Rationalizing Tool and Machine Parameters for Micro Friction Stir Welding of Dissimilar Aluminium Alloys AA2024 & AA6061 Using RSM

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A thesis submitted in partial fulfillment of the requirements for the degree of

MS Design and Manufacturing Engineering

Thesis Supervisor:

Dr. SHAHID IKRAM ULLAH

Thesis Supervisor's Signature: ____

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MASTER THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: Mowiz Cheema (Reg No. 00000205390)

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Dedicated

To

Parents for Inspiration and Support

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Abstract

Friction Stir Welding is a welding technique invented in last part of twentieth century in which a high speed rotating tool traverses through the two base materials to be welded in solid state below melting temperature. Heat input for FSW is considerably less than conventional welding techniques like TIG, MIG. Micro FSW was performed in this research work on Aluminium alloys AA 6061-T6 and AA 2024-T3 with thickness of 1mm. Process parameters and tool end features were varied to optimize the mechanical and microstructure properties. Three types of tool with varying tool shoulder end features was used for the process and results analyzed. RSM was used for Design of Experiments and Design Expert-12 was utilized to apply RSM and evaluate results. Microstructural analysis was carried out to analyze the microstructure. Four distinct zones were formed, namely base material, stir zone, heat affected zone & thermo-mechanically affected zone. UTS was found through tensile test while micro-hardness test was carried out to find hardness of different zones formed. Results of the experiments show that traverse rate was the most influential parameter while tool end features improved the weld strength as well as the microstructure of the welded samples. Optimal parameters found were tool speed 1750 rpm, traverse rate 40 mm/min and tool with most number of holes at its shoulder base. The results highlight the fact that optimized heat input is the key to successful welds. Insufficient heat input reduces strength and lead to improper material mixing while heat input more than required causes damage to base material and leads to defects like weld flash etc.

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Chapter 01: Introduction

1.1. Background

Friction stir welding was developed at The Welding Institute, Cambridge in 1991 by Thomas Wayne. The project funded by NASA aimed to find a joining technique that would not lead to addition of mass to orbital spacecraft. Initially intended for some specific series of aluminum alloys which presented difficulties in achieving sound welds with conventional welding techniques, the process gained importance in the industry with more than 3000 patents up to 2013. (Carter, 2018)

In FSW, the tool pin is plunged into the base material which traverses through base material. This causes the major shearing effect in the material. On the other hand, the shoulder is major source of heat generation during the process. Different zones namely heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and stir zone (SZ) are formed during the process.

Friction Stir Welding has undergone many phases of research and development. Researchers have made efforts to utilize the process for different thickness ranges of different materials. Some have studied the feasibility of friction stir welding of dissimilar materials while research has also been performed on determining best suitable tool pin profiles, shoulder geometries and shoulder features. Some dimensions of research have been mentioned here, however, this is by no means an exhaustive list.

1.2. Scope and Motivation

Industries including aerospace, automotive, shipbuilding and electronics have vast application of friction stir welding. Research in this specific work has been intended at working on micro friction stir welding of dissimilar aluminum alloys. Alloys selected are aluminum alloy 2024 & 6061. They are utilized in fabrication of fuselage in aerospace industry and automobile panels in automotive industry. Typically, the 2xxx series of aluminum alloys is hard to weld with conventional techniques because of the oxidation effects taking place, thus affecting weld quality and strength. Much work is being carried out to enhance the utilization and increase the application of friction stir welding by experimenting on base metals with very low and very high thicknesses. Researchers are searching for optimized parameters to transfer heat sufficient for an effective bond. Thick sheets need large force and power for heat generation while thin sheets require accuracy and delicacy to not just generate the heat, but also to reduce the heat losses due to reduced thickness. This need for accuracy provides us the direction towards this research work.

1.3. Aims & Objectives

The focus of this research is butt welding of Aluminium Alloy 2024 and 6061 through friction stir welding. The thickness of the aluminum alloys is 1 mm. With more than one factors to be studied, Response Surface Methodology was used to get optimal parameters at a low experimentation cost (Aydar, 2018). Lastly, the testing of the samples prepared through FSW were tested and the results were analyzed.

The key objectives of this research include:

1. To analyze the effects of important process parameters i.e. traverse speed & tool rotation speed on weld quality
2. To design & utilize different tool shoulder geometries/ base features for the FSW process
3. To test material properties like tensile strength and hardness profiles of welded alloys
4. Microstructural evaluation of the welded samples
5. Analysis of variance

Chapter 02: Literature Review

Friction welding process is a solid state welding (SSW) process in which unlike conventional welding methods, joins the base material at temperatures below melting point.(Mishra, Mahoney, Sato, & Hovanski, 2016) A cylindrical tool at high rotational speed traverses through the base material. Tool constitutes of two features, tool shoulder and tool pin.

2.1 Types of Conventional and Advanced Welding processes

Variety of techniques have been used in past to join metals & their alloys. Each method has its specific advantages, limitations and applications. (Bharat, Singh, & Campus, 2014)

In Gas Tungsten Arc Welding (GTAW), heat is produced using an arc and electrode is used to fuse the joint area. It gives good joint quality, but the rate of welding is very slow.

An arc provides the heat in Shielded Metal Arc Welding (SMAW), but gases generated as a result of deposition of electrode provide the shielding effect. Its equipment requirement is quite simple and has vast applicability, but speed and efficiency are low.

Metal Inert Gas (MIG) Welding is an easier and quicker process. It has wide application and almost every industry utilizes this welding technique. It is also called Gas Metal Arc Welding (GMAW).

If we look at the periodic changes in technology, a report of NASA (Carter, 2018) highlights the trend of different techniques of welding aluminum at NASA. GMAW and GTAW were used initially in the years between 1950 -70. The next decade also saw GTAW as being the state-of-the-art technology, but not without defects. Invention of Plasma Arc Welding (PAW) in 1980's led to reduction of defects to large extent. Plasma welding was followed by adoption of Friction Stir Welding (FSW) by NASA in late 1990's and early years of the next century.

Electron Beam (EB) Welding and Laser Welding are also advanced welding processes. Both are similar to the extent that both use a focused, intense beam to instantly evaporate the base material and create a capillary which enables deep penetration welding. Moving this capillary along a weld preparation makes it possible to bond the base materials (Francis et al., 2019). The difference in both the processes is that electron beam welding utilizes a focused stream of high-speed electrons while focused beam of photons is used in Laser welding.

2.2 Friction Welding Processes

2.2.1 Types of Friction welding Processes

All friction welding processes share the common trait of utilizing friction to generate heat. Rotary Friction Welding has a stationary part which is pushed to rub against the other part that is rotating. Two variants of this process are inertia friction welding & continuous drive friction welding.

Linear Friction Welding is a process in which frictional heat is generated as one component is moved in a direct reciprocating mode relative to the other under normal pressure. (Li, Vairis, Preuss, & Ma, 2016)

Friction Stud Welding is advantageous in joining dissimilar materials (Jesudoss Hynes, Nagaraj, & Jennifa Sujana, 2012). Friction stud welding is a welding technique that involves high speed rotating stud forced against a substrate which generates frictional heat.

And Friction Stir Welding, the technique used in this research work, involves a rotating tool that is plunged and forced to travel through the base material which are welded together as a result of the heat produced.

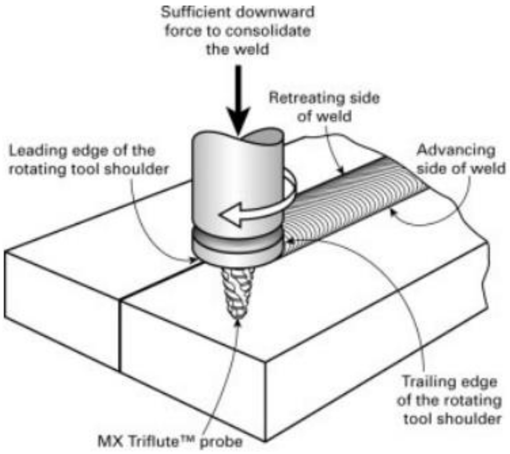


Figure 2.1 FSW Process (Photo Courtesy Thomas, Jhonson, & Wiesner, 2003)

2.2.2 Micro friction Stir Welding

Welding of sheets with thickness equal to, or less than 1mm is called micro-friction stir welding. Different authors have worked on micro FSW but research has not been reported on dissimilar micro FSW of Aluminium alloys AA 2024 and AA 6061.

- Nishibara and Nagasaka probed the feasibility of the micro-FSW on AZ31 magnesium alloys. (Nishihara & Nagasaka, 2004)
- Shuja Ahmad and Probir Saha developed a simple mechanical fixture to counter the fixturing problems faced during welding of utra-thin sheets. Experiments were performed on aluminium alloy 6061. Improved joint efficiency and ductility, along with other satisfactory results proved the feasibility of the fixture. (Ahmed & Saha, 2018)

- Y. Huang et al. studied micro-Friction stir welding for AA 6061 with sheet thickness 0.5mm. Process parameters were optimized and an optimum rotation speed and plunging depth was reported. (Huang, Meng, Zhang, Cao, & Feng, 2017)

2.2.3 Process Parameters in FSW

Following are the key parameters that affect the mechanical and microstructural properties of the weld (Pasha, Reddy, & Ahmad Khan, 2014):

- Tool rotation speed (rpm)
- Tool traverse rate (mm/min)
- Tilt angle
- Plunge depth
- Tool material
- Preheating or cooling
- Tool geometry
- Axial force

Of the above parameters, some affect the results more than the others. E.g. tool rotation speed and tool traverse rate are the critical parameters as the heat generation and material mixing depend mainly upon these two parameters. This consequently affects the mechanical properties and the microstructure of the welded samples. Y. Huang et al. states that frictional heat and flow of material play significant role in reduction of sheet thickness. This reduction effect can be improved by selecting an optimum rotational velocity. They also reported that increased rotational speeds lead to broader NZ, TMAZ and HAZ. (Huang et al., 2017)

Significance of tilt angle depends on the overall design of tool. It helps in improving material diffusion by circulating the sheared material towards the tool pin (Sithole & Rao, 2016) but due to the reduction of sheet thickness observed in FSW of thin sheets, zero degree tilt angles have been investigated with success. (Leal, Leitão, Loureiro, Rodrigues, & Vilaça, 2008)

Tool material is important to be considered while designing the experimental process. Harder composite materials require harder tools while softer materials like aluminum can be welded using softer steel tools. Selecting an improper tool material may lead to issues like increased wear or brittleness. It is also reported that higher rotational speeds increase tool wear, therefore tool life can be optimized by applying optimum process parameters. (Chandrashekar, Kumar, & Reddappa, n.d.)

