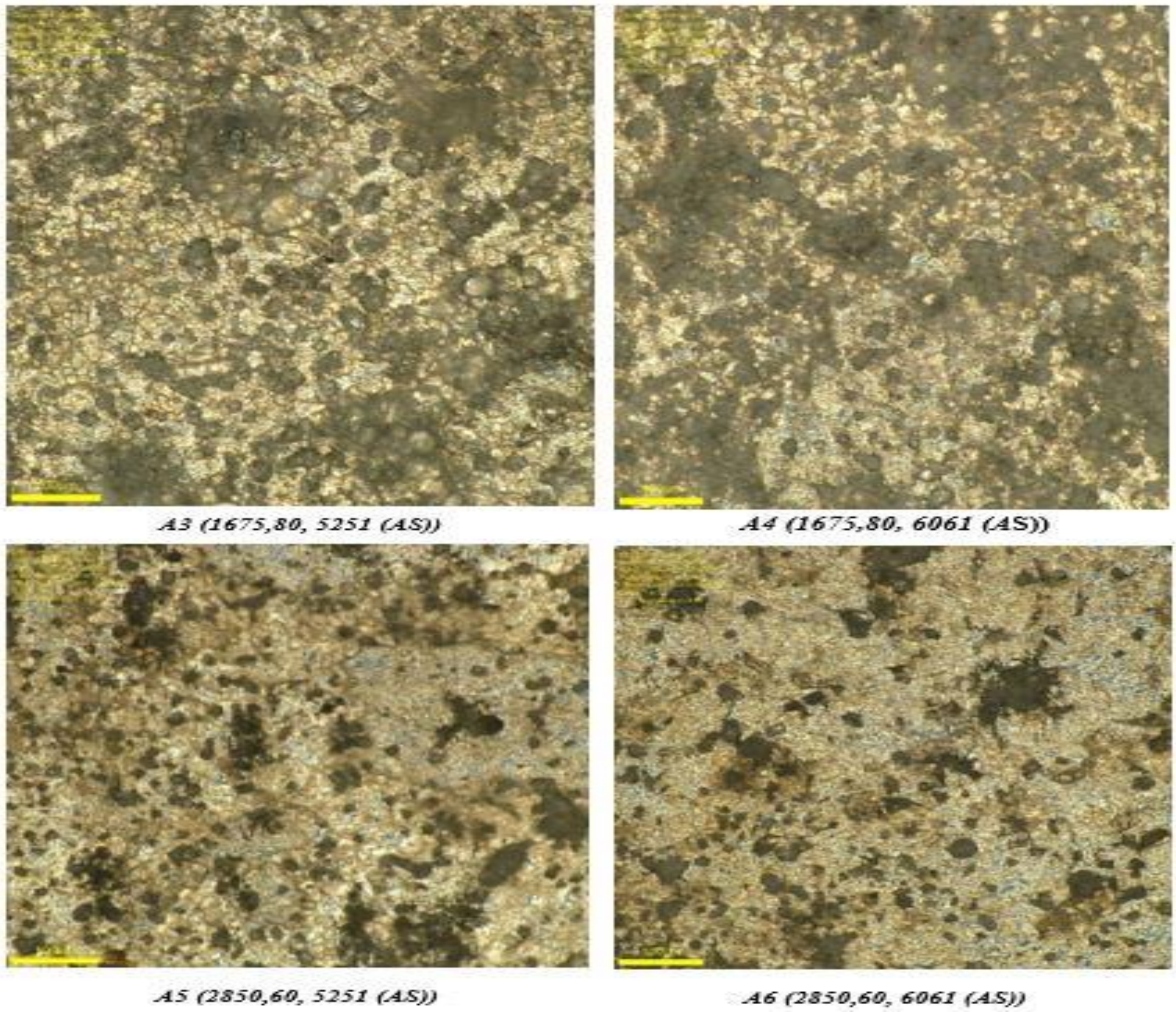


***Figure 30:* Optimal micrographs: A3,A4,A5,A6**

4.5 Micro Hardness

The micro-hardness is conducted on a mounted sample after grinding and polishing across the zones of weldment and base material. The experimental values obtained in NZ, HAZ and BM showed that the micro hardness of NZ was greater than the base material (6061-O & 5251-H22). However, in HAZ region largest value of average micro hardness determined was on advancing side as this side experienced