Friction Stir Welding of dissimilar aluminum alloys

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June, 2018

Declaration

I certify that this research work titled "*Friction Stir Welding of dissimilar aluminum alloys"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Abstract

Friction Stir Welding (FSW) is the most important process developed in the field of welding during last decade of twentieth century. FSW is Solid State welding technique which allows metals to be welded below melting temperature. Heat input required for FSW is very less as compared to other welding processes such as TIG, MIG etc. The mechanical properties of weld produced by FSW are not highly different from its base metals. FSW technique is applied to various alloys of aluminum and high quality weld is obtained. Joining aluminum alloys of different series is difficult task due to difference between properties but FSW has enabled them to weld with good results. In FSW rotating tool comprising of probe and shoulder plunges into workpiece and traverse along a weldment line. Heat is generated both due to friction between tool shoulder and workpiece and plastic deformation. This study applies the Taguchi method to investigate the relationship between the ultimate tensile strength, Impact Strength and process variables in a friction stir welding of joining dissimilar 6061-T651 and 5083- H321 aluminum alloys. The effects of various welding parameters including Welding Speed, Traverse speed and Tool probe shape were studied. The experimental results show that the Traverse speed is most influencing parameter in both the quality characteristics. Other important finding is that the heat input is found to be in strong relation with tool welding speed. Optimal Welding speed, Traverse rate and tool probe shape for both Tensile Strength and impact strength are 1000 rpm, 10mm/min and hexagonal probe respectively.

Key Words: *5083-H321 Al alloy; 6061-T651 Al alloy Process parameters; Taguchi method; optimization, Mechanical Properties.*

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List of Abbreviations

TWI	The Welding Institute
NASA	National Aeronautics and Space Administration
FSW	Friction Stir Welding
TIG	Tungsten Inert Gas
MIG	Metal Inert Gas
BM	Base Material
SSW	Solid State Welding
HAZ	Heat Affected Zone
TMAZ	Thermo- Mechanically Affected Zone
WN	Weld Nugget
ANOVA	Analysis of Variance
EDX	Energy
DOF	Degree of Freedom
EDM	Electric Discharge Machining
ASTM	American Society for Testing and Materials

CHAPTER 1: INTRODUCTION

The research work has been carried out to find optimal process parameters for friction stir welding of aluminum butt joint. This optimization process can be divided into two parts. First stage includes process of defining problem and carry out experimentation on specified set of aluminum alloys according to some calculated way. At second stage, interpret the obtained results and analyze using some statistical software package. The ultimate goal of research is to find the optimal set of process parameters necessary to produce good quality sound weld.

1.1 Background, Scope and Motivation

Friction Sir welding belongs to Solid state welding family, which was developed in 1991 by Wayne Thomas at The Welding Institute (TWI). The research at TWI was funded by the National Aeronautics and Space Administration (NASA) for developing a welding method that would not add further mass to orbital spacecraft and this lead to development of FSW. In FSW the base material does not reach the melting point during welding producing good quality weld with less risk of welding defects such as cracking, voids and porosity which are often related with fusion welding. Other benefits of FSW includes the capability to make welds in "hard-to-weld" materials and in dissimilar metals.

FSW scope is not limited to some specific field as it is successfully employed in aerospace, automotive, electronics, ship building, etc. industries [1]. Similarly, FSW is not limited to some specific materials, as it can be used to join both similar and dissimilar materials with good results. Aluminum alloys being extensively used in manufacturing different components in almost all of the industries, so need is to weld it in most economical way.

FSW of Aluminum has been studied with different alloys, but still there is great scope of carrying out research in this field.

1.2 Aim and objectives of research

This research focuses on butt joint of AA6061-T651 to AA5083-H321 sheets through FSW. Taguchi technique is used for optimization of process variables at very low cost [2]. Finally, testing and characterization of FSWed sheets, joined at different process parameters was carried out to find optimal parameters.

The main objective of research includes:

1. Study effect of important process parameters mainly rotational speed (ω, rpm), Tool shape (Flat on cylinder type) and tool traverse speed (v, mm/min) affecting FSW.
2. Tensile testing of welded sheets.
3. Impact testing of welded parts.
4. Analysis of Variance
5. Microstructure analysis of base metal (BM) and welded sheets.
6. Hardness profiling of cross-section of welded parts.

1.3 Introduction to welding techniques

Welding is a process in which two or more material parts are permanently joined at contacting surface by application of either heat or pressure. In layman terminology, a weld is made when two or more isolated pieces of material to be fused combine and form one piece. Welding process can broadly be classified into three categories as given in figure 1. Welding can be accomplished mainly by following methods:

1. Heat alone i.e. with no pressure
2. Pressure alone i.e. with no external heat
3. Combination of both heat and pressure

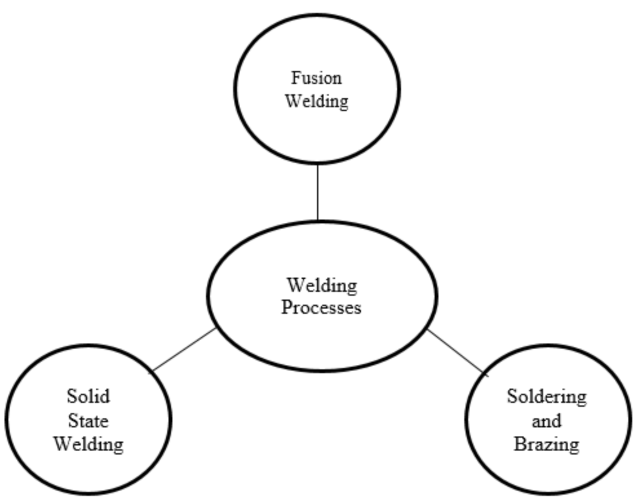

Figure 1: Classification of Welding Processes

Filler material can/cannot be used for joining materials by welding process. Assembly of two or more components joined with the help of welding is called weldment. Welding is generally associated with metal parts, but same can also be applied to join other material such as plastics with good results.

1.3.1 Fusion Welding

Welding Processes in which heat is used to melt the base metals are known as Fusion welding [3]. In many of the fusion welding processes, strength of the weld is achieved by using filler metal, which is added to the weld pool during welding process. A fusion-welding operation in which no filler metal is added is referred to as an autogenous weld [4]. In these processes changes in microstructure, phase transition and mechanical properties occur due to involvement of high temperatures [5]. Fusion welding can further be classified into three following categories.

1. Gas welding:
    - Oxyacetylene welding
2. Arc welding:
    - Shielded metal arc welding
    - Gas–tungsten arc welding
    - Submerged arc welding
    - Electroslag welding
    - Flux-cored arc welding
    - Plasma arc welding
    - Gas–metal arc welding
3. High-energy beam welding:
    - Laser beam welding
    - Electron beam welding

1.3.2 Soldering and Brazing

Joining of two different/similar metals using a filler material into the joint in liquid state and allowed it to solidify. One of the important feature of these processes is that a permanent joint is produced without melting of parent work pieces material. Primarily three steps involved in solder/brazing process which are as follow:

1. Suitable heat source is used to heat the plates that are to be joined.
2. Placing and then melting of solder/brazing materials tailed by heating to the molten state.
3. Molten filler metal is filled between the faying surfaces of the components to be joined by capillary action and then solidifying afterwards which results in a joint.

Filler metal used in soldering system called solder (alloy of lead and tin), has low melting point (183-275 ^{0}C generally than 450 ^{0}C). Filler metal (alloys of Al, Cu and Ni) used in Brazing system uses comparatively higher melting point (450 -1200^0 C) [4]. Generally, brazed joints provide better strength than soldered joints. Accordingly, for higher load conditions brazed joints are used than solder joint [6]. Soldering is mostly used for joining electronic components whereas Brazing is commonly used for joining of tubes, tipped tool, pipes and wires cable.

1.3.3 Solid-State Welding

Solid state welding is a group of welding processes which produces joint at temperatures principally below the melting point of the base materials being welded. Time, temperature, and pressure are basic parameters involved in SSW. The metals being joined retain their original microstructural and mechanical properties without problems related to heat-affected zone due to base metal melting. Few SSW types are given below [7, 8]:

1. Diffusion Welding
2. Explosion Welding
3. Friction Welding
4. Forge Welding
5. Hot Pressure Welding
6. Roll Welding
7. Ultrasonic Welding

1.4 Introduction to welded joints

A joint is defined by The American Welding Society as "the manner in which materials fit together"[4]. Factors that affect the choice of edge preparation are material, thickness, welding distortion, welding process, extent of penetration required and cost. There are five basic types of weld joints shown in Figure 2 [9]:

1. Corner joint
2. Butt joint
3. T-joint
4. Edge joint
5. Lap joint

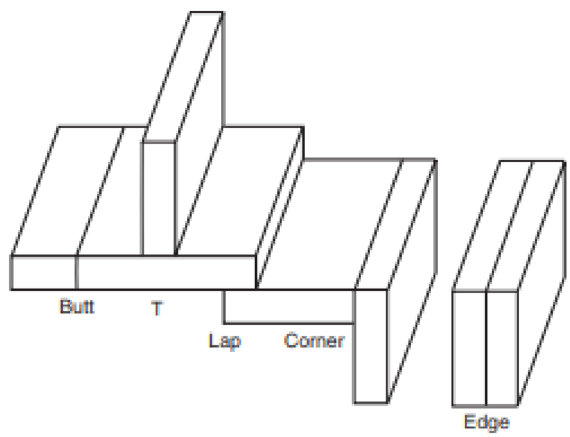

Figure 2: Different types of welded joints [9].

Butt joint configuration is used where high strength is required. They are most reliable and can bear stresses better than any of the other type of welded joint. Butt joint weld is further classified into Bevel-groove, V-groove, J-groove, U-groove, Flare-V-groove and Flare-bevel-groove [10]. The current research is carried out on solid state welding (Friction Stir Welding) and on butt joint configuration.

1.5 Research layout

The research has been carried out in an organized manner. Figure 3 shows the complete scheme which was followed in order to accomplish/complete the research. Research started with decision of alloy set on which study had to be carried out followed by alloy procurement. Once the verified alloy had been procured the experimentation was carried out according to OA made. Testing and compiling results are last phase of research.

Figure 3: Research Scheme

1.6 Thesis Overview

This thesis has been divided into chapters discussing different aspects of research that have been carried out. The arranged of chapters is in the same pattern as experimental procedure is carried out. The brief framework is given in text below.

1.6.1 Chapter 2: Literature review

This chapter describes key findings from the literature review, particularly the advancement that has been done in joining of aluminum sheets through FSW. Effect of process parameters on different micro-structural and mechanical properties during FSW has also been discussed.

1.6.2 Chapter 3: Taguchi methodology

Chapter 4 discusses in detail about the various tools and technique used for process optimization, overview of Taguchi optimization technique and how Taguchi Technique can be applied on FSW.

1.6.3 Chapter 4: Experimental Methodology

This chapter discusses the experimental methodology adopted for FSW study. The main topic discussed are materials used, welding tools, welding fixture setup, Experimental plan, Impact testing, tensile testing, and hardness profiling and microstructure analysis.

1.6.4 Chapter 5: Results and discussion

Chapter 6 explains the results obtained from tests performed, the effect of process variables on different mechanical properties and material microstructure of butt joint of aluminum AA6061 and AA5083 sheets formed through FSW.

1.6.5 Chapter 6: Conclusion

This chapter concludes this research thesis and future recommendations in which research can be further carried out are provided.

CHAPTER 2: LITRATURE REVIEW

Friction Stir Welding is type of SSW technique in which coalescence is attained by the heat generated due to friction between two surfaces that are been joined. There is no noticeable melting of base material during friction stir welding, as is the case with fusion welding. A FSW run can mainly be distributed into three stages [11].

1. Tool plunging and dwell
2. Traverse along weldment line
3. Tool retraction

The localized heating results into softening of material around the pin. Combination of both tool rotation and traverse motion leads to movement of material from the leading side of the pin to the retreating side of the pin. Joint is produced in 'solid state' as a result of this process. During friction stir welding process, base material experiences intense plastic deformation at higher temperature, subsequently generating fine and equiaxed recrystallized grains [12-14]. Because of comparatively lower welding temperature, the properties of the welded zone usually have low distortion and has higher weld strength when compared to the welds produced from conventional welding methods [15]. Being Solid State welding process, FSW avoids noteworthy changes in microstructure and mechanical properties [16].

2.1 Friction Welding and Its Types

Friction Welding (FRW) process produces welded joint due to the compressive force contact of workpieces which can be either rotating or moving relative to one another. Friction is responsible for heat produced, which displaces material plastically from the joining surfaces [17, 18]. Some of the friction welding types are as follow[19]:

1. Rotary Friction Welding (Direct drive)
2. Rotary Friction Welding (Inertia)
3. Spin or Orbital Friction welding
4. Linear Friction welding
5. Friction Stir Welding
6. Friction Stud Welding
7. Friction Surfacing

In continuous drive Rotary friction welding, one of the two parts to be joined is rotated continuously by a motor and pressed against by a stationary component. In Rotary friction welding (Inertia), one component is held static whereas other part is connected to the rotating flywheel, as soon as the parts come in contact with each other the energy stored in the flywheel is converted into frictional heat, that is then responsible for coalesce of components. In Spin or Orbital friction welding both parts to be welded are rotated in the same direction and at the same speed. Linear Friction welding process consists of holding one component fixed with other part oscillate against fixed part under an applied load. In Friction Surfacing, coating material is used on the interface of the component to be welded. Coating material turns into a plastic layer due to application of frictional heat, which ultimately joins the components together after welded joint is cooled [19].