With the passage of time, techniques were developed to improve the FSW process. Preheating and post weld heat treatment were two of these techniques. When applied upon relevant materials, improved results were observed in tensile strength test, hardness test and microstructure analysis. In preheating, an optimum temperature was found which gave best mechanical properties. Different post weld treatment methods were used like heating, rapid cooling and natural ageing. Natural ageing proved to be the best option out of the ones used in the reported work. (Sivaraj, Kanagarajan, & Balasubramanian, 2014) (Safi, Amirabadi, Besharati Givi, & Safi, 2016)

Another significant parameter is tool geometry. Details of effect of tool shall be discussed in sections to follow.

2.2.4 Tool Geometry & Features

The FSW tool is a key part of the whole process. The tool usually consists of two parts, a probe called the pin, and the shoulder. Both have their own impact on the overall process, resultant material properties, and microstructure. Following figure shows the two components of the FSW tool. (Thomas, Johnson, & Wiesner, 2003)

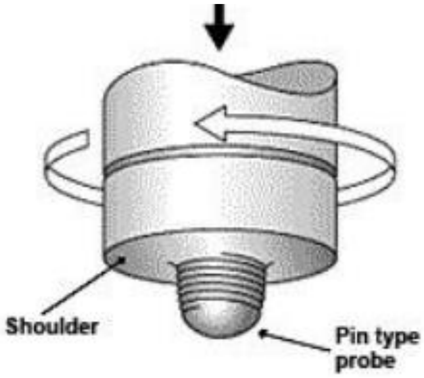


Figure 1.1 FSW Tool (Photo Courtesy Thomas, Jhonson, & Wiesner, 2003)

Tool Pin

The pin gets plunged into the workpiece and it is primarily responsible for the shearing effect in the stir zone of the two base materials (T, Lin, Wu, & Qu, 2014). Different authors have tried to study different pin profiles to optimize results of the FSW process.

Five different tool pin profiles along with different tool material and speeds were used by Padmanaban et al. and results were compared. Amongst the five pin profiles that included straight cylindrical, taper cylindrical, threaded cylindrical, square and triangular profiles, threaded pin profile gave the best results (Padmanaban & Balasubramanian, 2009). However, multiple researchers have concluded that square profile provides that optimum results in most conditions (Bayazid, Farhangi, & Ghahramani, 2015)(Emamian, Awang, & Yusof, 2018).

Tool Shoulder

Tool shoulder is primarily responsible for the generation of heat in FSW process. Optimum heat generation is critical for a sound and smooth weld. Cederqvist et al. studied the effect of tool shoulder geometry on FSW process and optimum temperature range for defect free weld was reached (Cederqvist, Sorensen, Reynolds, & Öberg, 2009). Work has also been reported on finding an optimum shoulder diameter. Such an attempt was made by varying ratio of shoulder diameter (D) to sheet thickness (d). An optimum ratio of D/d=3 was observed (Malarvizhi, Balasubramanian, & Annamalai, 2011).

Tool shoulder features affect the heat generation and flow of material during the welding and the final microstructure is dependent on collective effect of shoulder and pin. Krishna et al. studied the effect of different tool end features to minimize the size of the weld. Tool with ridges gave the best results due to enhanced material mixing at temperatures lower than that reached with other comparable tool geometries and features (Mugada & Adepu, 2018). Spiral shaped concentric circle features at tool end were also experimented and improvement in results was observed as compared to featureless tools. (Scialpi, De Filippis, & Cavaliere, 2007)

Although work has been done on tool end features, but it is mostly limited to FSW process on thick sheet of different materials, while study of the effect of tool end features on micro-FSW is very limited. With the work of micro-FSW even more delicate than the normal process due to reduced tolerances and defects like reduction in sheet thickness, an attempt to use tool end features for improving the process can be highly fruitful. This very need of the process improvement is the focus of this research work.

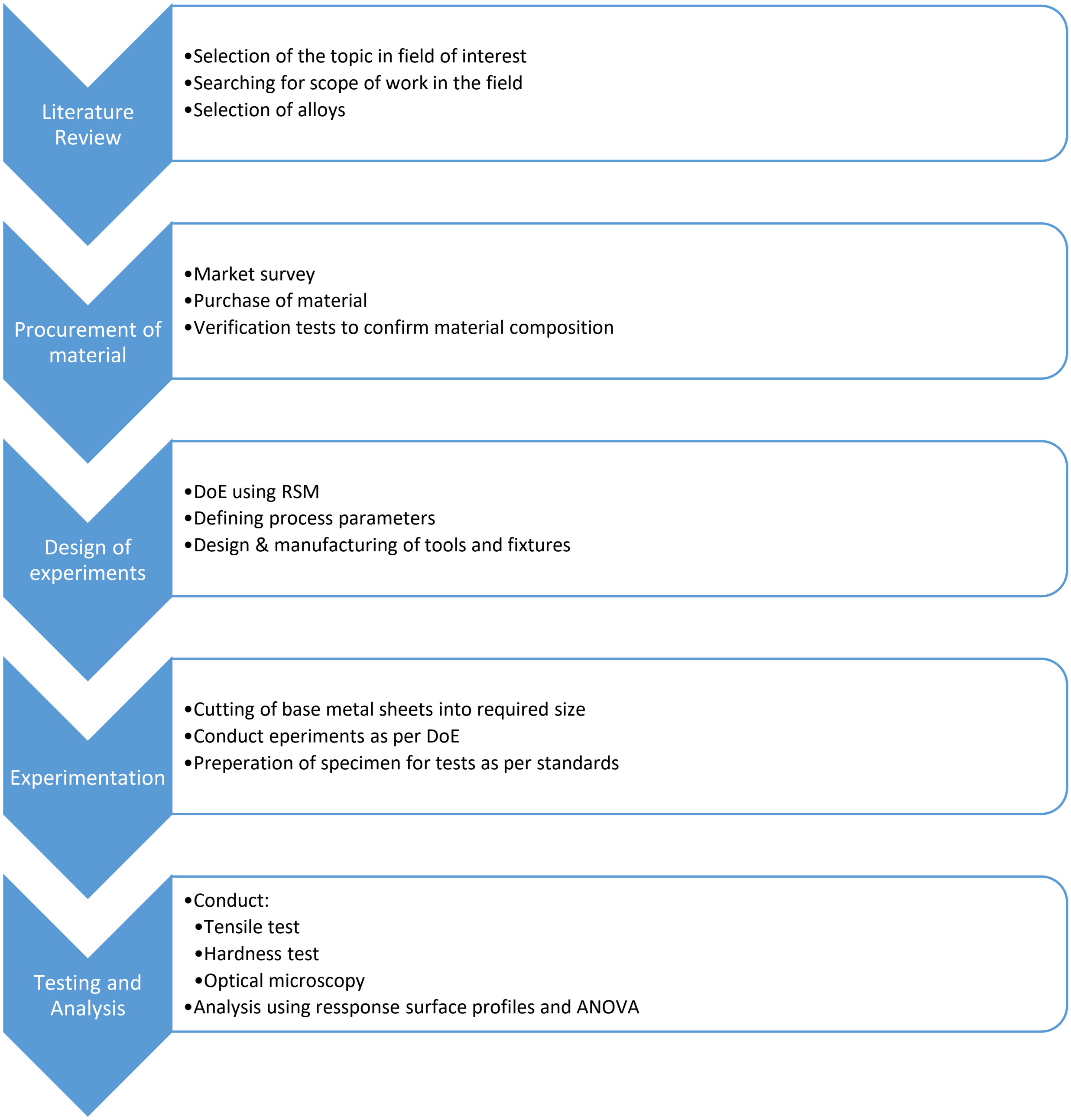
Chapter 03: Methodology

This chapter presents the details of the procedures adopted to perform the welding experiments and the analysis of the welded samples.

3.1 Methodology

Figure 3.1 shows the methodology of this research work.

Figure 3.1: Methodology



Literature Review

- Selection of the topic in field of interest
- Searching for scope of work in the field
- Selection of alloys

Procurement of material

- Market survey
- Purchase of material
- Verification tests to confirm material composition

Design of experiments

- DoE using RSM
- Defining process parameters
- Design & manufacturing of tools and fixtures

Experimentation

- Cutting of base metal sheets into required size
- Conduct eperiments as per DoE
- Preperation of specimen for tests as per standards

Testing and Analysis

- Conduct:
  - Tensile test
  - Hardness test
  - Optical microscopy
- Analysis using ressponse surface profiles and ANOVA

3.2 Material

The materials used in this work were Aluminium alloys AA 2024-T3 and AA 6061-T6.The thickness of the sheets was 1 mm. The chemical composition of both the materials is presented in Table 3.1. Specimens of dimensions 150 mm x 75 mm were cut for welding. EDM wire cut was used to cut the specimen into the above mentioned size (Akkurt, 2015). This cutting technique helps maintain perpendicularity of sheets which is of much more significance in FSW of thin sheets than that of thick sheet.

