Examining the Friction Stir Welded AA 6063 Aluminum Alloys' Strength and Quality Using Response Surface Methodology

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Abstract
One of the most widely used aluminum alloys for automotive, marine, and aerospace applications is AA 6063, a precipitation-hardened alloy that mostly consists of silicon and magnesium. Friction stir welding is a cost-effective and adaptable solid state joining method for aluminum alloys as compared to traditional welding. Through impacting elements including defect formation, material fusion, residual stresses, and microstructure, a weld's quality directly impacts its strength. To achieve the best possible weld strength and performance, it is crucial to ensure high-quality welds through appropriate welding methods, parameter control, and quality assurance systems. Three crucial process variables that affect weld quality are traverse speed, rotation speed, and tool profile. In order to guarantee the design and development of flawless welded joints, these characteristics are optimized. The goal of this study is to comprehend the AA 6063 alloy friction stir welding method and how Response Surface Methodology (RSM) is used to optimize the input parameters. It also intends to evaluate the mechanical properties of the friction-welded alloy and the base alloy by performing micro tensile and micro hardness tests. The micro tension test is used to determine the weld's ultimate strength. The results indicate that the most important value of tensile strength, 131.66 N/mm^2, corresponds to 1000 rpm spindle speed, 20 mm/min table feed, and friction stir welded tool profile TTH (Tapered Threaded). Additionally, the average micro hardness values on the heat-affected zone, stir-zone, and thermo mechanically-affected zone were 84.5, 86, and 88.5 VH, respectively. This work also uses optical microscopy and X-ray radiography to examine the weld quality.

Keywords: Friction stir welding, Al 6063 alloys, ultimate tensile strength, micro hardness, material fusion, residual stresses, microstructure, mechanical properties, process parameters, RSM.

1. INTRODUCTION

The aluminum alloy AA6063, belonging to the 6XXX group, comprises of silicon and magnesium as its principal alloying elements, along with traces of copper and manganese to enhance its mechanical properties. Its qualities include low density, strong electrical and thermal conductivity, high corrosion resistance, superb surface finish, and light weight. It is heat treatable and can be readily used for welding. Hence it is preferred where weight reduction is crucial such as in the shipbuilding, and aerospace industry applications. It is easily extrudable and responds well to polishing, chemical brightening, anodizing and dyeing. Various grades of AA6063 aluminum alloy are available, each tailored to specific applications or manufacturing requirements, among these T6 is the commonly available grade. Researchers are focused on the selection and optimization of a suitable joining method for aluminum alloys. Prolonging the service life of aluminum alloy structures can be achieved by improving their resistance to corrosion using appropriate filler materials during welding or by providing protective coatings after joining. Welding or brazing techniques can frequently fix damaged parts, reducing the need for replacement expenditures. Aluminum alloys can be joined using a variety of techniques, including friction stir welding, high-power density fusion joining using laser and electron beam welding, arc welding, and MIG (Metal Inert Gas) or TIG (Tungsten Inert Gas) welding. Because there is no melting at the weld nugget, friction stir welding is one of these that can be used on these materials with success [1]. For both similar and dissimilar high strength aluminum alloys, the Welding Institute (TWI Ltd., England, and UK) developed friction stir welding in 1991 as a cost-effective joining method [2]. A plasticized area is formed in the work piece material surrounding the probe due to frictional heat generated by relative movement between the tool and the substance. A solid-state welding technique called friction stir welding (FSW) is used to fuse materials together, particularly metals like copper, titanium, aluminum, and their alloys. FSW produces welds without ever melting the materials to be linked, in contrast to conventional fusion welding methods. Because of this feature, FSW is especially helpful for materials that are challenging to fuse together with traditional techniques, like those that have high melting temperatures or are prone to deformation and flaws when melted. The Friction Stir Welding (FSW) machine, often known as an FSW machine, is a device that fuses materials together without melting them by applying mechanical pressure and frictional heat.