2.2 FSW and its Salient Features

FSW is achieved by using a non-consumable rotating tool. The tool is forced and traverse along a weld line of the components to be welded together. Material around tool gets softened along both of the components interface. Tool blends/stirs material from all the components around the interface to provide bonding [20]. Following are some of the salient features of FSW:

1. FSW Joints are more efficient due to reduction of cracks, distortions and porosity [21].
2. HAZ produced by FSW is considerably small due to low heat input needed to carry out process.
3. As no consumable electrode, shielding gas or filler material is required for FSW therefore it is one of the most economical welding process.
4. FSW can be applied to not only metals joining but also to polymers, composites etc. [13].
5. As low energy is required and no gas emission occurs during process, FSW is considered to be green and environmental friendly welding.
6. Surface finishing of the joints formed by FSW is relatively better than that produced by Fusion Welding as constant pressing force is maintained during the process.
7. It can be easily programmed for complex shape welds.

2.3 FSW Process Parameters

Process variables greatly affect the quality, mechanical and microstructural properties of the weld produced by FSW. Material flow pattern and temperature distribution during welding process are greatly affected by welding process parameters influencing the microstructural properties of material. [22]. Some of the factors that affects the post weld properties are given below [23].

1) Traverse rate
2) Rotation speed
3) Axial Force
4) Tilting angle
5) Advancing/ retreating side
6) Tool Geometry
    i) Probe Diameter
    ii) Shoulder Diameter
    iii) Probe Profile
    iv) Shoulder diameter to Probe diameter ratio
    v) Probe length

Frictional heat is directly linked to two main factors namely welding speed (tool rotational speed) and traverse rate (rate at which tool is being moved along weld line) [24]. For a constant traverse rates, a low tool rotational speed leads to formation of inner voids and defects since the frictional heat is not adequate to promote material flow. Increasing the tool rotational speed, these defects disappeared, but for very high tool rotational speed defects like inner voids, surface cracks and lack of bonding are initiated due to excessive expulsion of the material [25].

Tool tilt angle is another important parameter, a suitable tilt (usually 2º -5º) of the spindle against the direction of translation ensures that the tool shoulder holds the stirred plasticized material and move material from the front to back side of the tool probe [26, 27]. Table 1 shows process parameters and there influence on weld properties.

Table 1: Effects of main process variables in friction stir welding [28].

Sr. No.	Variables	Effects
01	Welding rotation speed	Frictional heat
02	Traverse rate	Heat control, Appearance
03	Tilting angle	Weld Appearance, Thinning of cross-section
04	Welding force	Frictional heat

2.4 FSW Tool

The tool welds the base material when come in contact with workpiece. Tool has two main purposes, firstly produces the thermos-mechanical deformation and secondly generation of frictional heating necessary for material stirring. The friction stirring tools consists of two main parts namely a pin (aka probe), and shoulder. Pin is responsible for thermos-mechanical deformation whereas shoulder of tool produces frictional heat. This frictional heat expands the zone of softened material [12]. The pin shape of the tool effects the flow pattern of material being plasticized hence affecting weld quality. Tool with optimized dimensions is necessary to produce sufficient heat required to achieve efficient stirring.

Tool Shoulder

Most of the heat is generated by shoulder hence the shoulder diameter of the tool is important for optimal weld. It grips on the plasticized materials and establishes the material flow pattern. Heat is generated both due to sliding and sticking whereas sticking causes material flow. For a good FSW joint, the material should be sufficiently softened for flow, the tool should have sufficient grip on the plasticized material [12].

Shoulder Surface

Broadly shoulder types can be classified into three type’s flat, convex and concave tool as shown in figure 4. FSW tool are produced with shoulders containing features which can enhance the volume of heat required for material to be plasticized by the shoulder, resulting in better stirring

[29]. FSW tool shoulders can contain features link grooves, ridges or knurling, scrolls and concentric circles [30].

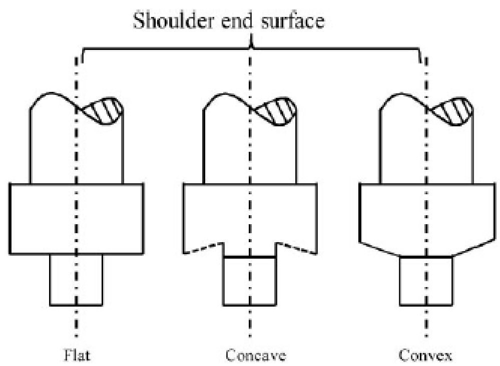

Figure 4: Shoulder types [27]

Tool Pin (Probe)

Flow pattern of plasticized material is affected by the probe shape of the tool. Optimizing pin (probe) geometry results in achieving more efficient "stirring". The effective stirring has two main benefits i.e. improved breaking and mixing of the oxide layer and more efficient heat generation. More heat generation enables usage of higher traverses rate with enhanced quality [31]. Some of the pin (Probes) shapes are given in figure 5.

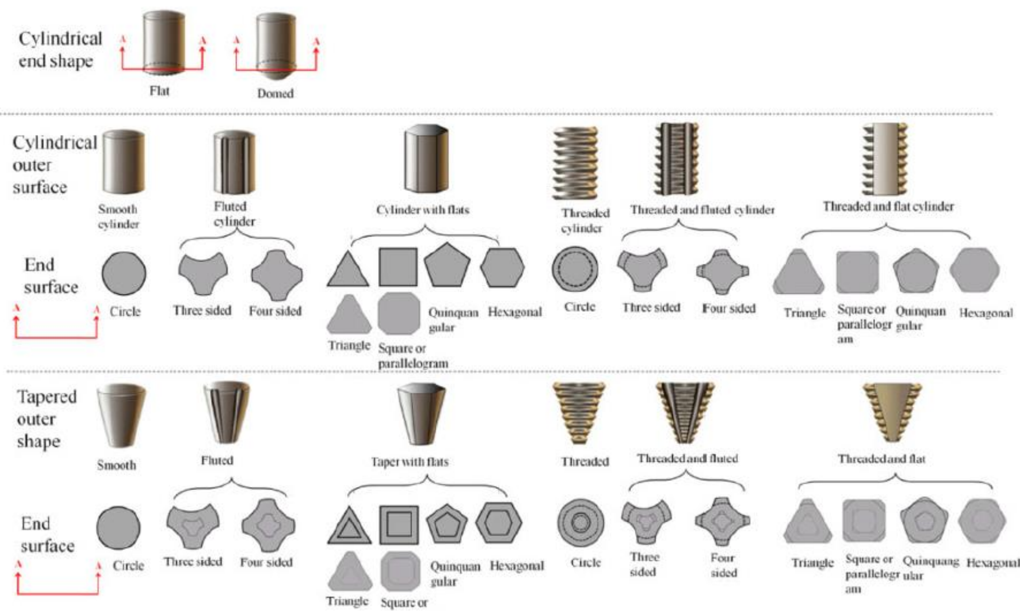

Figure 5: Different Pin Shapes [27].

Recent study on FSW tool design (Complex Motion Tools) have increased the tool travel speed, increased the volume of material swept by pin-to-pin volume ratio, and/or increased the weld symmetry. Many of these tool designs are focused on tool motion and not specifically on the tool pin design, although each type of complex motion have an optimal tool design [21].

2.5 Classification of FSW Zones

From the microstructural point of view, friction stir weld cross section can be divided into four different zones (see Figure 6). Naming convention might differ from source to source, but most commonly used names are used here in the following text [32].

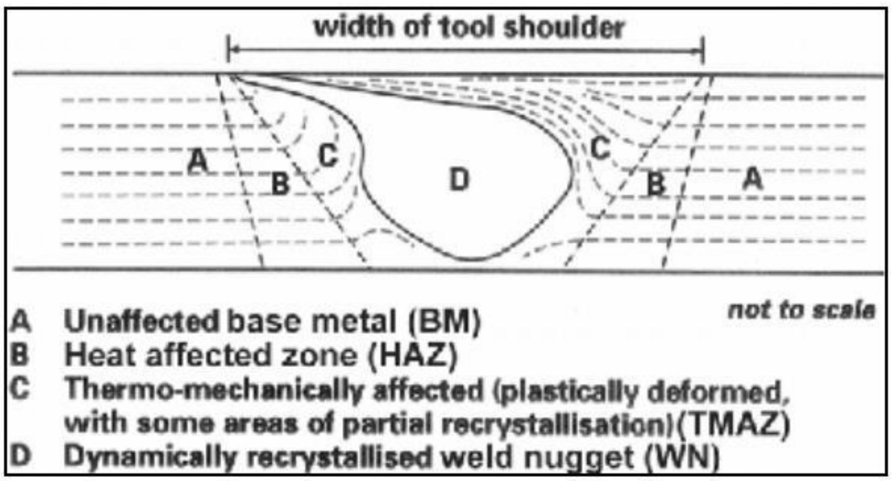

Figure 6: Distinct FWS'ed Zones [33]

Unaffected or parent (base) metal (BM)

This is the zone most distant from the weld line. Inspite of the possible temperature changes in the zone, the material exhibits the same microstructural and mechanical properties as it had before the welding process. Due to this reason it is also known as uneffaced zone.

Heat affected zone (HAZ)

Zone next to BM zone in the direction towards the weld center line. The temperature changes in this zone are significant to modify material microstructure and mechanical properties. But no plastic deformation occurs in this zone. The temperatures are relatively lower in HAZ as compared to that in TMAZ. The age-hardened aluminum alloys exhibits poorest mechanical properties in this region [21].

Thermo-mechanically affected zone (TMAZ)

Zone next to HAZ zone in the direction towards the weld center line is TMAZ. This zone experiences plastic deformation along with structural changes. In case of aluminum, this zone is often defined to be without recrystallization. Recrystallization in TMAZ occurs in some other materials such as copper, austenitic stainless steel, titanium and its alloys etc. [34].

Stir zone

Weld nugget is also given name as Stir zone, is the region in TMAZ where recrystallization takes place. Material in this region is heavily deformed and its dimensions roughly corresponds size of the probe. Equiaxed grains are produced within the stir zone that are comparatively smaller in size than the grains of parent material.

2.6 5XXX and 6XXX Aluminum alloy

5XXX: 5XXX contains Magnesium as major alloying element. Moderate-to-high-strength work hardenable alloys are formed when Magnesium is used as a major alloying element or with manganese. Alloys of 5XXX series possess good resistance to corrosion in marine atmospheres and good welding characteristics. [35].

6XXX: 6XXX series contain silicon and magnesium as a major alloying elements. Presence of silicon results in formation of magnesium silicide (Mg_2Si), thus making them heat treatable. 6XXX series alloys have machinability, corrosion resistance, good formability and weldability with medium strength. [35].

2.7 Past work on 5083-6061 alloys

Work has been done in past on 5083-6061. Few of the notable work in field is discussed in following text:

I. SHIGEMATSU el al. (2003) joined three different set of aluminum alloys i.e. 5083-5083, 6061-6061 and 5083-6061 using FSW. The tensile strength of the 5083-5083 joint was almost 97% of that of the parent material. Contrary to that, tensile strength of the 6061-6061 joint was almost 63% of that of the base material. The tensile strength of the 5083-6061 joint was almost equal to that of the 6061-6061 joint. At the 5083-5083 joining zone, due to grain refinement the hardness was slightly higher than the original value. However, in the 6061-6061 joining zone, the hardness dropped sharply. The hardness in 6061 depends on the precipitate distribution such as Mg_2Si. Low hardness was attributed to the re-solution of the precipitates during FSW [36].

A. Chandrashekar el al (2016) studied different tool pin profiles and its effect of welding on mechanical properties of AA5083. For 1000 rpm, Triflute tool was found to be the optimum tool, while at 600 rpm, tapered threaded tool profile was found to be the optimum tool, at 1000 rpm, tapered unthreaded tool profile also produced good results. Tensile strength increased by 48.62 % for Tapered unthreaded tool as the rotational speed was increased from 800 rpm to 1000 rpm, On the other hand, 65.77% decrease for Tapered threaded and 33.36 % increase for Triflute tool when speed was increased from 600 to 1000rpm. The decrease in tensile strength was found for tapered unthreaded tool profile and increase for triflute tool in comparison with other tool [37].

D. Devaiah el al (2018). Studied optimal FSW process parameters for dissimilar aluminum alloys (AA5083 and AA6061). The results indicated that tool welding speed, and traverse rates were most significant factors, whereas tool tilt angle was least significant among the three selected in affacting the mechanical properties of FSW aluminum alloy. The resulting optimal process parameters found by study were Welding speed at 1120 rpm, Traverse rate at 70 mm/min and tool tilt angle at 2^0, for the best multiple performance characteristics with minimum cost [38].