elevated temperature. This phenomenon is due to recrystallization of previous grains into more fine grains as per the Hall-Petch effect. The reason behind this phenomenon is formation of small grains and more grain boundaries in NZ while moving away from NZ the size of grains started increasing from HAZ to BM which ultimately reduced hardness. The result can be viewed in a graph as represented by Figure 31 below.

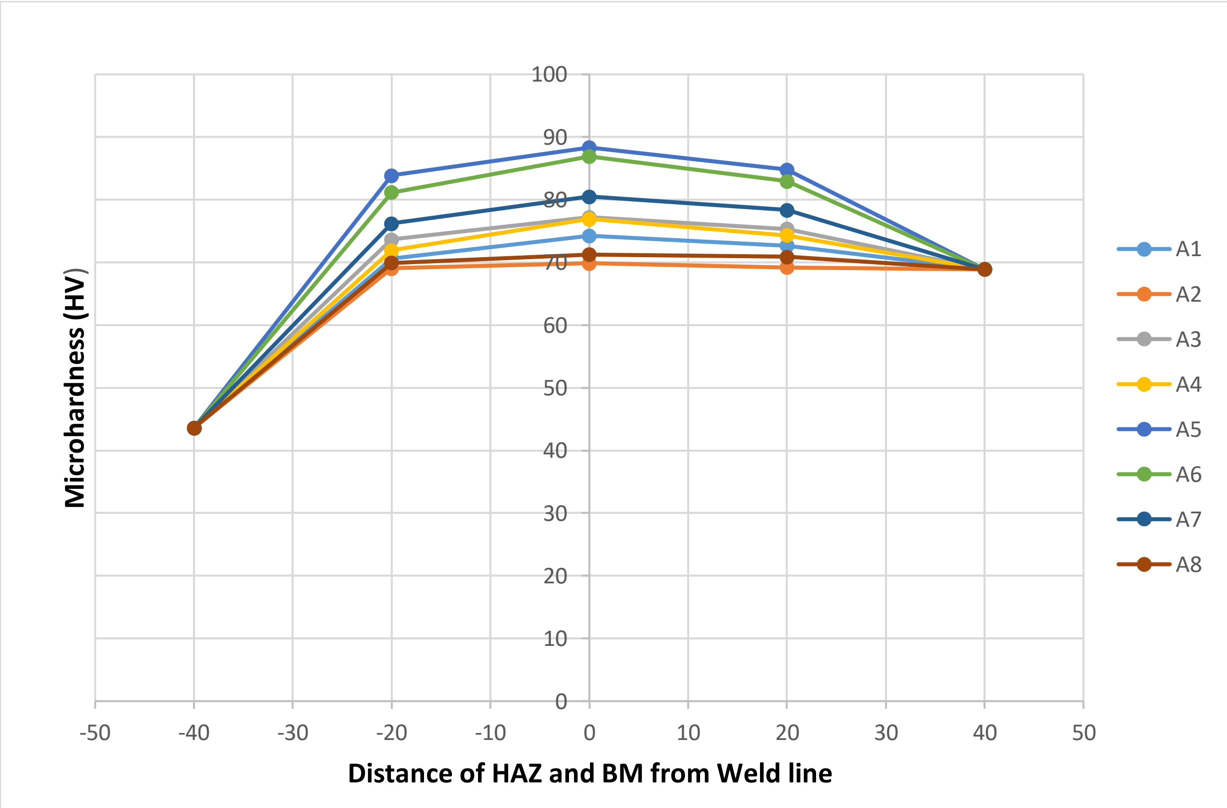
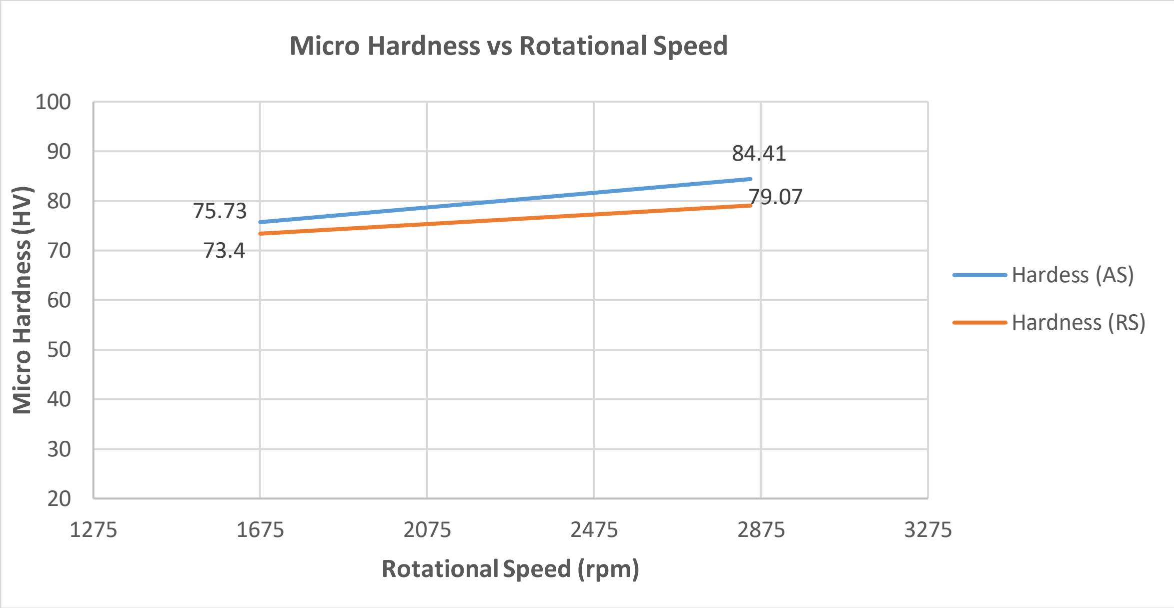