Table 3.1: Chemical Composition of Base Materials

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
AA 2024	.11	.21	4.44	.6	1.63	.04	.07	.03	Remaining
AA 6061	.69	.27	.24	.06	1.06	.18	.17	.03	Remaining

Table 3.2 presents the mechanical properties of alloys:

Table 3.2: Mechanical Properties of Base Materials

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation %
AA 2024	469	327	16
AA 6061	316	265	12

3.3 Experimental Plan

3.3.1 Experimental Setup

Vertical milling machine was used to weld specimen for analysis. Samples were prepared at three different traverse rates and tool rotation speeds. These two factors have been constantly reported as most significant factors affecting the weld quality and strength. Third factor varied in this experimental process was tool shoulder. Three types of tools were used in this work. All tools had a square shaped pin. Working parameters i.e. traverse rate and tool rotation speeds were defined using previous literature on alloys under study and trial experiments. Tool tilt angel was kept to zero as it is a cause of thickness reduction in FSW of thin sheets (Leal et al., 2008). Table 3.3 shows the different parameters used in the present work.

Table 3.3: Working Parameters

Tool Speed (RPM)	Traverse Rate (mm/min)
1500	20
1750	40
2000	80

Figure 3.2 shows the clamping arrangement for holding together the specimen to be welded. Specimen are placed on a base plate and then clamps are inserted at four points to hold the specimen.

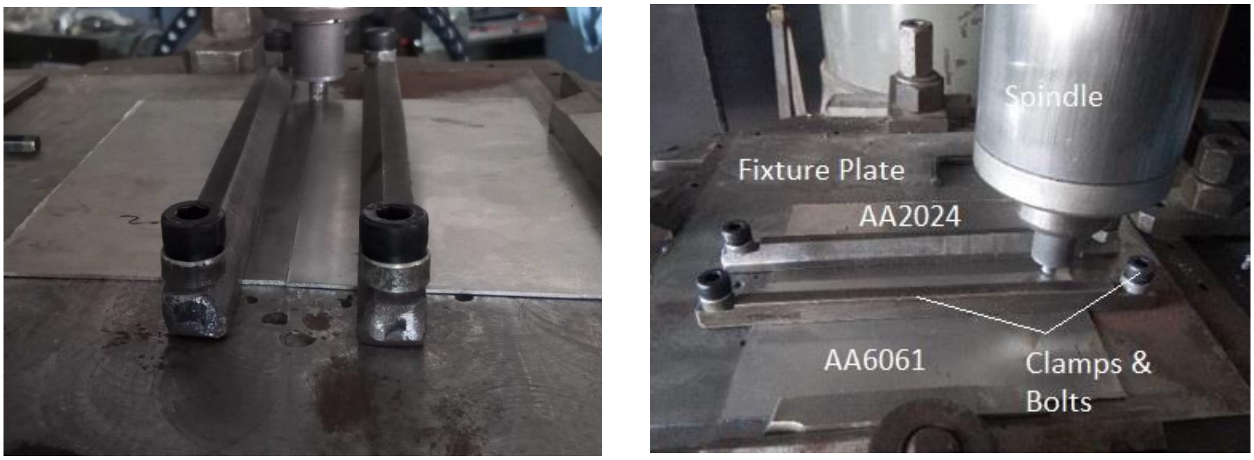


Figure 3.2: Clamping arrangement (left) & experimental setup (right)

3.3.2 Tools

Tool shape and features play an important role in overall weld quality in FSW. Tools were made of H13 tool steel. Much work has been reported on tool pin profiles. Square shaped pins give better results in most cases.

As mentioned in previous chapter, tool pin provides the shearing effect in FSW process while the tool shoulder generates heat and material flow. In this research work, tools with three different features were used. Inefficient mixing of the semi molten base material leads to defects and reduction in quality of the weld. Hence to counter this issue, small holes were drilled at the end of the tool, thus given the name ‘tool end features’.

Holes hold up the semi molten base material, thus improving material mixing during the process. To compare the results and for analysis purpose, first tool used was without any end features. Second tool had six holes and the third tool had 10 holes at its shoulder end. This variation in number of holes helped in assessing the effect of these holes on FSW process.

Tools were passed through a heat treatment process after the initial machining to increase their hardness. The heat treatment process was performed as per ASTM A 681.

Figure 3.3: Tool Design: Featureless base (top left), 6 Holes (top right), 10 holes (bottom right), tool dimensions (bottom left)

3.4 Design of Experiments (DoE)

The design of experiment (DoE) can be defined as the optimization of the experimental effort required to highlight variables that influence the experimental process (Majdi, Esfahani, & Mohebbi, 2019).

3.4.1 Response Surface Methodology (RSM)

Taguchi and Response Surface Methodology (RSM) are used as statistical analysis tools. In the current work, RSM was used. Table 3.4 presents a comparison of the two techniques.

The RSM investigates an appropriate approximation relationship between input and output and identifies the optimized operating conditions for the process under study or a region of the factor field that fulfils the operating requirements (Aydar, 2018).

Table 3.4: Comparison of Taguchi and RSM

Taguchi	RSM
Helps screen out important process parameters	Helps optimize the key process parameters
Costlier due to larger number of experiments	Cost efficient due to lesser number of experiments
Mostly used in linear interactions only	Shows significance of all possible combinations
Provides the average response value at given levels of parameters	Three dimensional surfaces produced by RSM help visualize the effect of input parameters on output in the entire range mentioned

Three parameters were varied during the experiments and consequently their effect was observed on tensile strength, and micro-hardness. Microstructure was also observed to analyze the grain formation in different zones of the welded material. Table 3.5 shows the design matrix used during experimental work. Software Design-Expert 12 was used to design the experiments.

Table 3.5: Design matrix for experimental analysis

Sr. No	Traverse Rate (mm/min)	Tool Speed (rpm)	Tool Type
1	80	1750	2
2	80	1500	3
3	80	2000	1
4	80	1500	1
5	80	2000	3
6	40	1500	1
7	40	2000	1
8	40	1750	3
9	20	2000	3
10	20	1750	1
11	20	1750	2
12	20	1500	3
13	40	2000	2
14	40	1500	2
15	40	1750	1

3.5 Tensile Testing

Tensile testing was carried out on specimen prepared according to ASTM E8/E8M−16a standard (Fig. 3.4). Specimen were cut from the welded sheets using EDM wire cut.

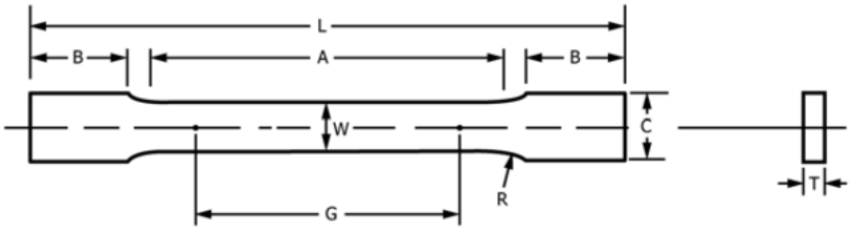


Figure 3.4: Standard sample for tensile test

Table 3.6: Dimensions for tensile test (sub size) specimen as per ASTM E8/E8M−16a

G – Gauge length	25 ± 0.1 mm	A – Length of reduced cross section	32 mm
R – Radius fillet	6 mm	B – Length of grip section	30 mm
L – Overall length	100 mm	C – Width of grip section	10 mm
W – Width	6 ± 0.2 mm	T - Thickness	1 mm

SHIMADZU universal testing machine (Figure 3.5) was used for performing tensile tests. Tests were carried out at a strain rate of 0.5 mm/min. The results reveal ultimate tensile strength, yield point and percent elongation.

Figure 3.5: Universal testing machine

Figure 3.6: Specimen for tensile test

3.6 Microstructural analysis

Microstructure of the welded materials undergoes changes due to heating and shearing effect. This change is of vital importance in understanding the mechanical and material properties of the welded material. Hence microstructure of the different zones formed on the welded samples was analyzed.

But before the analyzing stage, the specimen were prepared as per the ASTM E3−11 standard. This preparation is important as it makes the surface of sample smooth, thus making it possible to view the surface of the material through microscope. Sample preparation is also important for hardness tests as hardness test cannot be carried out on rough surface. The steps in preparation of the samples are detailed below:

3.6.1 Sampling

Samples were cut from welded specimen using EDM wire cut. Their size was 25mm x 10 mm x 1mm.

3.6.2 Mounting

Samples of small size require mounting to be carried out so that grinding and polishing is done with ease. Bakelite powder was used for mounting the samples in a mounting press.

3.6.3 Grinding & Polishing

Grinding of the mounted samples was carried out on grinding machine using SiC emery papers of grit sizes starting from 150, 300, 600, 800, 1200 and finally 2000. Water was used a coolant to avoid damage to surface of sample due to heat and light pressure was exerted with hand. Grinding was followed by polishing which was carried out using alumina paste on velvet cloth.

Figure 3.7: Grinding & Polishing Machine

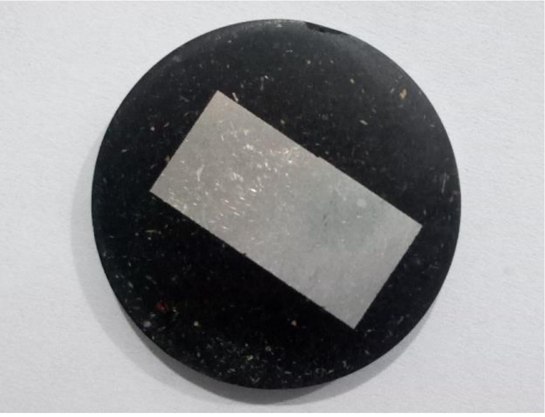


Figure 3.8: Mounted Sample

3.6.4 Optical Microscopy

Microscopic evaluation of the welded samples was carried out to observe the grain structure before and after the weld. Optical light microscope with magnification up to 800x was used to view the microstructure of the base materials, heat affected zone and the nugget zone. Attached camera was used to take photographs. Figure 3.9 shows the microscope used.

Figure 3.9: Optical Microscope

Figure 3.10: Micro-hardness Testing Machine

3.7 Hardness Testing

Micro-hardness tests were performed across the various zones developed as a result of the welding process. 100g force was used to make the indent on the polished specimen. Figure 3.10 shows the equipment on which the hardness test was performed.

Since AA2024 is a natural ageing material, the micro-hardness and tensile tests were conducted one week after the welding process in order to recover sufficiently the natural mechanical properties of the material.