S. Jannet el al. (2013) studied the mechanical and metallurgical properties of MIG, TIG and Friction Strir Welded joints dissimilar AA 5083-O and 6061-T6 alloys and compared there properties. Post weld aging treatment greatly affects the tensile properties of AA 5083-O and 6061-T6 aluminum alloy welded joints. Post weld ageing treatment increase the tensile properties as compared to as welded joints condition. FSW joints showed good mechanical properties compared as compared to weld produced by TIG and MIG. Micro Hardness value was relatively lower in the HAZ and higher in the weld region i.e. nugget zone. Similarly micro hardness in weld region were high in case of FSW compared to MIG and TIG welding techniques. Moreover, the joints produced by FSW process show better mechanical and metallurgical properties compared to joints produced by TIG and MIG [39].

CHAPTER 3: TAGUCHI METHODOLOGY

The process of determining the best operating condition for any process is called optimization. Initially engineer makes hit and trial decisions with a hope to reach an optimal design. However, if there are many variables to be adjusted with certain constraints, the experience-based optimization cannot be able to identify the optimum design [14]. This give birth to complete different field called process optimization. Process optimization is the field of fine-tuning a process so as to optimize some given set of parameters while keeping all other parameters within their constraints. The most important aim of study is to reduce cost, enhance productivity and efficiency. Obtaining a valid, accurate model of the design problem is the ultimate goal in optimization.

3.1 Tools and technique used for process optimization

Various modeling, simulation, and process optimization techniques are used for finding the optimal process variables in the Friction stir welding. Detailed analysis has to be carried out to establish interactions between process parameters and weld properties. Following are some methods used for optimization of any process and its parameters [15].

1. Simulation
2. Genetic Algorithm
3. Fuzzy Logic
4. Artificial Neural Network
5. Finite Element Methods
6. Taguchi and ANOVA approach

Taguchi optimization approach has been used for Friction stir welding of dissimilar aluminum alloy sheets. Dr.Taguchi has given important statistical tool regarding total quality management. It enables us to design high quality system at very low cost.

3.2 Overview of Taguchi optimization technique

Traditional experimental design methods are too intricate and time consuming, hence not easy to use. A large set of experimental works has to be carried out if number of process variables are large. To resolve this problem, Taguchi suggested a specially designed scheme called the use of orthogonal array to study the entire parameter space with minimum number of experiments to be conducted [40]. Optimization problems are treated by Taguchi Method in two main domains namely.

1. Static Problems
2. Dynamic problems

Static problems deals with process, which has to be optimized having several control factors that directly affects the desired value of the response. Static problems are further divided into three further categories. Whereas in Dynamic problems product is to be optimized has a signal input which directly governs the output, this type of optimization involves determining the optimum control factor levels so that the "input signal / response" ratio is closest to the desired relationship e.g. accelerator pedal in cars.

In Static problems, Taguchi recommends the use of the Taguchi loss function to measure the quality characteristics that are deviating from the targeted response value [40]. The value of taguchi loss function is further converted into signal to noise (S/N) ratio. Mostly, Quality characteristics can be classified into three categories to analyze the S/N ratio.

1. Larger the better
2. Smaller the better
3. Nominal the best

3.3 Application of Taguchi Technique on FSW

The aim of the Taguchi technique is to minimize variations in weld strength even though noise is present in the FSW process. Taguchi method consists of a plan of experiments with an aim to obtain data in an organized way about the behavior of a given process [2]. Following are the steps involved Taguchi method:

3.3.1 Identify the main function and its side effects

Main function is actually Friction stir welding of AA6061 and AA5083 alloys. Side effects is variation in welding strength which can be due to any reason. At first place, it is necessary to pen down all the important factors that influence the welding. Out of these factors differentiate the noise and control factors. The “Factors” that affect FSW operation are listed in the table 2.

Table 2: Factors affecting FSW

Control Factors	**Noise factors**
Rotation speed	Machine Vibration
Traverse Speed	Variation in material
Tilting angle	Environmental Temperature
Axial Force	Machine backlash
Tool Geometry	Operator Skills and repeatability

After listing down all the noise and control factors, decisions has to be taken on the factors that significantly affect the response i.e. weld strength and only those factors are taken into account in constructing the orthogonal array for experimentation. All other factors other than the control factors are treated as Noise Factors [40].

3.3.2 Identification of the testing conditions and quality characteristics

Quality Characteristic: Ultimate tensile strength
Impact Strength

Work piece material: AA 6061-T651
AA 5083- H321

Welding tool: Tool Steel H13

Operating Machine: Milling machine

Testing Equipment: Universal Testing Machine
Charpy Impact machine
Micro Vicker hardness tester
Equipment for microscopy

3.3.3 Identification of the objective function

Objective Function in this case is **Larger the Better.**

S/N Ratio for Larger-the-Better. function: $\eta_j = -10 \log_{10}((1/n)\sum(Y_i)^2)$………………(1)

Where,

Y_i: quality characteristic of ith test

n: number of tests

3.3.4 Identification of the Control Factors and their levels

In order to conduct experiments control factors with their different levels are to be decided based on a previous research. The control factors with their levels are shown in table 3.

Table 3: Control factors and their levels

Level	R Welding Speed (rpm)	T Traverse Rate (mm/s)	S Probe Shape (Cylinder with flats)
Level 1	800	10	Square
Level 2	1000	20	Pentagonal
Level 3	1200	30	Hexagonal

3.3.5 Orthogonal Array Selection

In order to select an appropriate orthogonal array (OA) to carry out experimentation, the degrees of freedom are to be calculated. The same is given below:

Degree of Freedom (DOF) = Number of levels -1………………………(2)

For each control factor, DOF:

DOF for Welding speed (R)= (3 – 1) = 2

DOF for Traverse rate (T)= (3 – 1) = 2

DOF for Tools Shape (S)= (3 – 1) = 2

DOF assigned to the error (E)= 2

Total Degrees of Freedom: 8

Array size = 1 + Total Degree of Freedom…………………………… (3)

Array Size 1 + 8= 9

L9 array is the most suitable orthogonal array (OA) for experimentation

3.3.6 Conduct Experiment

Experimentation needs to be carried out with control factors and their levels as mentioned in table 3. The experimental layout L9 array with different values of the factors is shown in Table 4. Each of the experiment is repeated 3 times (27 experiments in all) to minimize variations that could have occurred due to the noise factors.

Table 4: Orthogonal array for experimentation

Experiment. No.	Welding Speed (R)	Traverse rate (T)	Tool Shape (S)
1	800	10	Square
2	800	20	Pentagonal
3	800	30	Hexagonal
4	1000	10	Pentagonal
5	1000	20	Hexagonal
6	1000	30	Square
7	1200	10	Hexagonal
8	1200	20	Square
9	1200	30	Pentagonal

Results obtained from experimentation with ANOVA analysis is discussed in chapter 4 and chapter 5.

CHAPTER 4: EXPERIMENATAL METHODOLOGY

This chapter discusses the experimental methodology adopted for current study. The main topic discussed are materials, welding tools and fixture, Experimental plan, Tensile testing, Impact testing, Hardness and microstructure analysis.

4.1 Material

In current research Aluminum AA6061-T651 and AA5083-H321 were used as base material. The Energy Dispersive X-ray EDX result of both above stated materials are shown in figure 7 and figure 8 respectively. The Base material was in form of cold rolled sheets with 6.2mm thickness. The dimensions of rectangular cut coupons were 150mm x 75mm. Cutting was carried out on CNC milling machine. Cutting Oil was used to ensure proper cooling, in order to avoid changes in material microstructure. Perpendicularity of edges were ensured and deburring of plate edges was carried out where required [23]. Acetone was used as cleaning agent for the cut rectangular coupons afterwards. The Chemical composition and Mechanical properties are given in Table 5 and Table 6 respectively.

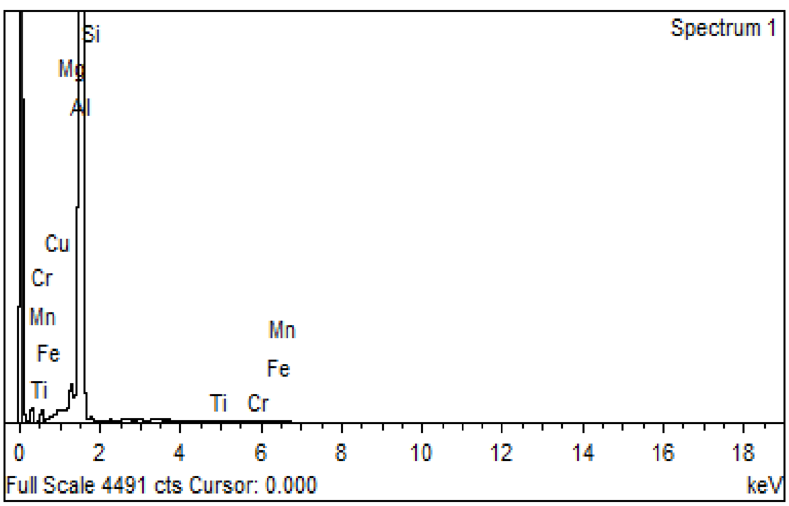

Figure 7: EDX Spectrum of AA6061

Table 5: Chemical composition (% weight)

Material	Mg	Mn	Si	Cr	Fe	Zn	Cu	Al
AA5083	4.18	0.52	-	-	0.29	0.35	0.30	Remaining
AA6061	0.76	-	0.62	0.41	0.56	-	0.13	Remaining

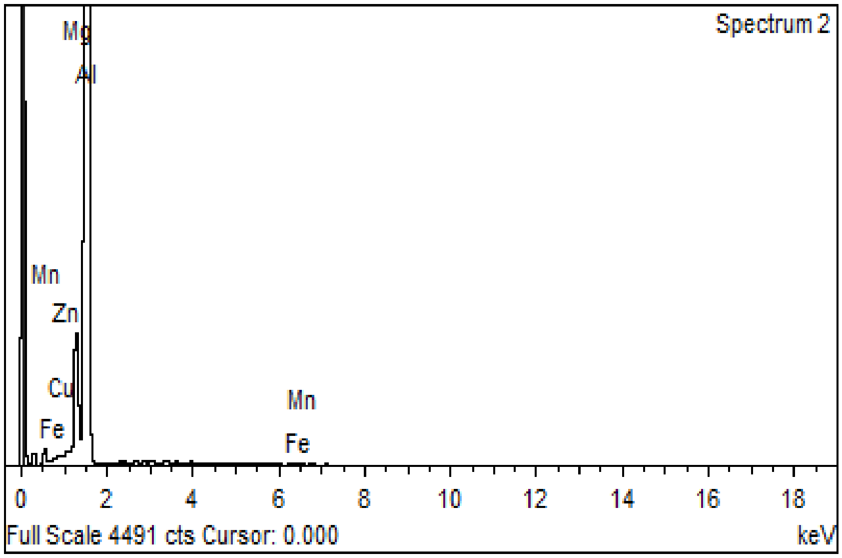

Figure 8: EDX Spectrum of AA5083

Table 6: Mechanical properties of alloys

Base Material	0.2% Proof strength (MPa)	Ultimate tensile strength (MPa)	% Elongation	Impact Strength (J)
AA5083	248	320	21	36
AA6061	260	326	23	34

4.2 Welding Tools and Fixtures

In present research optimization of family of tool (cylinder with flat type) is carried out. The tool used has concave type shoulder i.e. displaced is fed in cavity during plunging process. Three different tool probes are used namely square, pentagonal and hexagonal as shown in fig. 8. One of the primary purpose of research is to find out the optimum number of edges in cylinder with flat type probe tools. The number of edges affects the stirring pattern and heat generation. The tool is made of H13 tool steel which has good heat conductivity as well as mechanical properties. Manufacturing of tools were carried out with the help of CNC turning machine. In order to manufacture flats on circular probe, CNC milling machine was used. The tools were then heat treated to 50HRC to protect tools from wear. The basic dimensions of tool is shown in table 7 and complete manufacturing drawing is shown in figure 10.

Table 7: FSW Tool basic dimensions

Shoulder Diameter (mm)	Probe Diameter (mm)	D/d Ratio	Probe length (mm)	Shoulder type	Probe shapes
22	6	3.66	5.9	Concave	1. Square 2. Pentagon 3. Hexagon

CAD models of the tools indicating different probe shapes used are shown in figure 9. Surface area of probe increase from square to hexagon.