Rajinsh Singh[1] obtained the mechanical characteristics of tensile strength, bend test, and micro-hardness, while the weld joint's qualities are assessed based on the presence of weld flaws and microstructure. For every process parameter and tool shape, the hardness of welded samples at the nugget zone is about the same. On the other hand, it was discovered that the tensile and bending strengths decreased with transverse speed but varied with rotational speed [3].

Itai Mumvenge's[1] study on the microstructure progression and its correlation with micro hardness profiling of friction stir welded butt joints on comparable AA6061-T6 Aluminum alloys1. For this investigation, rotational speed and feed rate were the only variables that were employed and changed. Tool steel, W302, was utilized, and the tool's shape remained unchanged. Friction stir welds were assessed using the X-ray digital radiography method in addition to visual inspection. By looking for the presence or absence of weld faults, evaluation made it possible to evaluate the weld integrity. The findings showed that there are no root problems in the welds. The assessment of the micro structural joint contact revealed total penetration in the X-rays [4].

Huseyin Tarik Serindag[1] has empirically and mathematically examined the friction stir welding (FSW) method's ability to weld magnesium alloys, which are challenging to fuse together using fusion welding. To achieve this, several welding conditions were used to join magnesium alloys. Friction stir welding of AZ31 Mg-alloy plates was done at 1200 rev/min rotational speed and 80, 100, 120, and 140 mm/min translational speed. K-type thermocouples that were embedded were used to measure the temperature evolution in the weld zone during the welding process. Ten thermocouples were used to measure the temperatures on the advancing and retreading sides. The mechanical characteristics and the hardness distribution of the weld were assessed using tensile and Vickers hardness tests, respectively. Friction and plastic deformation during FSW produce heat. Since heat generation has a significant impact on mechanical characteristics and microstructure, understanding the temperature distribution is essential. It was noted that when the translational speed decreased, the heat produced by the FSW process increased and the grain structure became more refined. The temperature and stress distributions in the welded joint during FSW were ascertained by performing finite element analyses using ANSYS software to model the FSW process. To replicate the FSW process, an APDL (ANSYS Parametric Design Language) code was created. There were two phases to the transient nonlinear finite element analyses. The first is thermal analysis, which measures the heat transfer from the pin and shoulder to the plates [5].

This study provides a thorough evaluation of the tensile strength and weld quality of AA6063 alloy friction stir welded (FSW) joints through careful examination. To aid in analysis, the three input parameters—rotational speed, welding speed, and tool profiles—that are essential for FSW are carefully tabulated using Response Surface Methodology (RSM). The assessment includes an investigation of the FSW joints made specifically using AA6063 alloy in terms of micro tensile strength, micro structural analysis as well as an x-ray radiography analysis to determine the overall quality of the weld.

2. MATERIALS AND METHODS

The material used for friction stir welding is AA 6063- T6 alloys of specified dimensions. The chemical composition of the AA 6063 substrate is obtained using icp-AES (DW-TY-9900). Single pass butt weld was produced on AA 6063-T6 aluminum alloys of 6mm thickness to fabricate similar FS welded square butt joints of 125 mm length. The substrate plates were resized to a dimension of 125mm × 50mm × 6mm as shown in figure1 (a) with the help of a power hack saw machine (PRECIDRILL HP200). The schematic representation of the substrate was stipulated on figure 1(b).