Chapter 04: Results and Analysis

In this chapter, the results of different tests performed to evaluate the experimental process have been mentioned and subsequent discussion on those results has been presented. It also highlights the key parameters which affect the mechanical and material properties of the alloys during FSW. DesignExpert 12 was used to analyze the results.

Figure 4.1: Butt joint formed through FSW

4.1 Tensile Strength

Universal testing machine was used to determine tensile strength at room temperature. Complete array and values of tensile strength obtained have been given in Table 4.1. Details of the sample preparation for tensile strength tests have already been discussed in the previous chapter.

Tensile strength achieved for successful welds was less than that of base materials. Strength of base material alloys is 469 MPa and 316 MPa for aluminium alloy 2024 and 6061 respectively. Maximum value of strength achieved for welded samples is 255MPa which is 81% of the strength of the base material.

Sample No. 1, 3, 4 & 10 are the one with the defects. Different causes of these defects were observed e.g:

- Lack of sufficient heat generation
- Excessive heat generation
- Flash formation

Table 4.1: Experimental array and UTS results

Sr. No	Traverse Rate (mm/min)	Tool Speed (rpm)	Tool Type	Tensile Strength (MPa)	Weld Quality
1	80	1750	2	181	Defective
2	80	1500	3	210	Defect free
3	80	2000	1	154	Defective
4	80	1500	1	58	Defective
5	80	2000	3	209	Defect free
6	40	1500	1	189	Defect free
7	40	2000	1	209	Defect free
8	40	1750	3	255	Defect free
9	20	2000	3	234	Defect free
10	20	1750	1	161	Defective
11	20	1750	2	238	Defect free
12	20	1500	3	194	Defect free
13	40	2000	2	234	Defect free
14	40	1500	2	220	Defect free
15	40	1750	1	197	Defect free

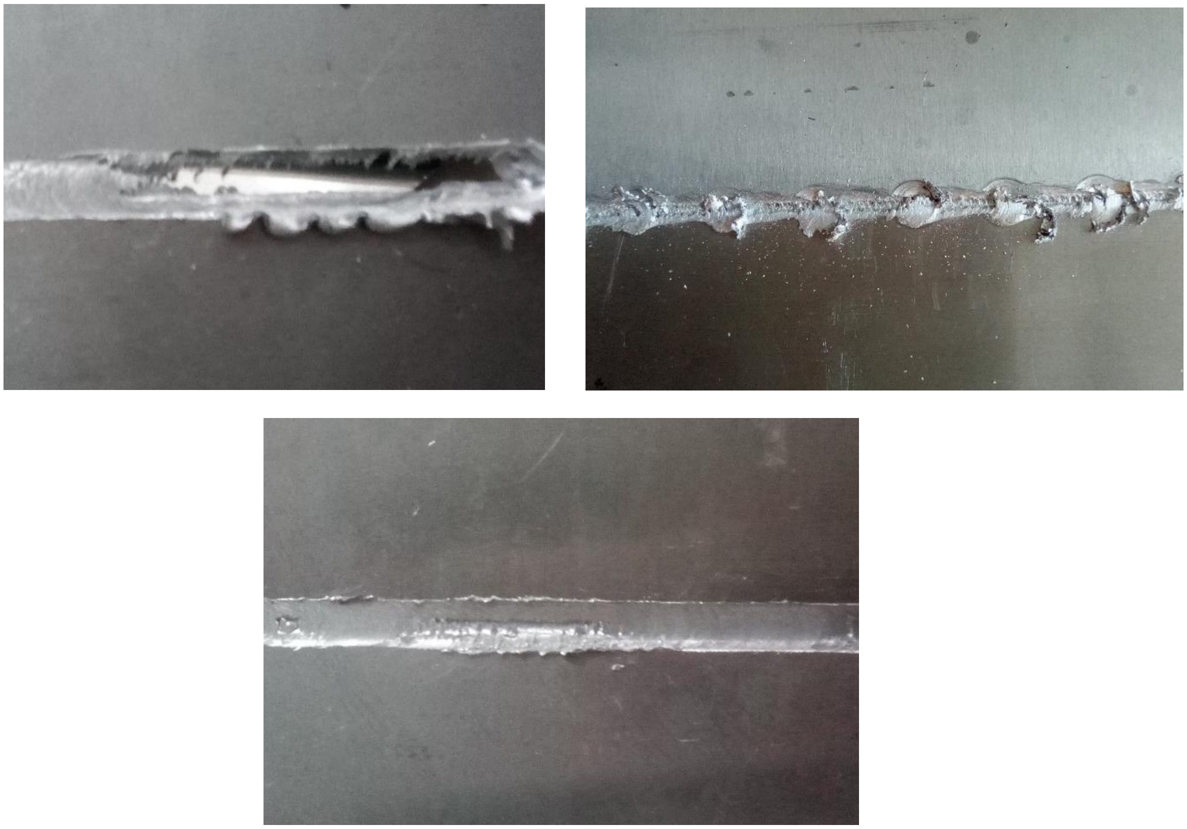


Figure 4.2: Defective welds

4.1.1 Response Surface Profiles

Results show that both, quality of weld and weld strength, are affected by changing the parameters under study. The focus of this study was to explore the effect of tool shoulder features on the results and considerable improvement in strength due to additional tool features is evident in the graphs in Figure 4.3 and response surface profiles in Figure 4.4. Each graph and profile show the results for tensile strength for a single tool. Response surface profiles provide a clearer comparison of the effectiveness of the tool features.

Another point evident in results is that decreasing the traverse rate strengthens the weld up to an optimum level after which degradation in weld quality begins due to excessive heat generation. Similarly, very high traverse rates lead to insufficient heat generation, thus leading to defects resulting in low weld strength and tunnel defect (Figure 4.2). Limitation to UTS can be attributed to weak HAZ at AA6061 side undergoing severe deformation.