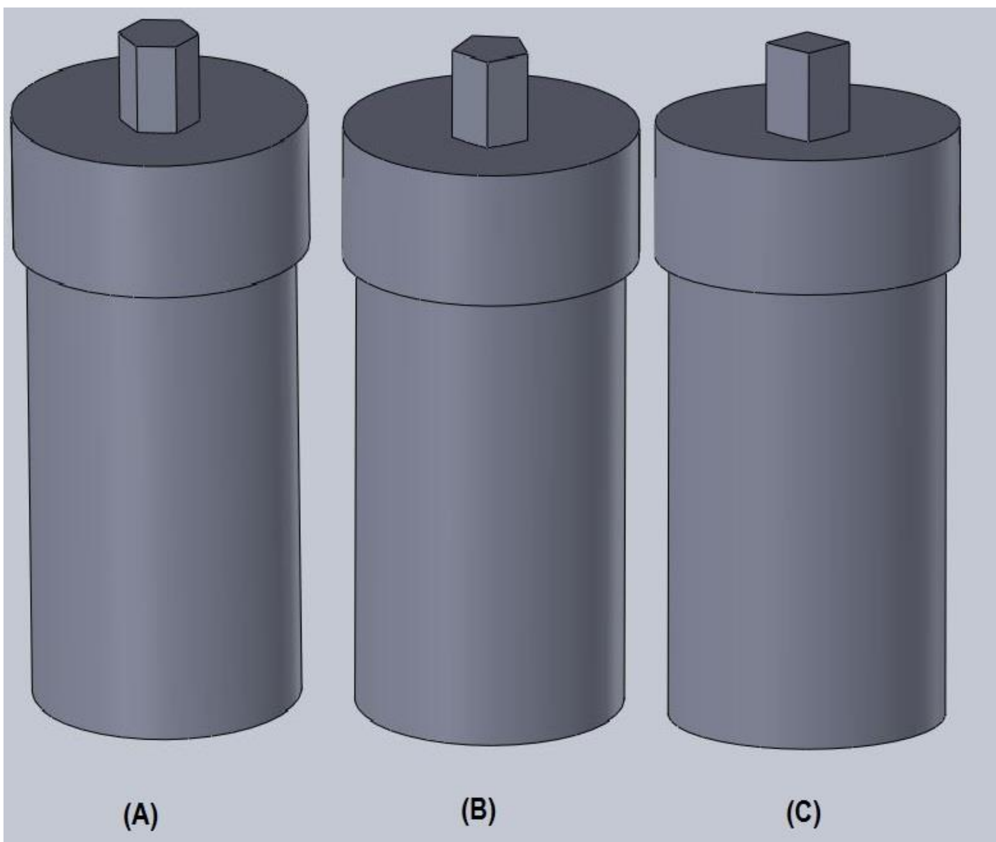

Figure 9: 3D CAD models of tools

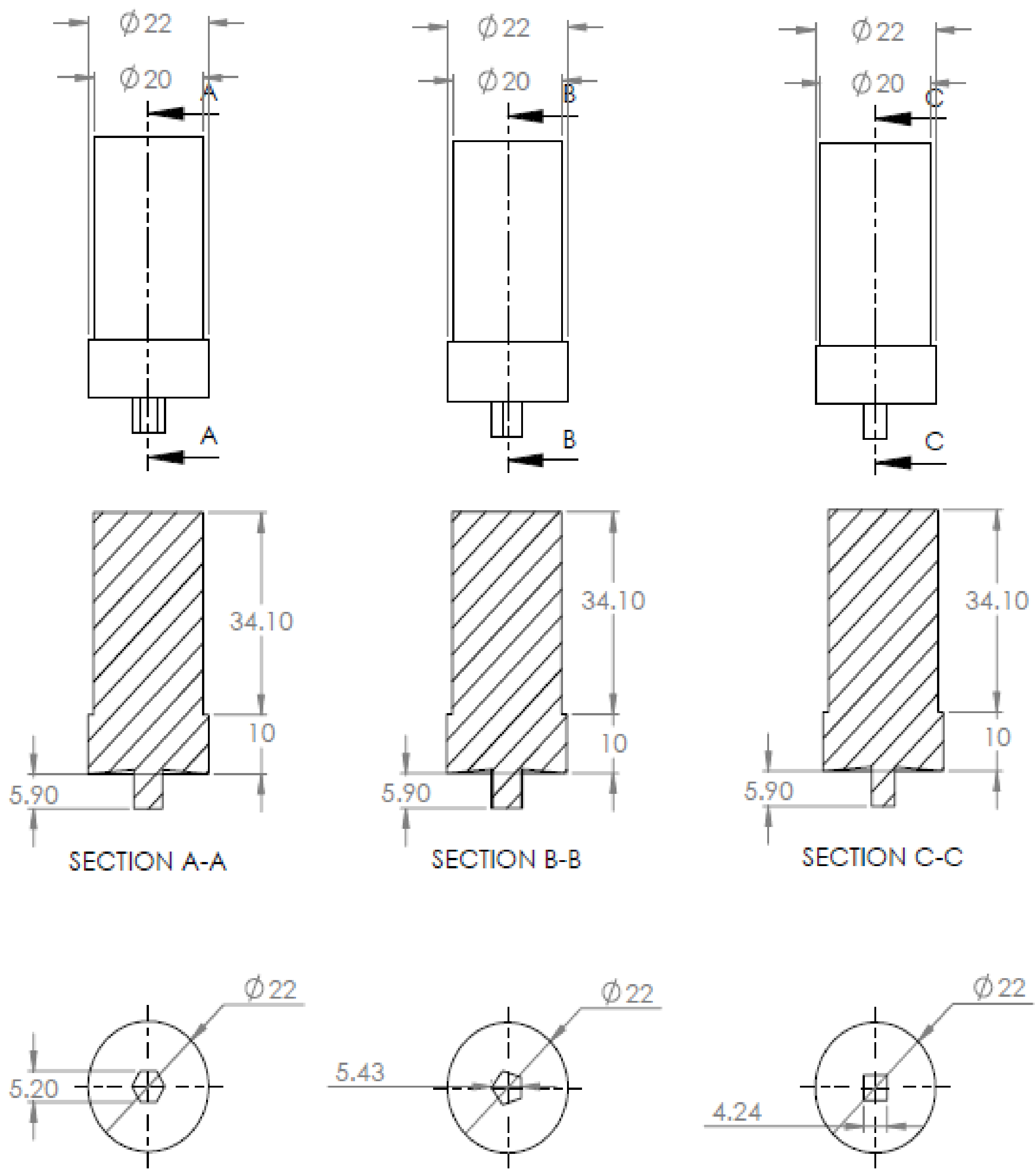

Figure 10: Manufacturing drawing of tools

In order to ensure rigid clamping fixture plate was used. The Mild Steel fixture with 12mm thickness was used as shown in Figure 8. Both sides of the plate was machined in order to ensure perpendicularity of both faces. Two support MS plates were used to tightly hold aluminum plates that were to be welded as shown in figure 11.

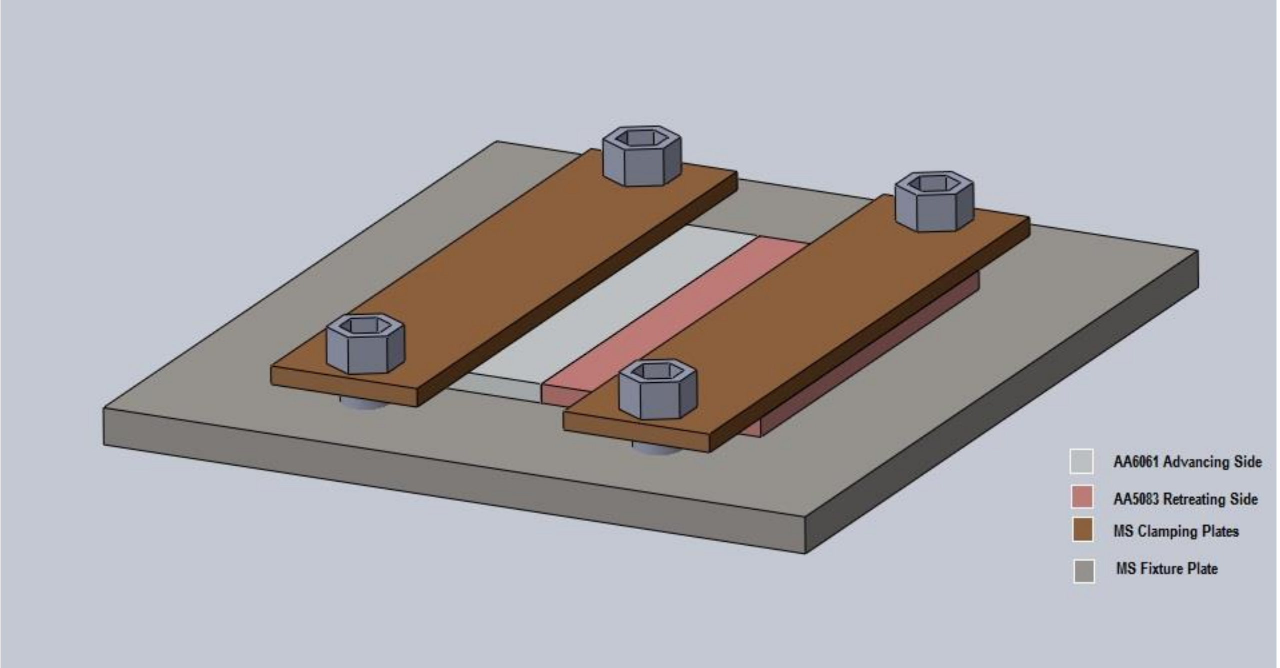

Figure 11: Fixture Setup for experimentation

4.3 Experimental plan

In order to apply Taguchi technique for optimization apart from Control factors, the remaining factors are kept constant. On the basis of literature review and preliminary experiments values of those factors is decided. Table 8 explains constant factors with explanation.

Table 8: Constant Factors kept constant in experimentation

Sr. No.	Factor	Value	Explanation
01	Tool tilt angle	3^{o}	Tool tilting is essential to confine the plasticized material reservoir and to enable the trailing edge of the tool shoulder to produce a constant compressive forging force on the weld [27].
02	Dwell time	10 s	Before starting the tool traverse motion, the probe/ pin of tool is forced to plunge in material while it is rotated. This allows some time to tool to attain temperature [41].
03	Plunge depth	6.1mm	The tool is plunged in such a way that the tool shoulder is 0.2mm inside from surface of material. This helps producing more frictional heat. Vertical force is kept constant in experiments by keeping plunge depth constant [5].

4.4 Experimental setup

Experimentation was performed on Vertical Milling machine. FSW was conducted in square butt joint configuration i.e. the two aluminum plates being flat and parallel to each other. Files and emery paper is used to prepare the edges of plates. The AA6061 is placed on advancing side while AA 5083 is placed on retreating side [36]. This configuration was also checked with preliminary experimentation. Both plates were held rigidly with the help of fixture as discussed in previous section. The fixture plate was held secure on machine bed with the help of four T- clamps. Figure 12 shows experimental setup.

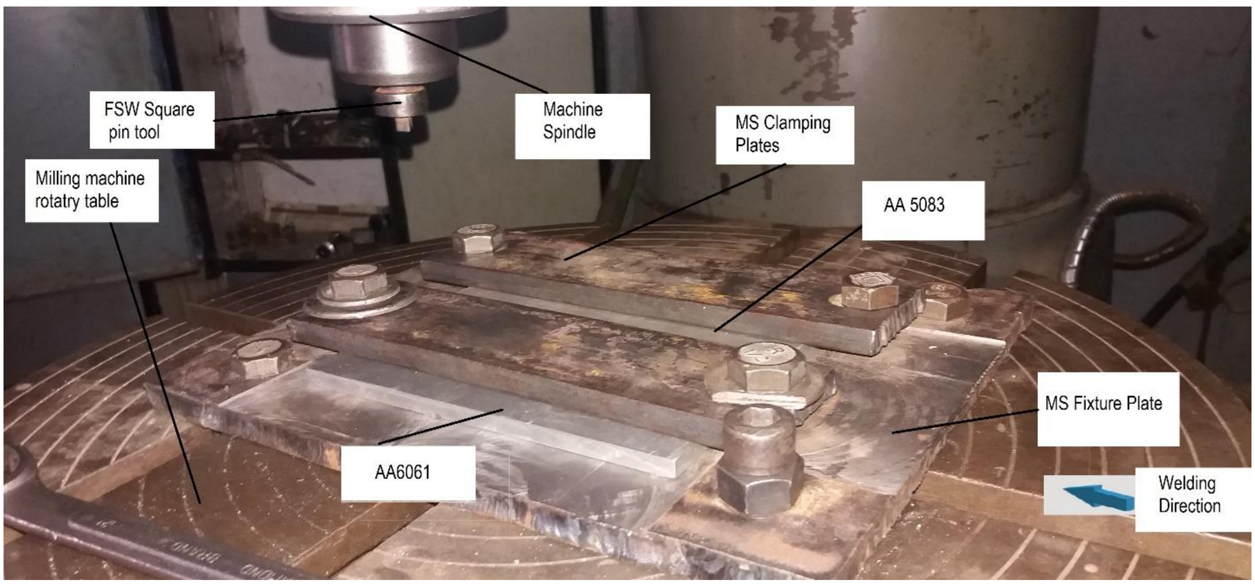

Figure 12: Experimental Setup

Every experiment was performed three times in order to ensure repeatability. Once all of the experiments are performed tensile specimen, impact strength specimen and microscopy specimen were cut with the help of same milling machine.

4.5 Tensile Testing

In Tensile testing, sample is subjected to a controlled tension until fracture. Tensile test was conducted according to ASTM E 8M – 04 standard [42]. The sample prepared was of subcompact size as shown in figure. Test reveals yield strength, % elongation and ultimate tensile strength of the base metal and FSW specimens. The cutting of specimen was carried out on Electric Discharge Machine (EDM). To minimize thickness variation in tensile test samples, emery paper of 2000 grit size was used for leveling the surface and edges of the specimens. Figure 13 and table 9 shows the CAD model and dimensions of subcompact tensile specimen used for study.