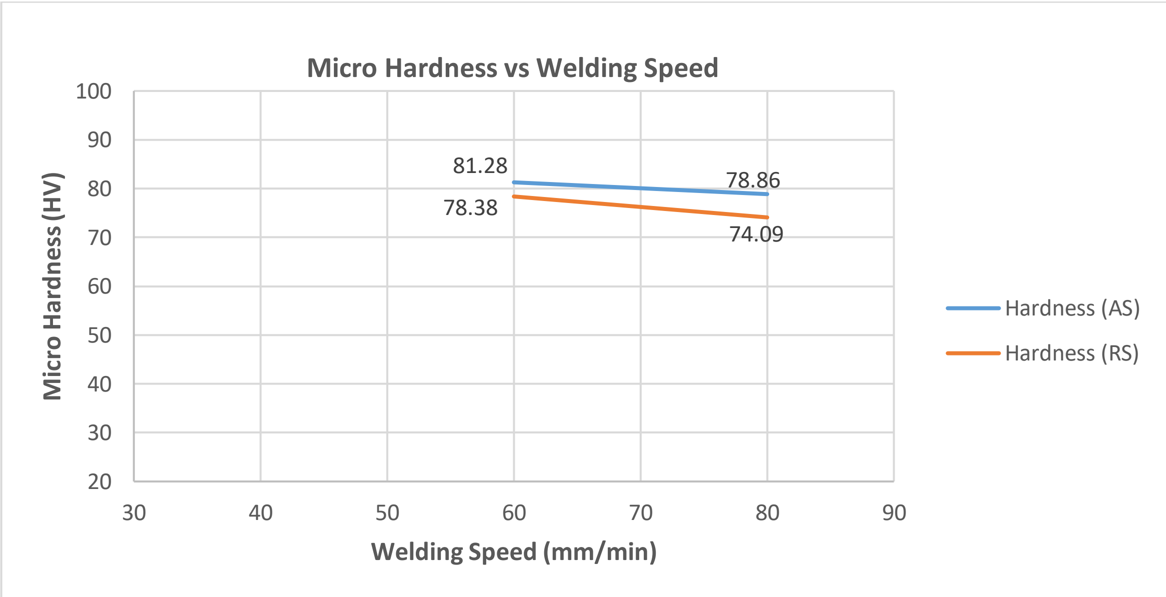
Figure 31: ***Micro Vickers across weld zone and BM***