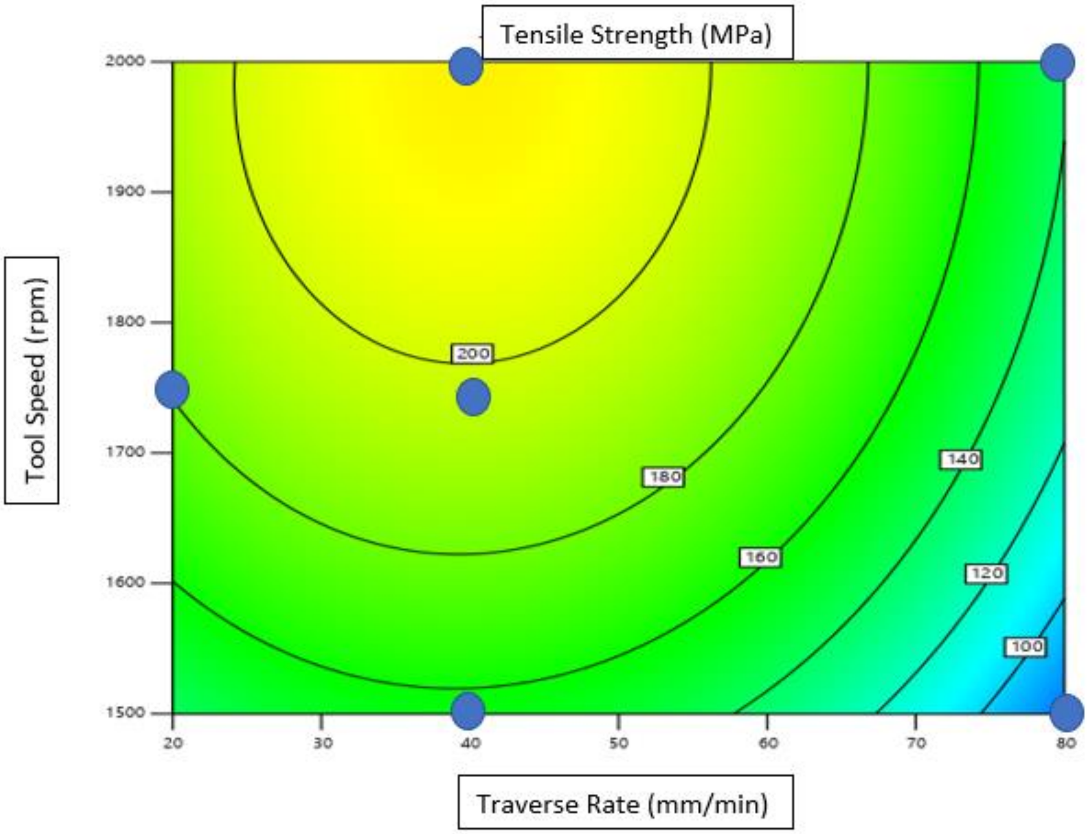


Figure 4.3 (a): Contour of Tool 1

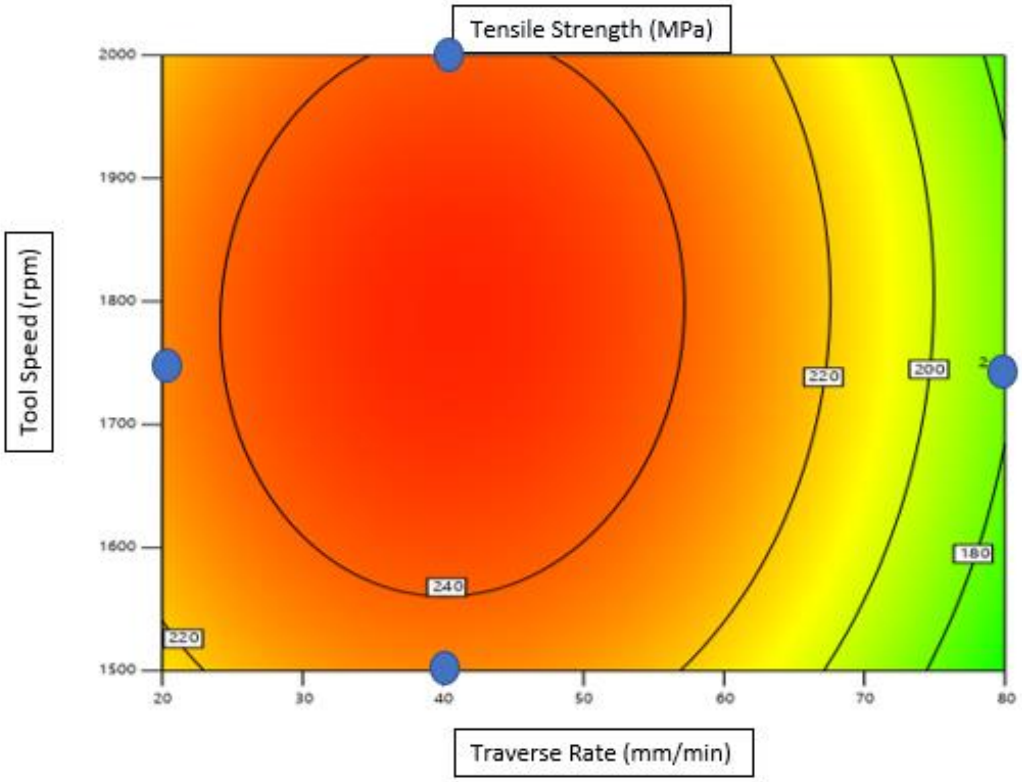


Figure 4.3 (b): Contour of Tool 2

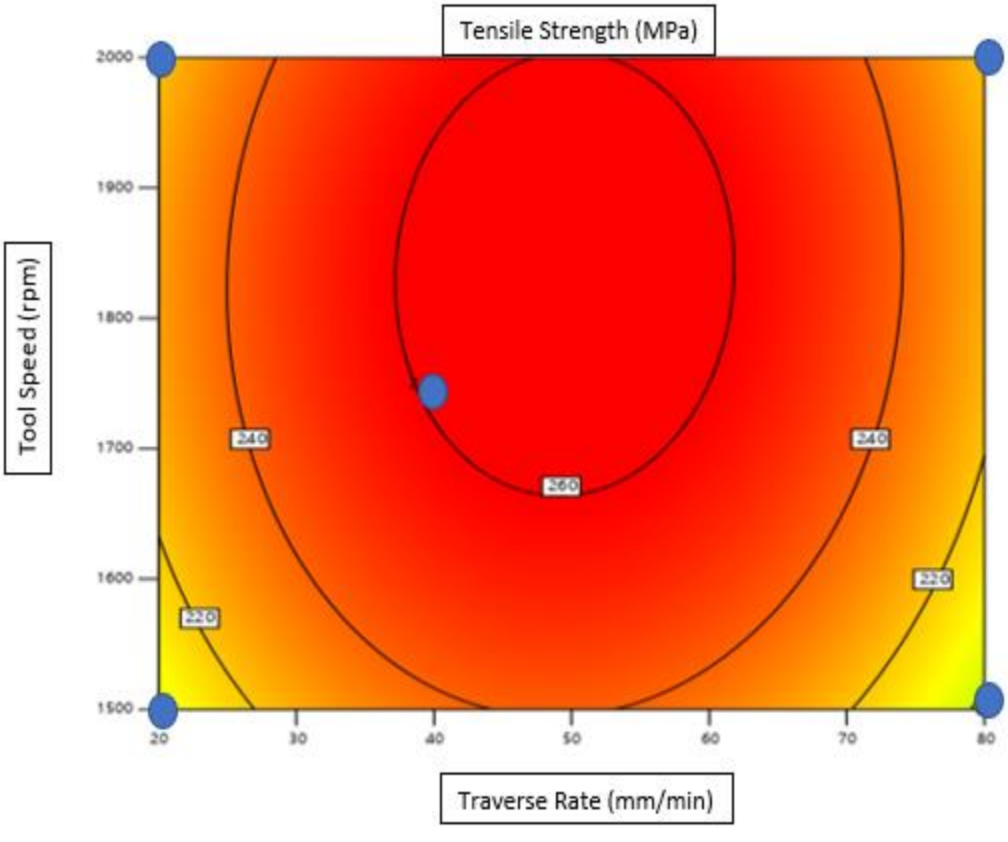


Figure 4.3 (c): Contour of Tool 3

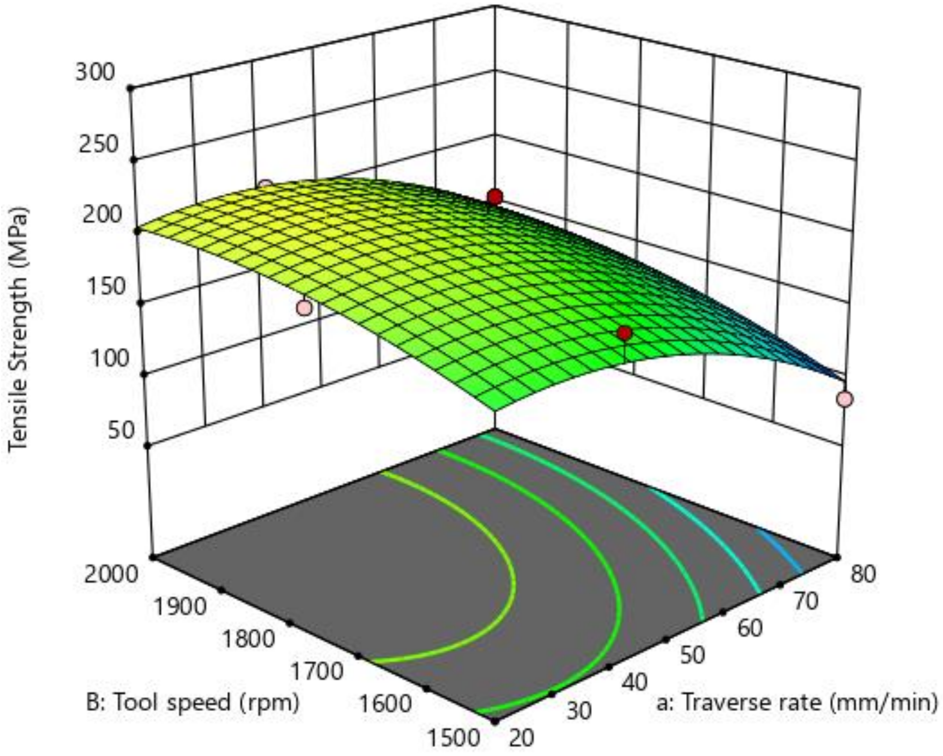


Figure 4.4 (a): Response Surface Profile for Tool 1

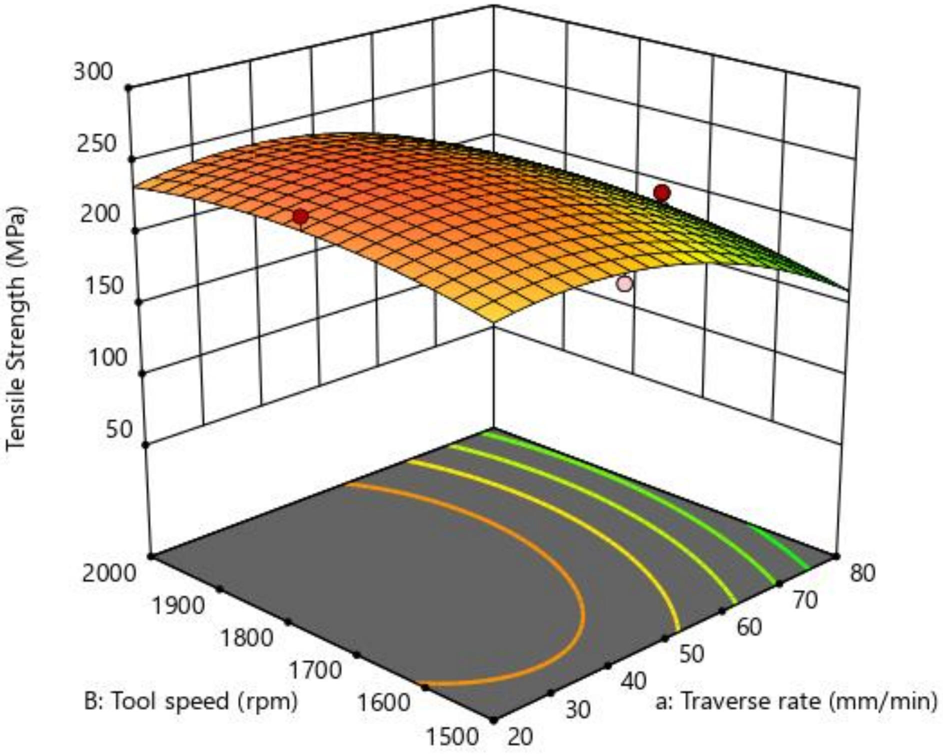


Figure 4.4 (b): Response Surface Profile for Tool 2

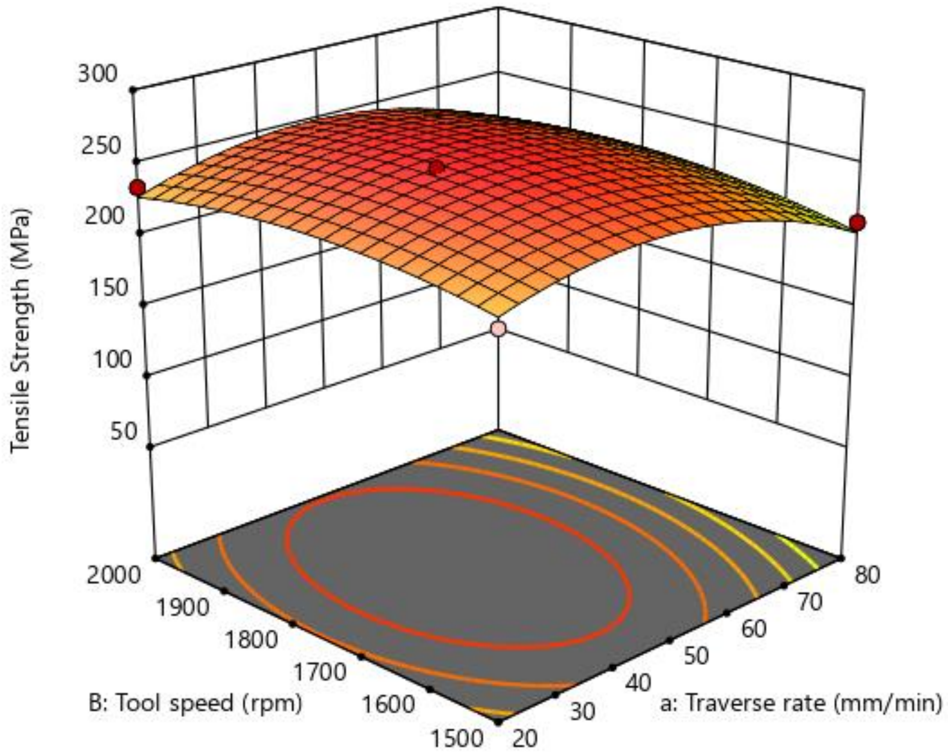


Figure 4.4 (c): Response Surface Profile for Tool 3

A steep dip in strength at higher traverse rates is observed for Tool 1 and 2, but the steepness reduces in case of Tool 3. The reason for the drop in strength for first two tools is that at higher traverse rates, heat input to the weld zone reduces, thus affecting the strength negatively, but in case of Tool 3, this lack of heat input is recovered by the additional holes on the tool shoulder base. These holes entrap the material sheared by the pin and cause further shearing and deformation in this material. This secondary shearing effect softens up and heats the material, which as a result produces a strong weld. It is noticeable that the temperature achieved in tool 3 is still less than that achieved by featureless tool. Although secondary shearing heats the material but it keeps the temperature lower than the featureless tool and compensates the heat input through combination of heat and better mixing mechanism. Therefore, we can conclude that additional features help achieve strong welds at relatively lower temperatures. Similar finding has been reported by Mugada (Mugada & Adepu, 2018).

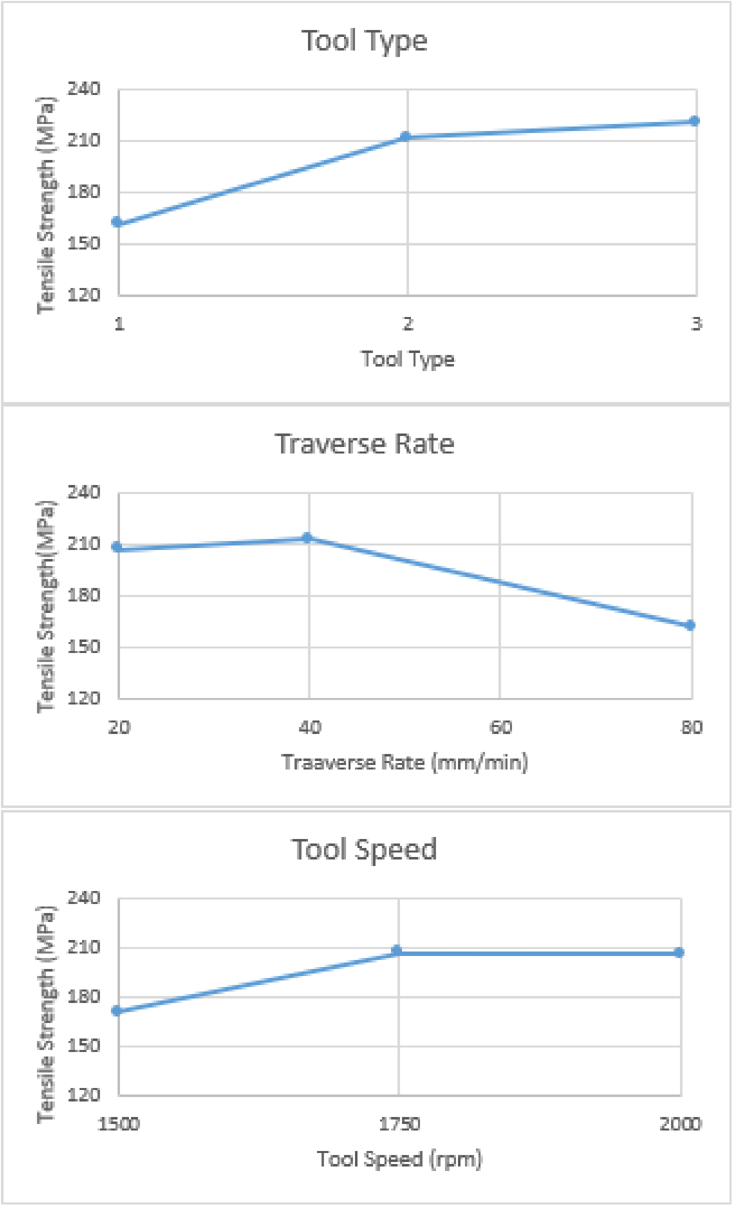


Figure 4.5: Main effects plot of means for UTS

4.1.2 ANOVA

Analysis of variance is a statistical tool used to evaluate the relative importance of the control factors. The result of ANOVA shows that the studied process variables are significant factors influencing the tensile strength of FSW joints. Quadratic model was used for ANOVA in this case.

Table 4.2:ANOVA for tensile strength

Factor	Term df	F-value	P-value
a:Traverse rate (mm/min)	1	11.49	0.0195
a^2	1	8.39	0.0339
B-Tool speed (rpm)	1	4.77	0.0808
C-Tool type	2	17.93	0.0048
aB	1	0.0315	0.8662
aC	2	2.78	0.1542
BC	2	.7087	0.5358
B^2	1	2.62	0.1667