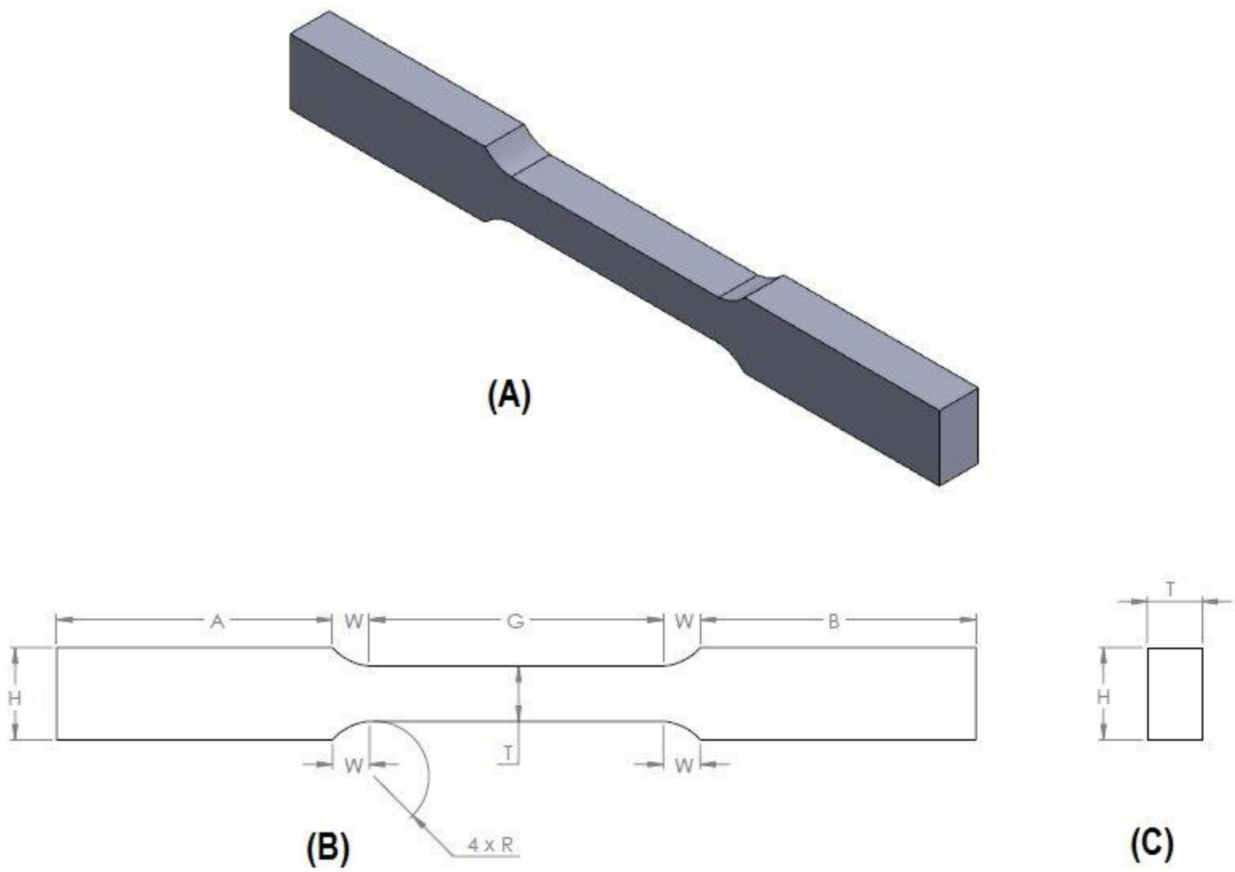

Figure 13: (A) CAD model of tensile specimen. (B) Orthographic front view of tensile specimen (C) Orthographic side view.

Table 9: Dimensions of symbols shown in figure 13.

Symbol	**Dimension (mm)**	**Symbol**	**Dimension (mm)**
A	30	**B**	30
G	32	**H**	10
T	6	**W**	4
R	6		

Tensile tests were performed on Shimadzu Universal testing machine shown in figure 16. The rate at which the sample stretched was set at 0.5mm/min. Force- linear deformation curve was obtained which was then converted to Stress- strain diagram. Obvious yield point cannot be located on stress- strain diagram of aluminum as undergoes large strains after the proportional limit is exceeded, an arbitrary yield stress may be calculated by the offset method. In Offset method a straight line is drawn parallel to the initial linear part of the curve on the stress-strain diagram. The offset value is 0.002 (or 0.2%) [43]. The point of intersection of the offset line and the stress-strain curve is its yield stress. The peak stress obtained is called ultimate tensile Strength (UTS) and yield strength (YS) was determined using offset method as shown in figure 14.

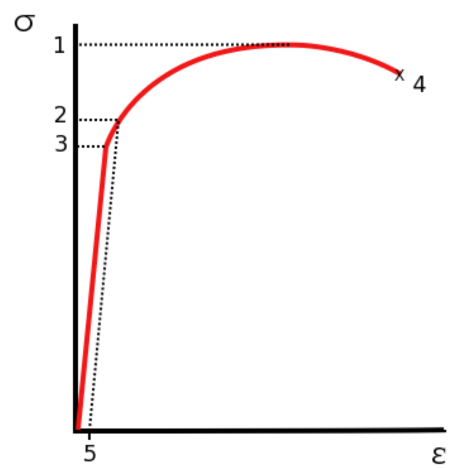

Figure 14: Stress- strain diagram for Aluminum [44]

Where,

1 Ultimate Tensile Strength, 2 Proof Strength

3 Proportional Limit Stress, 4 Rupture point

5 Offset Strain (usually 0.002)

The percent elongation is defined as follows:

$$\text{Percent elongation} = \frac{L_1 - L_0}{L_0}(100)$$

Figure 15: Micro Vicker hardness machine

Figure 16: Shimadzu Universal Testing Machine

4.6 Impact strength Test

Impact strength is the ability of any material to withstand a suddenly applied load i.e. Impact energy required to fracture. Material to have good impact strength must have a large volume with a low Elastic modulus and a high Yield strength [45]. Impact test was conducted according to ASTM - E23 standard [46]. This test is measure of toughness of material (ability of a material to absorb energy and plastically deform without fracturing) which is also related to the area under the stress–strain curve. As in case of tensile specimen, the cutting of Impact test specimen was carried out on Electric Discharge Machine (EDM). Shaper machine was used to carry out notching operation in specimen. Finally, emery paper of 2000 grit size was used for leveling the surface and edges of the specimen. Figure 17 and Table 10 shows the CAD model and dimensions of subcompact tensile specimen used for study.

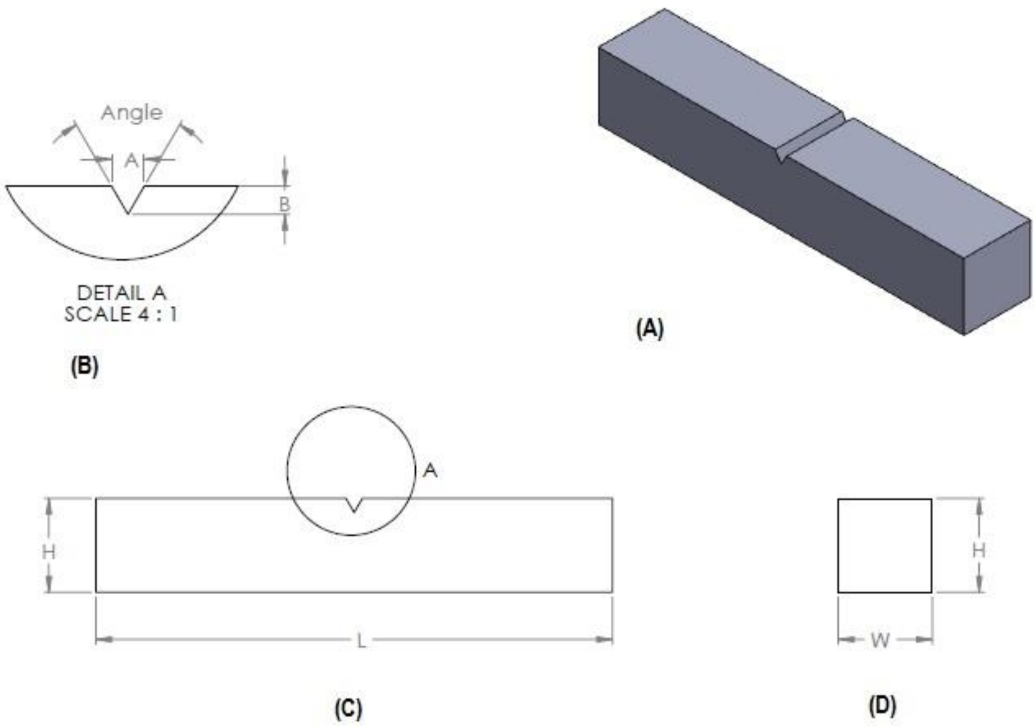

Figure 17: (**A)** CAD Model of Specimen, **(B)** Detailed view of notch, **(C)** Front View, **(D)** Side View

Table 10: Dimensions of symbols shown in figure 12

Symbol	Dimension (mm)	Symbol	Dimension (mm)
H	10	**L**	55
W	10		

Tests were performed on Charphy Impact testing machine. Schematic of Charphy impact machine is shown in figure 18. The specimen was constraint from both ends with notched end facing away from hammer. The hammer strike the specimen and reading on scale is obtained in Joules.

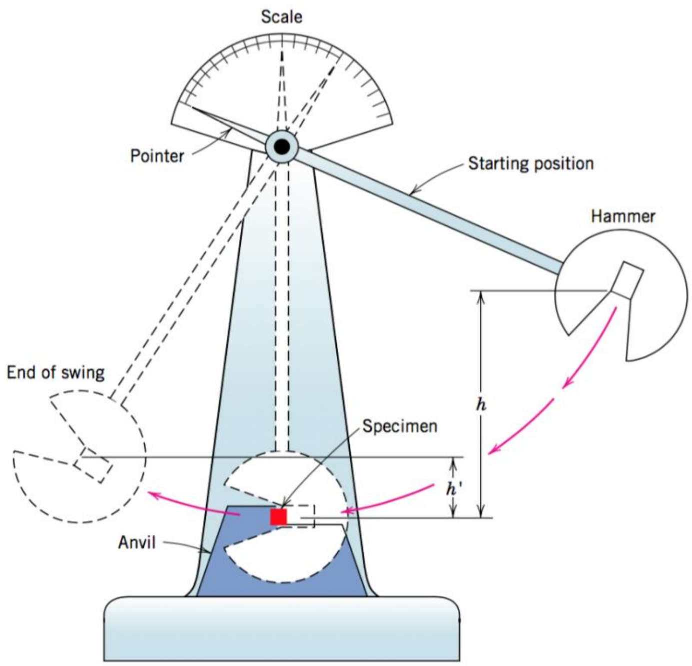

Figure 18: Charphy Impact schematic

4.7 Microstructural Analysis

An examination of the microstructure for FSW'ed specimen was carried out using optical microscopy to reveal the changes which took place during welding process. The process of optical microscopy comprises of following steps.

4.7.1 Sampling

The sample sectioned cross-sectionally in such a way that the welded joint was exactly at center having AA6061 at one end and AA5083 at other. The cut size of specimen was 40mm x 10mm x 6.2mm.

4.7.2 Mounting

For small sized specimen mounting is required, in this study the size of specimen was such that no mounting was required.

4.7.3 Grinding

After the specimen was cut to shape and mounted, it is made plain with the help of grinding machine. SiC Emery papers of different grit size were used starting for 100, 300, 600, 1000, 1200, 1600 and finally 2000 grit. Gentle pressure was applied during grinding process. Water was used as coolant in order to avoid any microstructural changes due to heating process. The grinding was done in cross each time at right angles so that previous scratches were removed [47]. The machine used for grinding in given in figure 19 and samples in figure 20.

Figure 19: Grinding machine used for samples

Figure 20: Grinded samples

4.7.4 Polishing

After the intermediate grinding or rubbing down, the specimen was ready for polishing. Polishing was done in two stages, 6 micron diamond paste was used firstly and afterwards 1 micron alumina slurry was used. Polishing machine was similar to grinding with polishing cloth instead of grinding paper. During polishing the sample was viewed under microscope for any scratches. Polishing of each sample was done until scratch free surface was obtained [47]. After polishing the sample was cleaned with alcohol and dried.

4.7.5 Etching

The main aim of etching is to optically improve microstructural features such as second phase features and grain size. Chemical etching react with specific microstructural features of material. Mixture of acids and bases are used as Etchant that are oxidizing or reducing agents [48]. Two common etching techniques include immersion and swabbing. The Tucker etchant used for this study with composition given in Table 11. The sample was swabbed for 10-15s.

Table 11: Composition of Tucker Reagent

Chemical	Volume
HCL	45 ml
HNO3	15 ml
HF	15 ml
H2O	25 ml

4.7.6 Optical Microscopy

After the sample was prepared it was view under the microscope at different magnifications to reveal microstructural changes in different welded zones. The pictures were taken at 50x, 100x and 200x magnifications. Results are discussed in chapter 5.