4.6 Discussion on Micro Hardness

The impact of rotational speed and traverse speed on micro hardness has been investigated and plotted as shown in a Figure 32. This is done by taking mean of each hardness value recorded in NZ on both sides of the samples (AS & RS) for the respective parameters.



(a)



(b)

***Figure 32:* (a) Rotational Speed Impact on Micro Hardness in NZ (b) Welding Speed Impact on Micro Hardness in NZ**

Figure 32(a) shows increasing trend of micro hardness for both advancing side (A.S) and retreating side (R.S) on increasing rotational speed. The highest value of average micro hardness is recorded as 84.41 HV for 2850 rpm on AS. On the other hand, there is a decreasing trend in micro hardness on increasing WS from 60mm/min to 80mm/min. The highest value of average micro hardness is recorded as 81.28 HV for 60 mm/min. However, micro hardness values are found greater for both rotational speed and welding speed when 5251-H22 is at AS. This comparison can be viewed in Figure 32(b).

CHAPTER 5: CONCLUSION

This research work has been conducted on dissimilar alloys of aluminum 6061-O and 5251-H22 possessing different thicknesses using square shaped pin and mild steel back plate. The core findings of the study are concluded on the basis of experimental results which are as follows:

1. All the trials were performed as per the Taguchi L8 OA and each experiment was repeated three times so that error in measurements can be minimized.
2. The dog bone shaped samples were thermally treated (T6 treatment) before conducting tensile tests and ANOVA was performed for the samples to determine the maximum impact of parameter (rotational speed, traverse speed, coupons position) on the response (weld strength)
3. The results showed that the optimal parameters were 2850 rpm and 60 mm/min and the effect of RS on weld strength was more than any other parameter.
4. It was found that the size of grains in the NZ was found smaller than HAZ and BM on 2850 rpm and 60 mm/min. This is due to more heat generation and proper consolidation of stir zone material with the pin. This grain size started increase as moving away from SZ of the weldment to BM which caused reduction in hardness.

CHAPTER 6: FUTURE RECOMMENDATION

In the light of current investigation, further research work must be carried out in the domain of FSW process:

1. The experimental work should be performed on the sheets with similar thickness using same parameters considered in this study.
2. The effect of different tool material and tool probe shape should be studied on the same sheets opted in this research work.
3. This study can be performed either by changing the surroundings (under water FSW) or by applying pre-heated coupons for the experiments.
4. Numerical investigation needs to be done to determine the behavior of parameters considered in this study on final weld quality.

ANNEXURE

Table 11: CNC Milling Specs

CNC Milling Machine Specification	
Model	MV-1060
Max travel range of X/Y/Z axis	1220/680×680
Max loading capacity	1000 Kg
Max traverse of X/Y/Z axis	30 m/min
Magazine tool capacity	24 pcs
Max spindle speed	8000 rpm
Automatic tool change system	Hydraulic System

Table 12: CNC EDM Wire Cut Specs

CNC EDM (Wire Cut)	
Model	DK 7732
XY travel	320×400 mm
Max cutting capacity	380×285 mm
Max job thickness	3 inches
Max cutting speed	≥300mm^2/min
Capacity of tank	60L

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