The relative significance of the three parameters calculated on the basis of F-values is enlisted in the table below:

Table 4.3: Relative impact of different parameters

Parameter	Relative Impact (%)
Traverse rate	33.61
Tool speed	13.96
Tool type	52.44

4.1.3 Regression Model

A mathematical model is developed for each tool type to predict the tensile strength of friction stir welded AA6061 and AA2024 aluminum alloy joints. The coefficients of the regression model for tensile strength were calculated at 95% confidence level using Design-Expert 12.

Equation 1:

TS (Tool type 1) = -825.05121 + 2.78467* Traverse rate + 1.02814*Tool speed - 0.000177*Traverse rate*Tool speed - 0.034885*(Traverse rate)^2 - 0.000265*(Tool speed)^2

Equation 2:

TS (Tool type 2) = -668.90515 + 2.85930* Traverse rate + 0.962602*Tool speed - 0.000177*Traverse rate*Tool speed - 0.034885*(Traverse rate)^2 - 0.000265*(Tool speed)^2

Equation 3:

TS (Tool type 3) = 718.05302 + 3.71584* Traverse rate + 0.975371*Tool speed - 0.000177*Traverse rate*Tool speed - 0.034885*(Traverse rate)^2 - 0.000265*(Tool speed)^2

The regression model predicted tensile strength values near to the actual experimental values, e.g. the strength obtained from Eq. 3 for optimal parameters was 229 MPa as compared to the actual value of 255 MPa.

4.1.4 Optimization of Parameters and Confirmation Test

Optimized results were obtained for the parameter values shown in Table 4.4. The confirmation test was carried out for tensile strength and it was concluded that value obtained from regression model (229 MPa) was near to the values obtained (246 MPa) after actual test conducted according to optimal process parameters.

Table 4.4: Optimized parameters

Parameter	Optimized Value
Traverse rate (mm/min)	40
Tool speed (rpm)	1750
Tool type	Tool 3

The optimization of parameters to have a weld of high strength was also carried out through software utilizing the same data and using the same software which was used for DOE and ANOVA i.e. Design-Expert 12. Values obtained were identical to the experimental results.

4.2 Microstructure

Microstructure of the welded samples was analyzed through an optical microscope. Specimen were prepared for microscopic analysis using conventional method discussed in Chapter 3. The different zones formed near the weld line along with base material are shown in Figure 4.5.