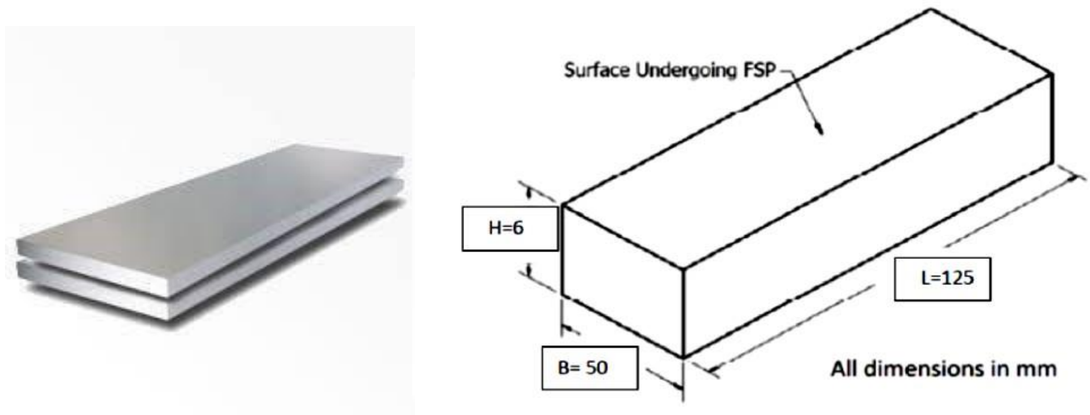


Figure 1. (a) AA 6063-T6 substrate used for FSW and its (b) schematic diagram.

2.1. Tool Design and Set-Up

The design of the tool is important because a well-made tool can improve the quality of the weld and allow for the fastest possible welding speeds. It is evident that for all welding temperature ranges, the tool material needs to be suitably robust, resilient, and hard. To reduce heat loss and thermal damage to the machinery, it should also have a low thermal conductivity and strong oxidation resistance. Tool profile, spindle rpm, and feed rate are tool-related process parameters that influence the tensile strength of the weld. *P Biswas* [1] found that tools with tapered pins produced better mechanical properties for the friction stir welded joints [6–9]. Several high carbon steel tool profiles, such as tapered threaded, have been selected for the current study are shown in figure 2.

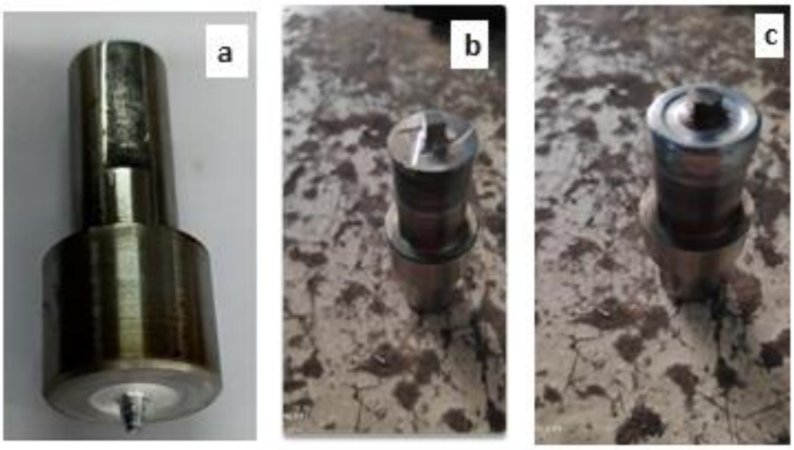


Figure 2. FSW Tool Profiles (a) Tapered Threaded [TTH], (b) Square Cylindrical [SQC] and (c) Hexagonal [HEX] configurations.

2.2 Response Surface Methodology (RSM)

One statistical method used in the Design of Experiments (DOE) process is Response Surface Methodology (RSM). It is especially helpful for streamlining procedures or systems when several input variables (factors) affect the response of interest (such as the quality, yield, or performance of a product). RSM entails building a mathematical model that explains how the response and the input variables relate to one another. The term "response surface" comes from the fact that this concept is frequently depicted as a surface in multidimensional space. Depending on the objective (maximizing yield, minimizing defects, etc.), the purpose is to determine the best possible combination of input variables that maximizes or minimizes the response.

Usually RSM consists of three primary steps: Creating experiments with the goal of gathering information on the response variable at various input variable levels. Creating a response surface description by fitting a mathematical model to the experimental data. Examining the model to determine the best input parameters for obtaining the intended result. One kind of response surface methodology (RSM) utilized in Design of Experiments (DOE) is the Box-Behnken design. It is an efficient and well-balanced architecture for response surface estimation, especially when it comes to fitting a second-order polynomial model with three levels for each factor.