4.8 Hardness Profiling

The Hardness profiling was carried out on Wolpert W Group Micro Vicker hardness machine as shown in figure 15. Hardness measurements were performed across the Base Material, Thermo-Mechanically Affected Zone, Heat Affected Zone, and Nugget zone on the traverse cross-section of the welded joints. The variation in hardness across the section differentiate the zones. Complete Hardness is discussed in chapter 5.

CHAPTER 5: RESULTS AND DISCUSSION

This chapter details the effects of tool rotation rate (rpm) and tool traverse rate (mm/min) on the mechanical and microstructural properties of FSW'ed butt joints of 6061 and 5083 sheets (shown in figure 21). Microstructure evolution and mechanical properties such as, percentage elongation, ultimate tensile strength, Impact strength and hardness of all the FSW'ed samples and parent sheet are analyzed.

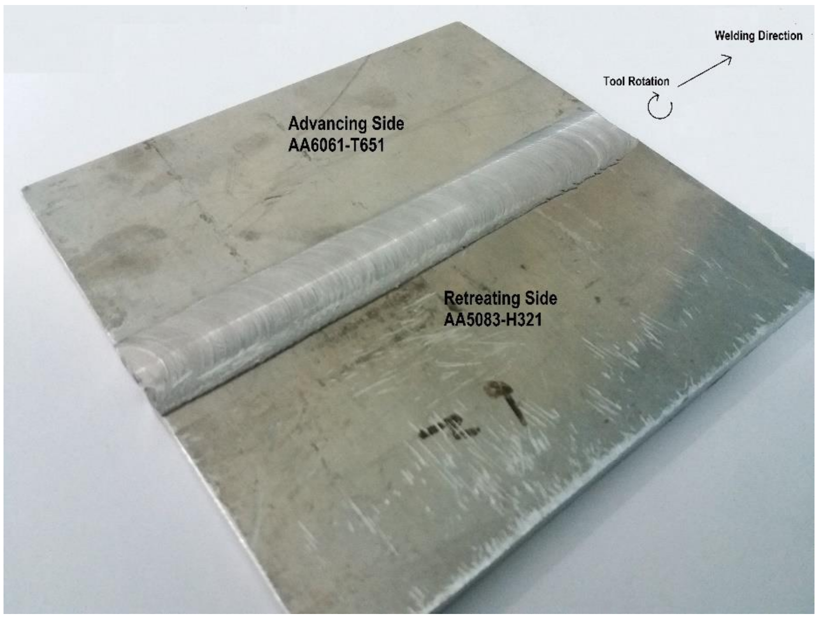

Figure 21: FSW'ed Sheet

Experiments were performed as per orthogonal array (as shown in Table 4) created by using Taguchi DOE technique. The results obtained were then analyzed using ANOVA in MINITAB 16.0. This enables us to reach on conclusion i.e. importance of each process parameter on responses (Tensile Strength and Impact Strength).

In order to perform Taguchi analysis, firstly experimental data is transformed into Means and S/N ratio. The main objective of research is maximization of the quality characteristics i.e. tensile strength and impact strength hence larger the better S/N ratio is to be calculated. Equation 1 is used to calculate the S/N ratio. Larger SN ratio, corresponds to better quality characteristics i.e. it has minimizing effect of noise on response [23]. Optimal setting were found using Mean and S/N ratio values.

5.1 Tensile Strength

Computerized universal testing machine is used to estimate Ultimate Tensile strength at room temperature. Welded bead was kept in center while preparing tensile specimen. Tensile results for complete array and calculated values of S/N ratio for tensile strength by analyzing taguchi array are given in Table 12. Figure 22 shows the cross-section of each sample.

Table 12: Taguchi Analysis - L9 orthogonal array results

Sr. no.	Welding Speed (S)	Traverse rate (R)	Tool Shape (T)	Mean tensile strength (MPa)	SN ratio	Weld Quality
1	800	10	Square	155.52	43.83	Defect Free
2	800	20	Pentagonal	153.64	43.73	Defect Free
3	800	30	Hexagonal	101.48	40.12	Defective
4	1000	10	Pentagonal	222.67	46.95	Defect Free
5	1000	20	Hexagonal	210.60	46.46	Defect Free
6	1000	30	Square	148.42	43.43	Defective
7	1200	10	Hexagonal	233.13	47.35	Defect Free
8	1200	20	Square	134.48	42.57	Defective
9	1200	30	Pentagonal	91.00	39.18	Defective

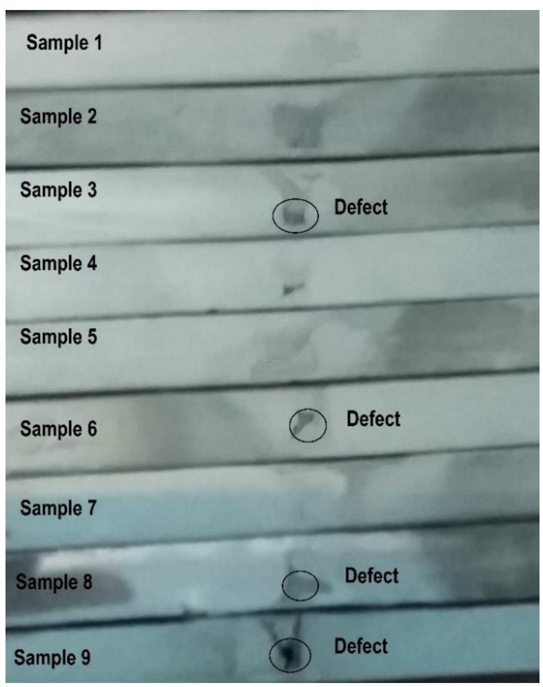

Figure 22: Cross-sectional view of samples showing defects

The quality of weld is greatly dependent on traverse rate as it can be seen Table 13. The Sample No. 3, Sample No. 6, Sample No. 8 and Sample No. 9 are the one with defects. These defects include Tunnel and micro porosity. Due to these defects, the strength of the specimen is also compromised/weaken, as it can easily be seen in Figure 22.

Table 13: Response table of Signal to Noise Ratio for UTS

Level	**Welding Speed (S)**	**Traverse rate (R)**	**Tool Shape (T)**
1	42.56	**46.05**	43.28
2	**45.62**	44.26	43.29
3	43.04	40.91	**44.65**
Delta	3.05	5.13	1.37
Rank	2	1	3

The optimal setting parameters based on signal to noise ratios $S_2R_1T_3$.

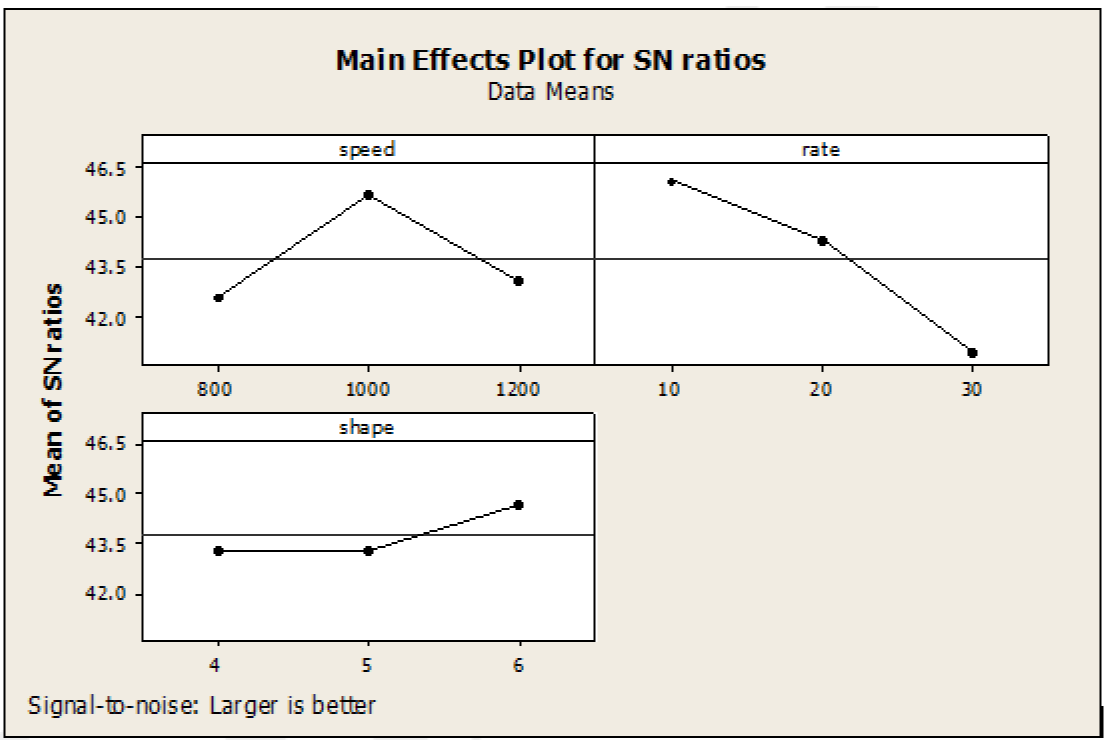

Figure 23: Main Effects plot of SN ratio for UTS

Table 13 and Table 14 shows the responses for Signal to Noise ratio and Mean respectively. It can be seen that the Welding speed of 1000 rpm, Traverse rate of 10mm/min and hexagonal probe shape are the optimal parameters derived from the study. The Graphs of responses for Signal to Noise ratio and Mean are shown in Figure 23 and Figure 24 respectively.

Table 14: Response table of mean for UTS

Level	Welding Speed (S)	Traverse rate (R)	Tool Shape (T)
1	136.9	**203.8**	146.1
2	**193.9**	166.2	155.8
3	152.9	113.6	**181.7**
Delta	57.0	90.1	35.6
Rank	**2**	**1**	**3**

The optimal setting parameters based on means is $S_2R_1T_3$.

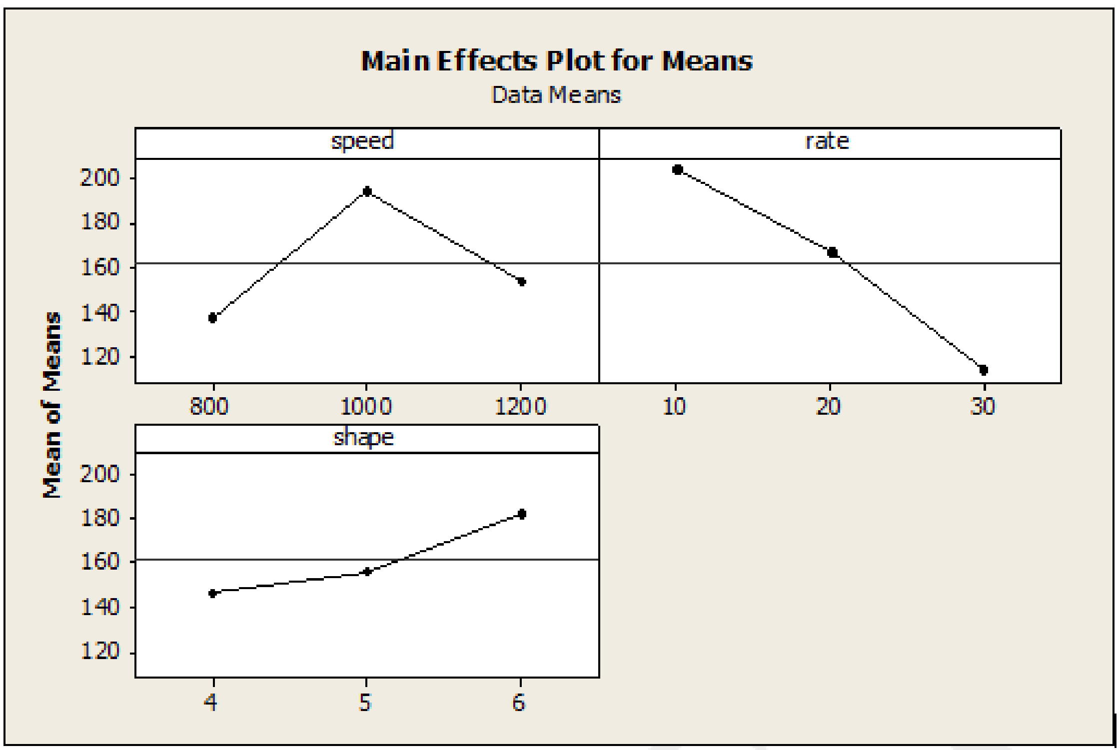

Figure 24: Main Effects plot of means for UTS

The study revealed that strength has inverse relation with traverse rate of tool i.e. strength increase with decrease in traverse rate, 10 mm/min being most effective of all. The good weld at low traverse rates can be attributed to more localize heating and proper stirring of material. Second most significant parameter is welding speed which also greatly affects tensile strength, 1000 rpm being most noteworthy of all. Least effecting parameter was found to be Probe shape, with the increase in number of edges from 4 to 6, strength continue to increase. This can be due more heat generation (surface area of the probe increases with increase in number of edges of probe) resulting into proper stirring of metal.