Figure 4.6 (a): Base Material 6061

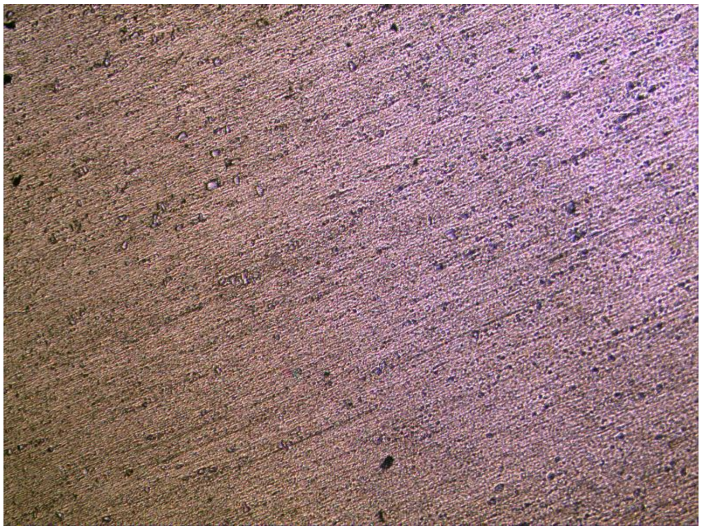


Figure 4.6 (b): Base Material 2024

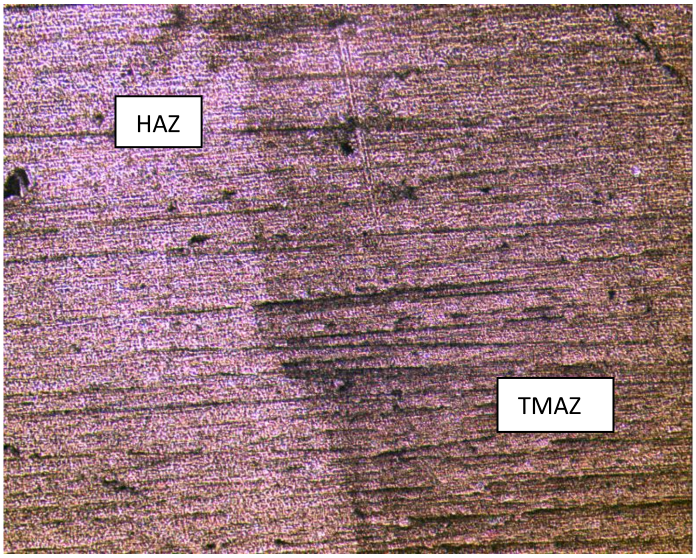


Figure 4.6 (c): HAZ & TMAZ 6061

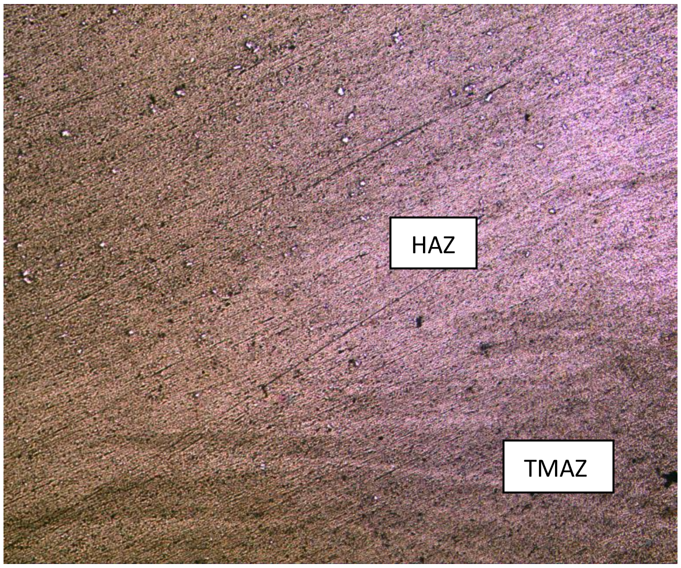


Figure 4.6 (d): HAZ & TMAZ 2024

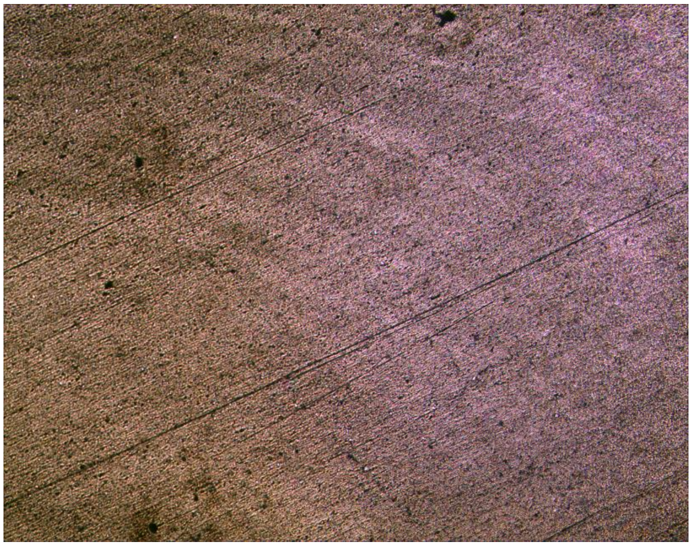


Figure 4.6 (e): Onion Rings in Stir Zone

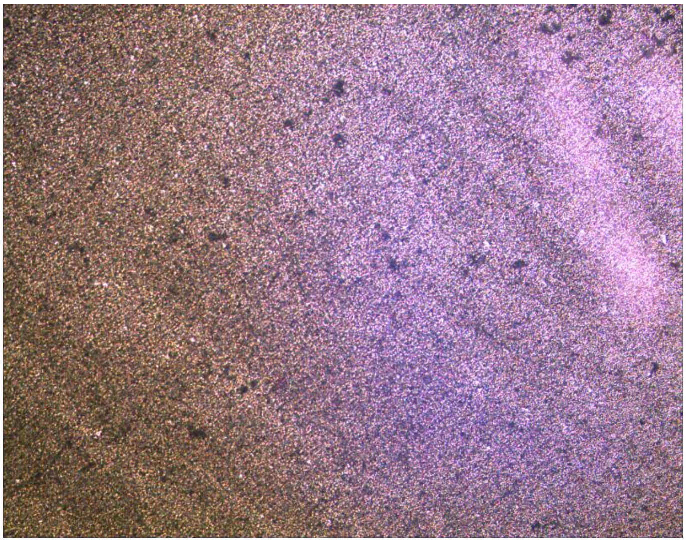


Figure 4.6 (f): Stir

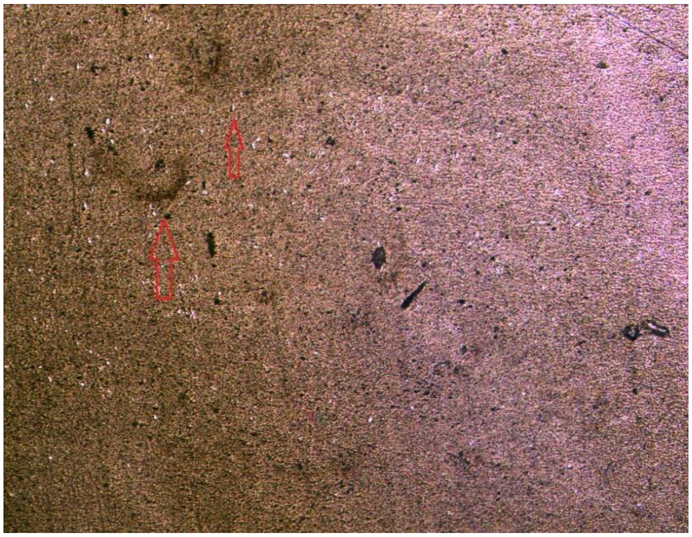


Figure 4.6 (g): Imperfect Mixing in sample

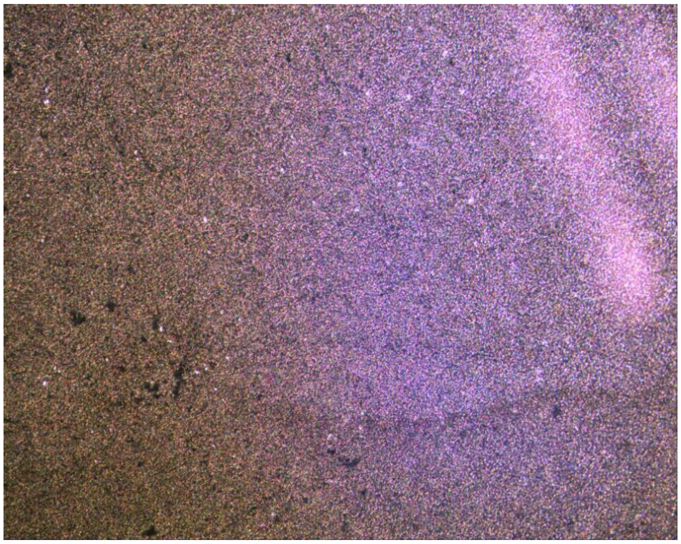


Figure 4.6 (h): Imperfect mixing in sample

Refinement of grain structure was observed in stir zone of the welded samples and grains finer than that of base materials were formed. Such structure is produced by the dynamic recrystallization and static grain growth after welding. 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. Typical onion rings are also visible in the microscopic image of the weld line. The images highlight a distinction between the different zones formed TMAZ and HAZ of both alloys are visible in the images (Fig. 4.5 (c) & 4.5 (d). Greater plastic deformation was observed for AA 2024. Amongst others, one reason for this is that it was on the advancing side and hence had the tool rotation and travel in same direction. The case was opposite on retreating side i.e. 6061, resulting in lesser deformation.

Although the trends mentioned above have been general in all welds, but process parameters still had an impact on the microstructure of the samples. It was observed that the weld appearance improved and flashing of material decreased with using tools with holes. This was because the holes provided better material flow and material mixing. The holes capture plastically deformed semi molten material and help in better mixing for a strong weld and prevent it from going out of the weld line to form weld flash. It is important to note that efforts to improve microstructure lead to decline in tensile strength of the weld and vice versa. Hence a compromise is necessary between microstructure & grain refinement and strength of the weld.

4.3 Hardness Test

Hardness test was carried out to determine the hardness at different zones formed as a result of the FSW process. Measurements were taken at HAZ, TMAZ, and base material of both alloys along with the combined measurement at stir zone. The results of the test are presented in Table 4.5. The effect of tool type and tool speed on hardness is shown in Figure 4.4 and the weld profiles have been presented in Figure 4.5.

Table 4.5: Results of microhardness test

Sr. No	Traverse Rate (mm/min)	Tool Speed (rpm)	Tool Type	Hardness
2	80	1500	3	90.8
5	80	2000	3	87.5
8	40	1750	3	96
9	20	2000	3	99.1
12	20	1500	3	92
11	20	1750	2	81.1
13	40	2000	2	94.4
14	40	1500	2	95.8
6	40	1500	1	79.8
7	40	2000	1	79.5
15	40	1750	1	86.8