A statistical and mathematical method called Response Surface Methodology (RSM) is used to model and examine the relationship between input variables, or factors, and one or more output variables, or responses. RSM is used to optimize the number of spindle speed and feed rate for various tool profiles. Understanding how various elements affect a response and optimizing a process or system for desired results are made easier with its assistance in experimental design and optimization. To improve the quality and efficiency of a system or process, RSM makes it easier to understand factor-response correlations, process condition optimization, and sensitivity assessments. RSM is used, in particular, in

friction stir welding (FSW) of aluminum alloys to model and optimize welding parameters for intricate processes, hence enhancing the performance and quality of the final weld [10, 11].
In this work, the highest weld strength is achieved by optimizing the welding parameters, such as feed, weld speed, and tool profile, using RSM. Twenty-seven samples were examined, and the results showed that the tensile strength was optimized.

2.3 Friction Stir Welding

The NC standard friction stir welding equipment FSW -2T-NC was used to weld 27 samples. On the AA6063 substrate, the friction stir welding depicted in figure.3 is performed using the parameter sets from Response Surface Methodology (RSM). There are three options for the spindle speed: 800, 1000, and 1200 rpm; the feed rate is 20 mm/min, 25 mm/min, and 30 mm/min. Figure.4 depicts the different zones and indicates that the thickness of the welded zone is 5.86 mm.

Figure 3. Friction Stir Welding (FSW) Process on AA 6063

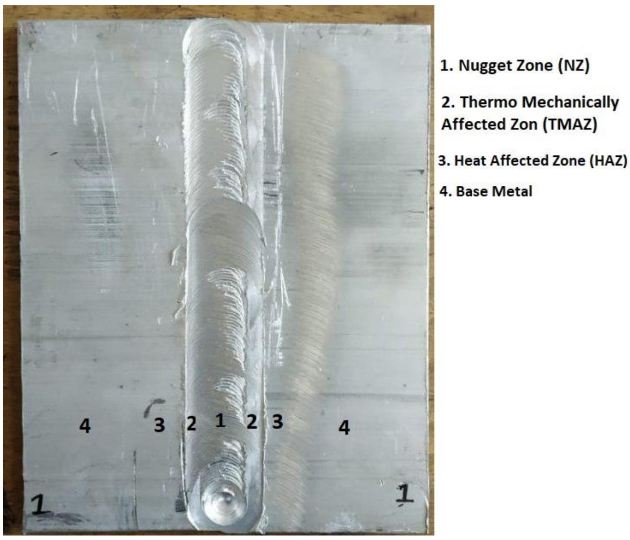


Figure 4. Friction Stir Welded Sample

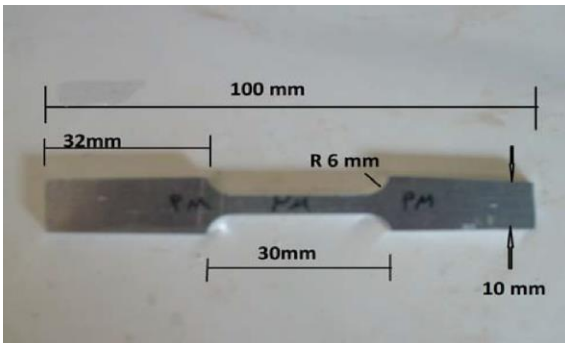


Figure 5. Micro tensile test sample.