Strength achieved was lower than that of the base metal, i.e. maximum Tensile Strength achieved was 234 Mpa which is almost 71% to 73% of base materials. This loss of strength after welding in 5XXX series alloys is due to the fact that material in HAZ goes to annealed state. Similarly in 6XXX alloys the HAZ is typically an over-aged region in terms of the precipitation hardening. The tensile specimen fractured from HAZ of AA6061 region which confirms the above stated theory.

5.1.1 ANOVA for Tensile Strength

Analysis of variance is a statistical tool used to evaluate the relative importance of the control factors. F-test for testing equality of variance is used to test the hypothesis of the equality of two sample set variances. F-test named after fisher also describes the process parameter significance on tensile strength. S/N ratios obtained by ANOVA for tensile strength are given in Table 15. It can be seen that most important and highly contributing factor towards weld strength is Traverse rate (rate at which tool is moved along a weld line).

Table 15: Analysis of variance of signal to noise ratio for UTS

Source	**Dof**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% Cont.**
Welding Speed	2	5190.2	5190.2	2595.1	3.90	0.204	24.88
Traverse rate	2	12302.4	12302.4	6151.2	9.26	0.098	58.98
Tool Shape	2	2033.5	2033.5	1016.8	1.53	0.395	9.75
Residual error	2	1329.2	1329.2	664.6			6.37
Total	8	20855.3					

The results of ANOVA shows that the studied process variables are significant factors influencing the tensile strength of FSW joints. The order of effectiveness is Traverse rate followed by Welding Speed and Tool probe shapes. The percentage contribution of each process parameter on Tensile strength in the form of Clustered column chart is shown in Figure 25.

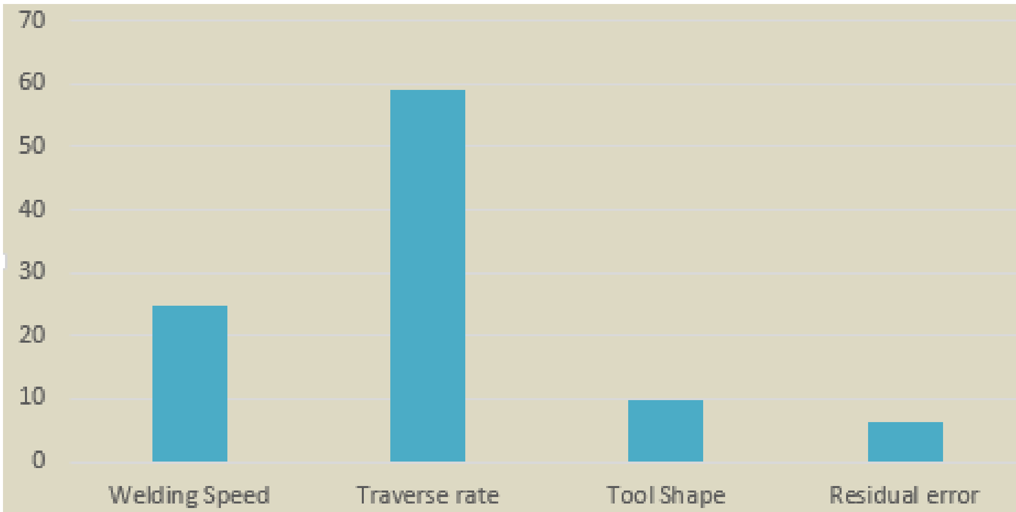

Figure 25: Percentage contribution of each process parameter on UTS

5.1.2 Regression Model and Confirmation Test

A mathematical model (eq. 4) is developed to predict the Impact Strength of friction stir welded AA6061 and AA5083 aluminum alloy joints. The coefficients of the regression model for Tensile Strength were calculated at 95% confidence level using Minitab 16.0.

$$TS = 178.516 + 0.0399784 * S - 4.50716 * R + 7.58483 * T \ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Where,

S: Welding Speed

R: Traverse rate

T: No. of probe edges

The confirmation test was carried out for tensile strength and it was concluded that value obtained from regression model (211 MPa) was near to the values obtained (238.5 MPa) after actual test conducted according to predicted optimal process parameters.

5.2 Impact Strength

Toughness of a material is measure of its ability to absorb impact energy during plastic deformation. Brittle material have small toughness because of small plastic deformation that material can endure. Impact strength is temperature dependent property, generally it decrease with decreases in temperature. Whether a material can be classified as being either brittle or ductile depending upon results obtained from Charpy tests. Little energy is absorbed by brittle material as compared to ductile material which as absorb large impact energy [49]. Charpy impact testing is one of the methods to measure toughness which is test consisting of striking a standard notched sample (ASTM- E23 standard) with a controlled weight pendulum swung from a set height. Table 16 shows the results obtained from experimentation and taguchi analysis.

Table 16: Taguchi Analysis – L9 orthogonal array results for Impact Strength

Sr. no.	Welding Speed (S)	Traverse rate (R)	Tool Shape (T)	Mean Impact energy (J)	SN ratio
1	800	10	Square	21	26.4444
2	800	20	Pentagonal	17	24.6090
3	800	30	Hexagonal	13	22.2789
4	1000	10	Pentagonal	24	27.6042
5	1000	20	Hexagonal	25	27.9588
6	1000	30	Square	18	25.1055
7	1200	10	Hexagonal	23	27.2346
8	1200	20	Square	13	22.2789
9	1200	30	Pentagonal	13	22.2789

The Sample No. 3, Sample No. 8 and Sample No. 9 with defects exhibits minimum impact strength. Impact strength of welded joint is below than that of base material. This can be due to increase in dislocation density inducing brittle nature in weld area. Impact strength has inverse relation with traverse rate of tool i.e. strength increase with decrease in traverse rate. The Traverse rate influences the heat input per unit length of weld which controls the degree of softening and flowability of plasticized material. Second most significant parameter is welding speed with 1000rpm being most efficient of all. With the increase in number of edges of tool probe from 4 to 6, strength continue to increase. This trend is very insignificant on impact strength. It can be seen that *hexagonal probe* being most efficient of all, more edges (more surface area) producing more friction, hence more heat.

Table 17: Response table for Signal to Noise Ratio (Impact Strength)

Level	Welding Speed (S)	Traverse rate (R)	Tool Shape (T)
1	24.44	**27.09**	24.61
2	**26.89**	24.95	24.83
3	23.93	23.22	**25.82**
Delta	2.96	3.87	1.21
Rank	2	1	3

The optimal setting parameters based on signal to noise ratios $S_2R_1T_3$.

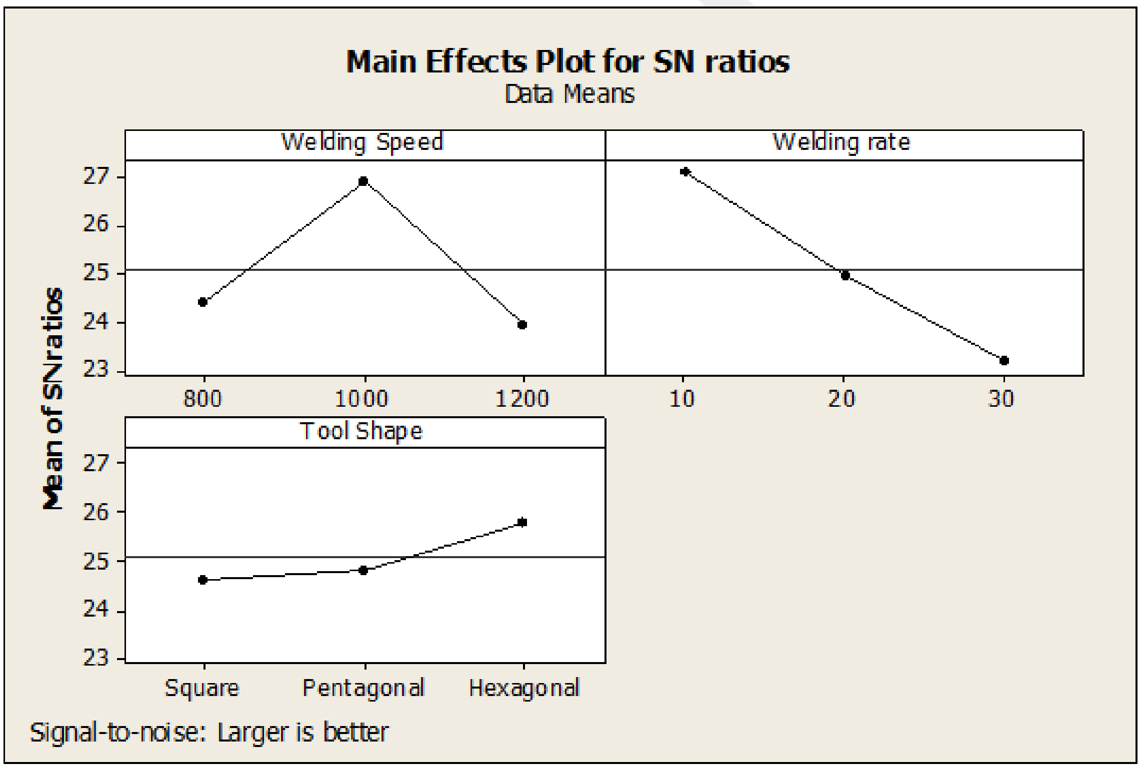

Figure 26: Impact Strength- Main Effects plot for SN ratios

Table 17 and Table 18 shows the responses for Signal to Noise ratio and Mean respectively. It is evident the Welding speed 1000 rpm, Traverse rate 10mm/min and hexagonal probe shape are the optimal parameters derived from the study. The graphs of responses for Signal to Noise ratio and Mean are shown in figure 26 and figure 27 respectively.

Table 18: Impact Strength - Response table for Mean

Level	**Welding Speed (S)**	**Traverse rate (R)**	**Tool Shape (T)**
1	17.00	22.67	17.33
2	22.33	18.33	18.00
3	16.33	14.67	20.33
Delta	6.00	8.00	3.00
Rank	2	1	3

The optimal setting parameters based on signal to noise ratios $S_2R_1T_3$.

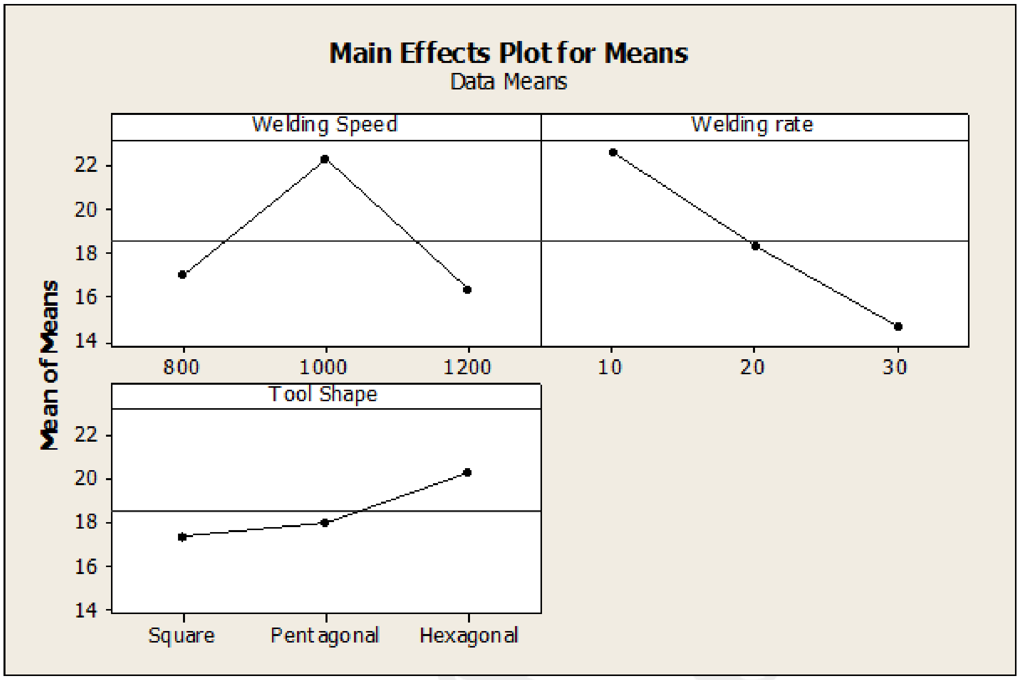

Figure 27: Impact Strength- Main Effects plot for mean

5.2.1 ANOVA Analysis for Impact Strength

Analysis of variance (ANOVA) test is conducted to find the process parameters that are statistically significant. In other words, Analysis of variance is a statistical tool used to evaluate the relative importance of the control factors. In addition, F-test named after fisher also describes the process parameter significance on impact strength. Generally when F is high, the variation of that particular the process variable significantly affects the quality characteristics. ANOVA results for Charphy impact tests of S/N ratios are given in Table 19. It can be seen that most important and highly contributing factor is Traverse rate.

Table 19: Impact Strength - Analysis of variance for signal to noise ratio.