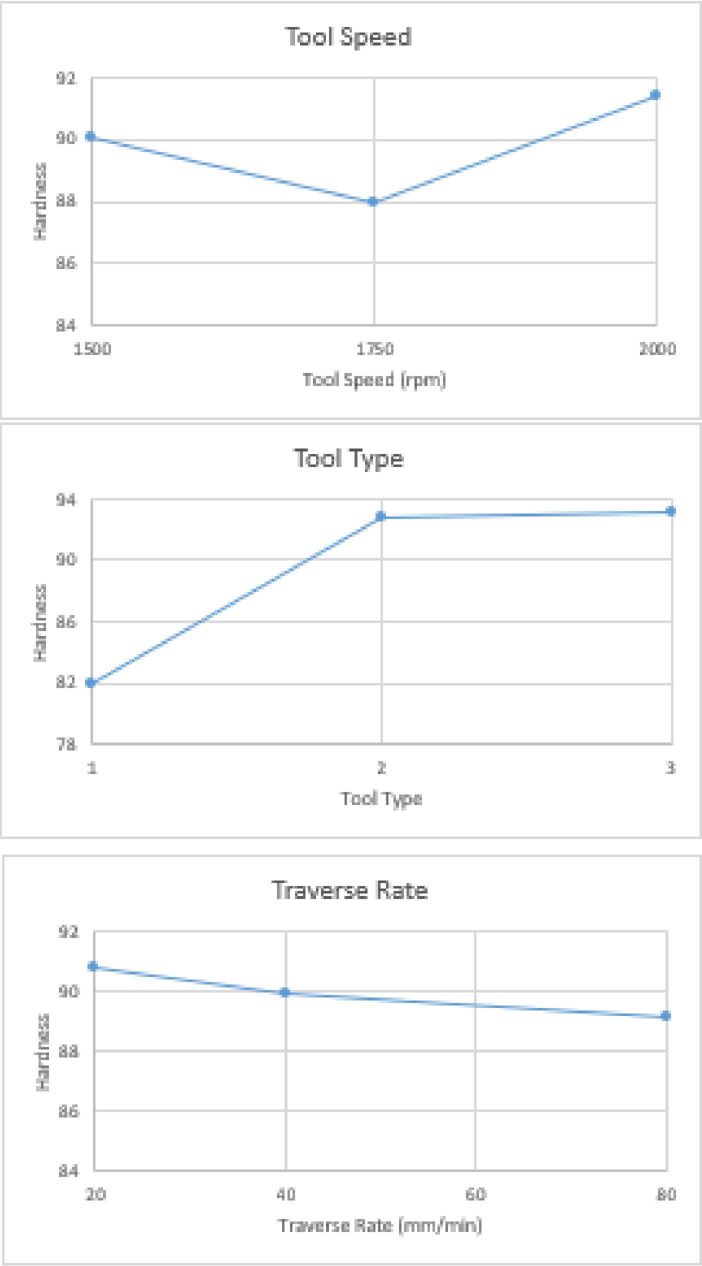


Figure 4.7: Main effects plot of means for hardness

Figure 4.7 highlights the fact that the tool type has the largest impact on hardness. As already mentioned, the holes on tool shoulder base entrap the material and lead to plastic deformation. This results in enhanced grain refinement in stir zone, thus improving the hardness. The effect of grain size on hardness is explained the Hall-Petch equation which says that smaller the grain size, higher the hardness (Zhu et al., 2014). This is also the cause of improved hardness of stir zone as compared to HAZ and TMAZ.

Following conclusions have been reached from the results of the hardness tests:

- The hardness of weld nugget was considerably lower than that of base material AA2024 but slightly higher than that of base material AA6061.
- Relative reduction of hardness moving from base material to HAZ was lesser for AA 2024 as compared to AA 6061. The reason was that severe plastic deformation imparted because of high speed stirring on advancing side (AA 2024) helped in grain refinement and strain hardening of HAZ of AA 2024.
- HAZ of AA6061 had least hardness value, even lesser than AA6061 base metal. This is because as we move away from the stir zone, the grain size starts to increase.
- Advancing side has higher temperatures which lead to greater hardness at that side.

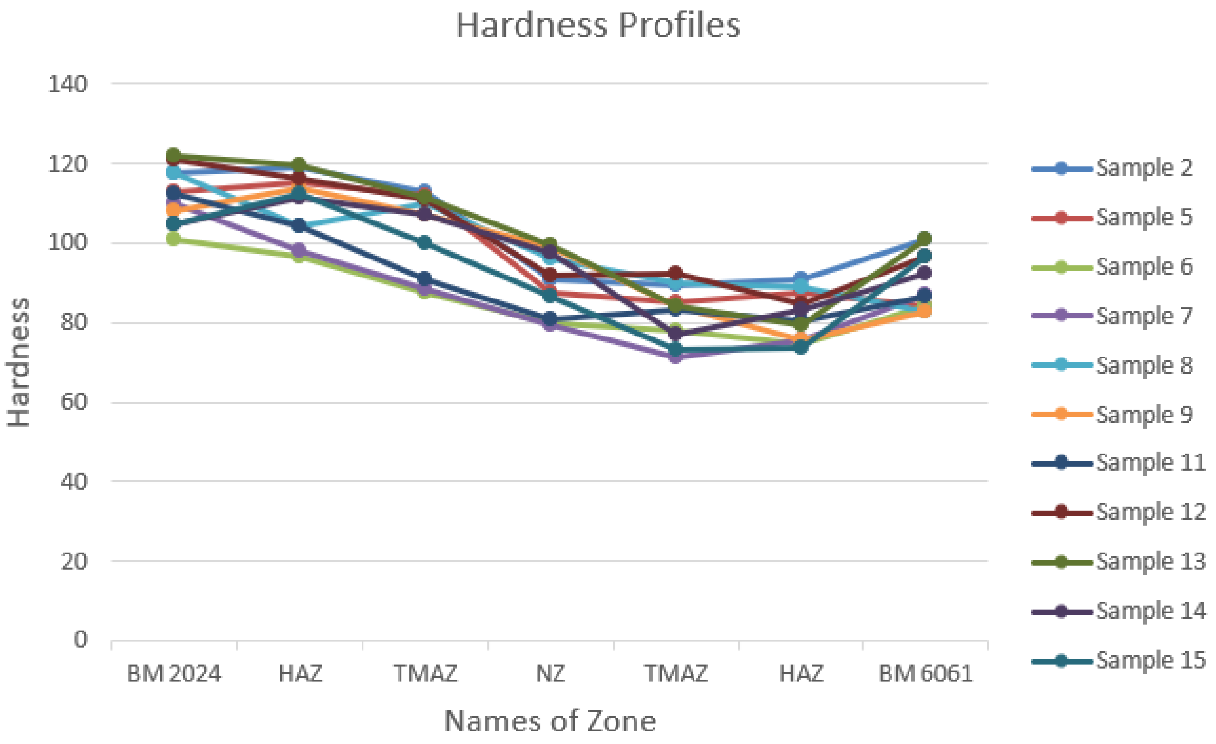


Figure 4.8: Hardness results

4.4 Benchmarking with Existing Literature

Benchmarking is recognized as an essential tool for continuous improvement of quality. It proves to be a concept helpful in innovation, rather than imitation (Rajashekharaiah, 2014). Past literature provides a foundation upon which efforts for further improvement can be based. It also provides rough criteria to analyze the results and provide a direction to future research.

Researchers working on bonding and joining of materials have tried to analyze their results by calculating the percentage of strength achieved in the joint to the strength of the base material. To analyze the strength achieved in this work, percentage strength achieved in past works for similar process and materials was studied. An overview of a few of those past works is presented in Table 4.5. Strength achieved in current research work is 81% of the base material AA6061 which is not only acceptable but also better compared to many cases.

Table 4.6: UTS obtained in past FSW research works

Sr. No	Title of Publication	UTS of welded sample / UTS of base material	% Strength Achieved
1	"Influences of tool shoulder diameter to plate thickness ratio (D/T) on stir zone formation and tensile properties of friction stir welded dissimilar joints of AA6061 aluminum–AZ31B magnesium alloys" (Malarvizhi et al., 2011)	190MPa / 216MPa	87%
2	"Mechanical, microstructural and fracture properties of dissimilar welds produced by friction stir welding of AZ31B and Al6061" (Dorbane, Mansoor, Ayoub, Shunmugasamy, & Imad, 2016)	87MPa / 110 MPa	78%
3	"Development and testing of fixtures for friction stir welding of thin Aluminum sheets" (Ahmed & Saha, 2018)	236MPa / 310 MPa	76%
4	"Friction Stir Welding of dissimilar aluminum alloys" (Khalid, 2018)	234MPa / 320MPa	73%
5	"Effect of basic parameters on weld strength in micro-FSW of Aluminium-5052" (Abbasi, 2018)	180MPa / 228MPa	78%

Hardness profiles were also studied to have an idea for analysis of the hardness profile obtained in this work.

Typically, a W-shaped profile is obtained for hardness test of samples joined through friction stir welding (Huang et al., 2017). It has also been usually observed that base material has the highest hardness as compared to other zones for FSW of dissimilar materials, as has been reported by Khalid et al. (2018). But for base materials which have a considerable difference between their properties, the curve of the W-shaped profile becomes less steep (Dorbane et al., 2016). Same has been the case in the current research.

Chapter 05: Conclusion

This research work was conducted in field of Friction Stir welding of thin sheet of dissimilar aluminum alloys. Conclusion of this research work including dimensions of research for future work in this field has been described below.

5.1 Conclusion

In this work, effect of tool rotation speed (rpm), tool traverse speed (mm/min) and tool shoulder features on the final quality of Friction Stir Welded butt joint of thin sheet (≤1 mm) of AA2024 and AA6061 was examined.

The quality of the Friction Stir Welded parts was characterized on the basis of tensile strength, microstructure and hardness. The main findings of the study are summarized below:

1. Experiments of FSW on thin sheet of Aluminum Alloy 2024 and 6061 were conducted successfully. RSM was used to design the experiments.
2. Focus of the research was to find optimum process parameters for quality characteristics like tensile strength, hardness & microstructure.
3. Optimized tool rotation speed and traverse rate found as a result of this research work are 1750 rpm and 40 mm/min respectively. Tool with the maximum holes at its shoulder end (Tool 3) gave the best results.
4. The heat input was found to be in strong relation with tool welding speed and traverse rates.
5. Visual and microscopic analysis of the welds showed defects in welds without featureless shoulder.
6. Enhanced mechanical properties were obtained with tool with most holes at its base giving a strength of 255 MPa (81% of base material) and hardness of 92 Hv. This is attributed to the complete mixing of material for both AA 2024 and AA 6061.

5.2 Recommendations for Future Work

Considering all the work that has been done in this research so far, following areas are recommended for future investigation:

- During FSW, heating and cooling rate plays vital role, especially in case of thin sheet where heat loss is of considerable significance. The effect of pre-heating and post heating on joint quality of AA2024 and AA6061 should be investigated.
- Design of fixtures for micro-FSW keeping in view the need to minimize the heat loss from bottom side of sheets being welded while at the same time maintaining the strength required for the fixture to support the system.

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