2.4. Tensile Strength Analysis

A computerized tensile testing machine (WDW 200 testing machine) with a maximum load capacity of 25 KN was used to conduct the tensile test. From each weld, a single test sample was removed from the stable welded area. Using a CNC milling machine, the FSW welded specimens are cut into the 32 mm x 6 mm x 6 mm cubical shape with an area of 36 mm^3, as required by ASTM E8M standard. The micro tensile strength of each of the 28 specimens—27 welds and one base specimen—was tested after they were prepared in accordance with the standard. It is seen that in the case of the welded specimen, the fracture occurred precisely at the stir zone. Figure 5 displays a typical sample along with its dimensions that was ready for a tensile test. The particular materials being machined, the cutting tools being used, and the machining process itself all affect the relationship between tensile strength and feed rate. Tensile strength and feed rate have a complicated relationship that needs to be carefully considered in light of a number of variables [12, 13]. Optimizing machining efficiency and quality can be achieved by conducting testing and experimentation, as well as by adjusting the feed rate correctly dependent on the material being machined. The feed rate, rotating speed, and tool profile can all have an impact on the quality of friction stir welding (FSW). Prioritizing excellent welding techniques, quickly addressing any weld defects, taking into account residual stresses and material properties, and customizing the machining strategy to the unique characteristics of the welded work piece are all necessary to minimize potential problems and maximize tool performance.

2.5. Micro Hardness Analysis

The device utilized in this instance is the VM 50 maker depicted in figure 6.The duration of the indenting force application is predetermined. The diagonals of the resulting indentation are measured and noted. There are variations in the forces and indenters used in the Vickers test. A fixed weight of 95 grams is applied to the square base pyramidal diamond indenter to push it into the substance to be examined. The force is delivered for a predetermined amount of time before stopping to allow the forces to reach static or equilibrium conditions. (10 to 15s during regular test periods) and is then eliminated. The value in millimeters is obtained by measuring and averaging the resulting unrecovered indentation diagonals. The Vickers hardness number (HV) is computed using these length measures.

Figure 6. Vickers Hardness tester.

The Vickers's hardness equipment consists of a indenting test material of diamond indenter. It consist of 5 components; positioning unit, loading unit, optical microscope unit, display unit, measurement unit. The test material after etching and microstructure analysis is subjected to Vickers's hardness test. The material is placed on the stage desk and the diamond indenter in the form of right pyramid having angle between opposite faces 136º is brought to the surface. A load of 95 g m is applied by turning 'Test Force selector knob' with a dwell time of 10 sec for indentation. After 10 sec the load gets unloaded and an indentation mark form on the surface of material. This mark will be in the shape of square. The diagonal of this indentation is measured using high magnifying lens. Comparing the diagonal length corresponding to the value in standard data table we can obtain the hardness number as VHN.

2.6 Micro structural Analysis of weld

Friction Stir Welding (FSW) is a solid-state joining process that produces high-quality welds without melting the materials. For aluminum alloys like AA 6063, which is commonly used in applications requiring good surface finish and high corrosion resistance, FSW offers several micro structural benefits. Here's an overview of the micro structural aspects of friction stir welded AA 6063 weld joints:

2.6.1 Micro structural Zones in FSW

FSW typically results in three distinct micro structural zones: Heat-Affected Zone (HAZ): This is the area around the weld that experiences a thermal cycle but does not undergo plastic deformation. The microstructure here may coarsen due to the heat. Thermo-Mechanically Affected Zone (TMAZ): This zone experiences both thermal and mechanical effects. The grains in this region are plastically deformed and elongated but retain some original material characteristics. Nugget Zone (NZ) or Stir Zone (SZ): This is the central part of the weld where the material is fully recrystallized due to intense plastic deformation and frictional heating. Fine, equiaxed grains typically characterize this zone due to dynamic recrystallization.

2.6.2 Grain Structure

Nugget Zone (NZ): The NZ in AA 6063 typically exhibits fine, equiaxed grains due to the dynamic recrystallization process during FSW. These fine grains contribute to the enhanced mechanical properties in the weld zone. Thermo-Mechanically Affected Zone (TMAZ): Grains in the TMAZ are elongated and deformed. The extent of deformation and grain refinement depends on the welding parameters such as tool rotation speed, traverse speed, and the tool's geometry. Heat-Affected Zone (HAZ): The HAZ usually shows coarsened grains compared to the base material due to the thermal cycle it undergoes during welding.