Source	Dof	Seq SS	Adj SS	Adj MS	F	P	% Cont.
Welding Speed	2	64.889	64.889	32.444	4.00	0.200	33.75
Traverse rate	2	96.222	96.222	48.111	5.93	0.144	50.06
Tool Shape	2	14.889	14.889	7.444	0.92	0.521	7.75
Residual error	2	16.222	16.222	8.111			8.44
Total	8	192.222					

The results of ANOVA shows that the studied process variables are significant factors influencing the tensile strength of FSW joints. The order of effectiveness on weld properties is Traverse rate followed by Welding Speed and Tool probe shapes. The percentage contribution of each process parameter on Impact strength in the form of Clustered column chart is shown in figure 28.

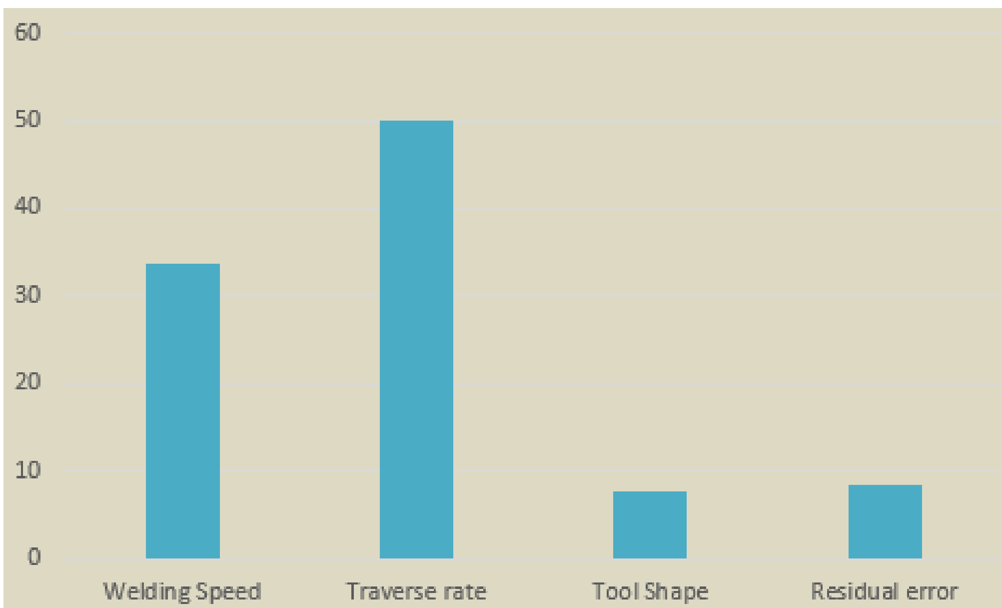

Figure 28: Percentage Contribution of each process parameters on Impact Strength

5.2.2 Regression Model and Confirmation Test

A mathematical model (eq. 4) is developed to predict the Impact Strength of friction stir welded AA6061 and AA5083 aluminum alloy joints. The coefficients of the regression model for Impact Strength were calculated at 95% confidence level using Minitab 16.0.

Impact Energy = 25.5 - 0.00166667 * S - 0.4 * R + 0.628205 * T …………… (3)

Where,

S: Welding Speed

R: Traverse rate

T: No. of probe edges

The confirmation test was carried out for tensile strength and it was concluded that value obtained from regression model (23.67 J) was near to the values obtained (26.3 J) after actual test conducted according to predicted optimal process parameters.

5.3 Micro-structural Analysis

Microstructural study of weld zone was conducted using optical microscope. Specimens for observation of optical microstructures near the weld zone were prepared using conventional method discussed in chapter 4.

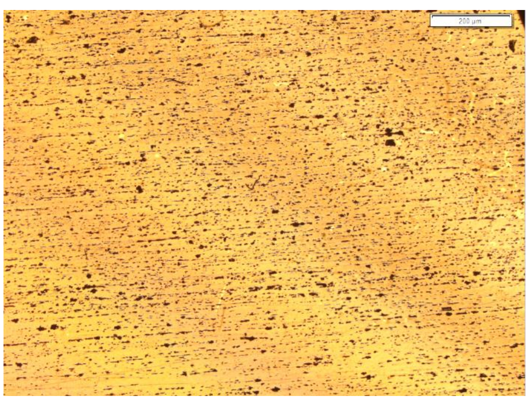

Figure 30: Microstructure of AA5083-H321

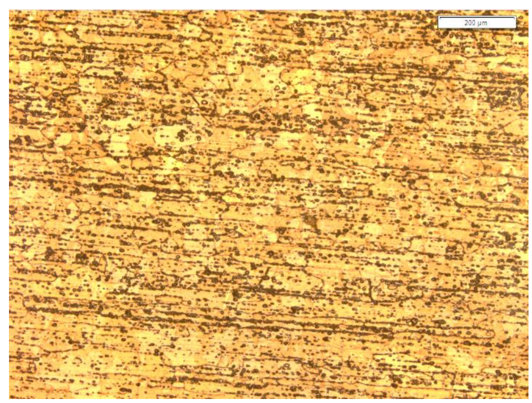

Figure 29: Microstructure of AA6061-T651

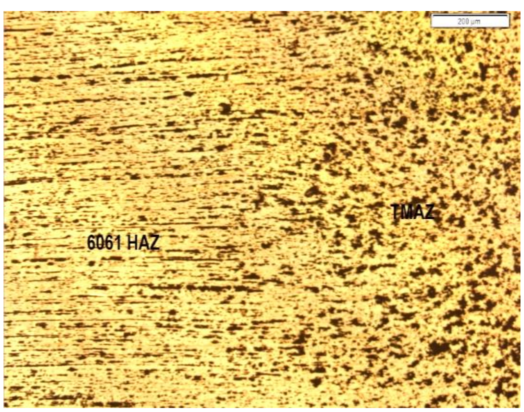

Figure 32: HAZ of AA6061

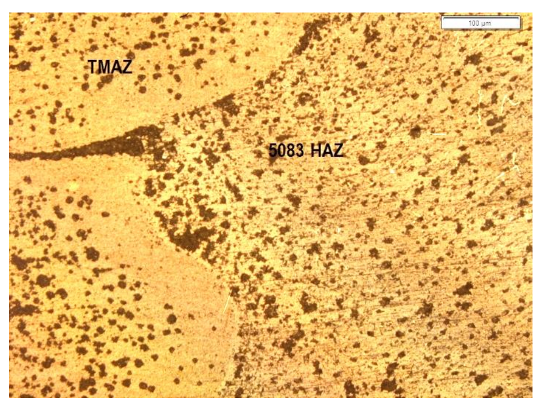

Figure 31: HAZ of AA5083

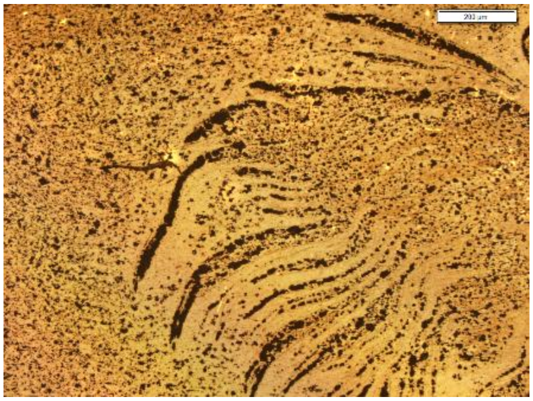

Figure 33: Onion Rings

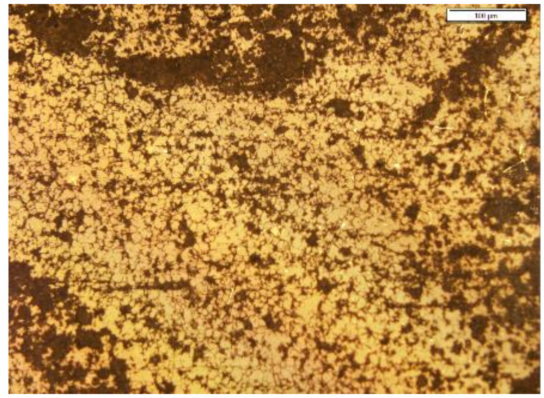

Figure 34: Nugget Zone

It is well established that in most materials, welding has an adverse effect on microstructure and properties, therefore optimized welding parameters are often a compromise between making sound weld at economical production rate and producing acceptable rather than ideal microstructure and properties.

Figure 30 shows microstructure of 6061-T651 sheets in which elongated grains with Mg_2Si precipitation formed as a result of aging were observed. On the other hand 5083-H321 sheet shows elongated Mg_2Si and Al_2Mg_3 precipitates as shown in figure 29. Fine and equiaxed grain with smaller size is observed in stir zone as compared to grains of the base material, this can be seen in figure 34. Such structure is produced by the dynamic recrystallization and static grain growth after welding. Figure 31 and Figure 32 shows that HAZ has a similar grain structure as that of Base material. In HAZ, temperature conditions were not significant to promote grain growth to change base material microstructure and HAZ can only be detected by a change in hardness. In Figure 31 and Figure 32 significant rotation of parent grains were observed. Onion rings a common observation in the FSW microstructure can be seen in Figure 33 typical characteristics of these rings include variation in dislocation density and texture effect.

5.4 Hardness profiling

Based on hardness values and microstructural analysis lines are drawn across the weld cross section showing different zones. Main points to be observed are:

a. The HAZ of AA 6061 has the lowest hardness across the weld cross section.

b. The combined study of microstructure and micro hardness reveal a zonal transition from the BM to a HAZ, a TMAZ, and a NZ in the center of the weld (Figure 36).
c. Measured hardness across cross section through each FSW zone. The hardness in each zone was below that of the Base material as shown in Figure 35.

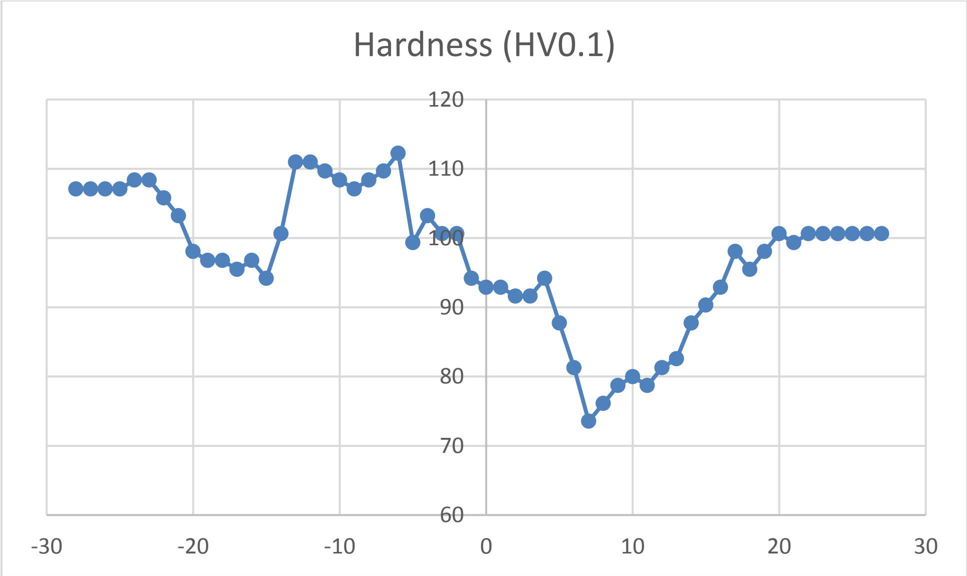

Figure 35: Hardness across weld cross- section

Figure 36: Weld cross-section with distant zones

CHAPTER 6: CONCLUSIONS

This research was conducted in field of Friction Stir welding of dissimilar aluminum alloy. Finding and conclusion of this research including future work is described below.

6.1 Conclusions

In this research, effect of Welding Speed (ω, rpm), tool traverse speed (ν, mm/min) and Tool probe Shapes on the final quality of FSW'ed butt joint of AA6061 and AA5083 sheets was examined. The quality of the FSW'ed parts was characterized on the basis of tensile strength, Impact Strength and hardness. The core findings of the study are summarized below:

1. The L9 Taguchi Orthogonal designed experiments of FSW on Aluminum AA5083 and AA6061 were conducted successfully.
2. Research focused on finding optimal FSW process parameters for quality characteristics i.e. tensile strength and Impact strength.
3. The heat input was found to be in strong relation with tool welding speed and traverse rates.
4. Optimal Welding speed, Traverse rate and tool probe shape for both Tensile Strength and impact strength are 1000 rpm, 10mm/min and hexagonal probe respectively.
5. The most prominent factor in both quality characteristics (Tensile Strength and Impact Strength) is Traverse rate. With increasing Traverse rate both impact strength and tensile strength decreases. This can be attributed to the formation of cracks and material defects due to low heat input at higher traverse rates.
6. Hexagonal probe shape being most efficient in producing defect free welds. With increase in stirring edges the quality of weld increases.
7. Defect free welds are obtained with 1000rpm being most efficient Welding speed.

6.2 Future Work

In light of all the work that has been done in this research so far, following areas are recommended for future investigation.

1. During FSW, heating and cooling rate plays vital role. The effect of pre-heating and post heating on joint quality of AA6061 and AA5083 should be investigated.
2. Welding tools belonging to different family types should also be studied.
3. Effect of temperature distribution and its effects on weld strength should also be studied.
4. DOE should also be applied on other process parameters which were assumed to be constant in current research such as tool tilt angle, axial force and tool geometry.

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