2.6.3 Precipitation Behavior

In AA 6063, the FSW process can influence the distribution and size of precipitates. The intense heat and plastic deformation can dissolve existing precipitates, and upon cooling, new precipitates can form.

Dissolution and Re-precipitation: In the NZ, the high temperatures can lead to the dissolution of strengthening precipitates (like Mg_2Si in AA 6063). Upon cooling, re-precipitation can occur, often resulting in a more uniform distribution of fine precipitates, which can enhance mechanical properties.

2.7 Radiographic Analysis of weld

[14] A popular non-destructive testing (NDT) technique for determining weld quality is radiographic analysis, which looks for discontinuities in the weld profile, detects internal defects, and assesses weld penetration. It entails penetrating the material with X-rays or gamma rays to provide an image that shows interior flaws or discontinuities in the weld. The most important samples were used for the radiography examination, and the most precise tensile strength values were acquired utilizing tapered threaded (TTH) tool profiles and a table feed rate of 20 mm/min. With a spindle speed of 1200 RPM, 1000 RPM, and 800 RPM, respectively, the samples are identified as Weld (W1), Weld (W2), and Weld (W3).

3. RESULTS AND DISCUSSIONS

3.1 Initial Micro structural Characterization

The chemical composition of AA 6063 Aluminium alloy obtained from the inductively coupled plasma (ICP) analysis is given below. With weight percentages shown, the inductively coupled plasma (ICP) analysis of the aluminum alloy AA6063 T6 reveals the elements' chemical makeup. It is important to note that the exact chemical composition of alloy 6063 can vary slightly depending on the supplier, manufacturing method, and specific alloy standards or specifications (e.g., ASTM, EN, and JIS). The obtained ICP-OES result of AA6063 T6 aluminum alloy is closely matching with the standard composition in accordance with UNS standard no. A96063. The weight percentage of various elements is Al- 98.66 %, Mg- 0.549 %, Si- 0.376 % and trace elements.

The as received AA 6063 aluminium alloy was obtained in the form of a sheet of thickness 6mm, and Fig 7 illustrates the initial microstructure of the alloy. The images labeled as (a), (b), (c) and (d) shows the optical micro graph obtained at various etching period such as 5 sec. 10 sec, 60 sec and 180 sec respectively.

It can be seen that the grains were somewhat elongated, with significant twinning: the average grain size measured by linear intercept method was about 10 µm. And the maximum grain size is 6.5 µm and the minimum grain size is 14.5 µm. And the grain distribution based on ASTM Standard E112 is shown in figure 8.

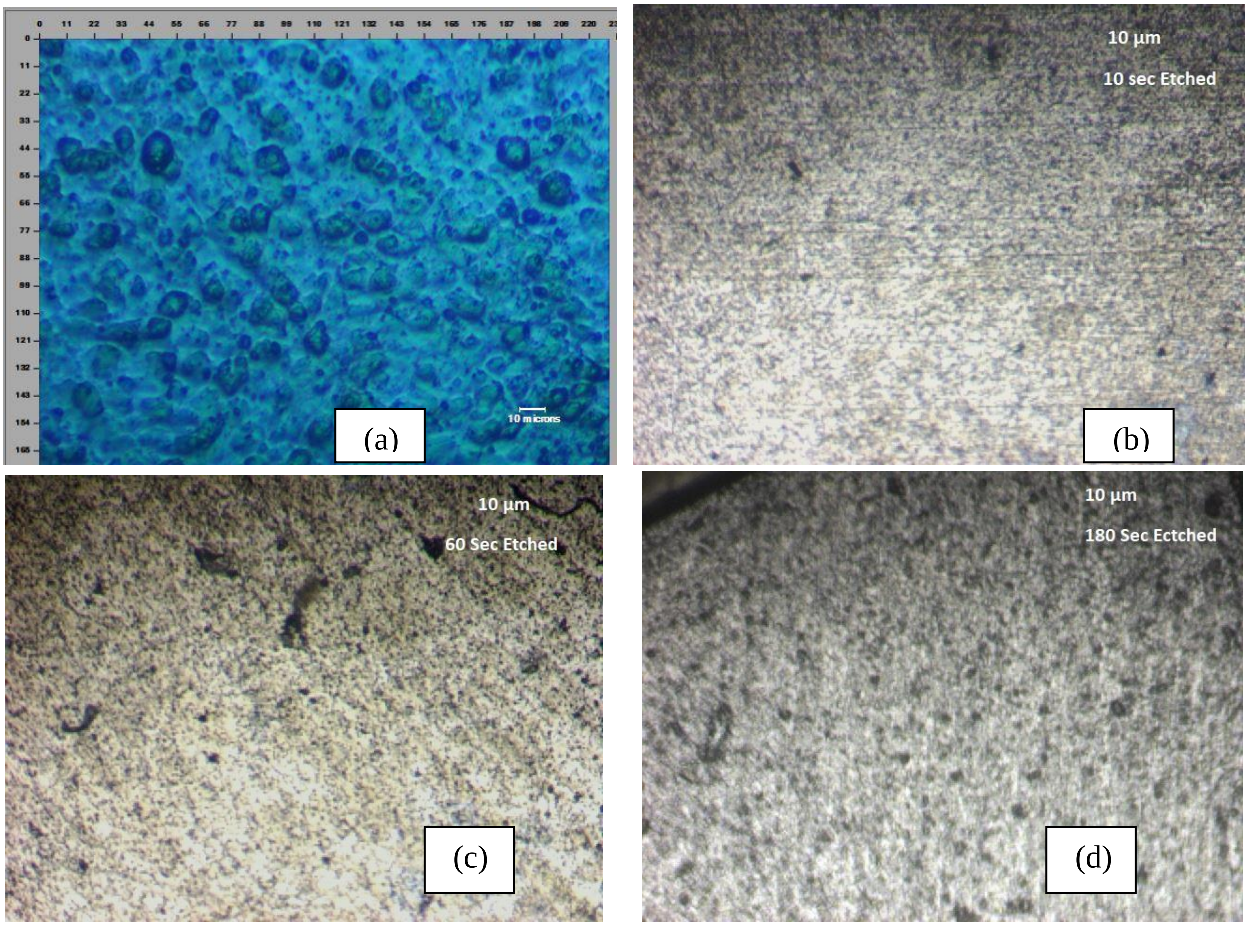
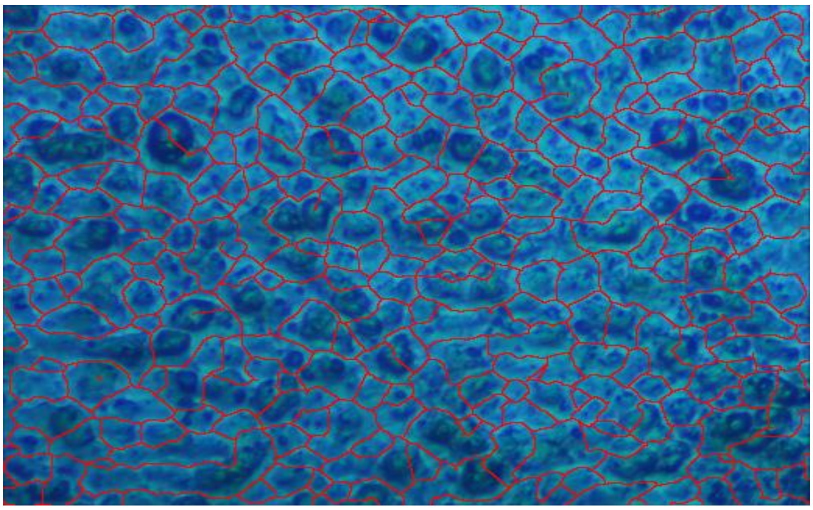


Figure 7. AA 6063 Aluminum alloy base metal as received at various etching periods



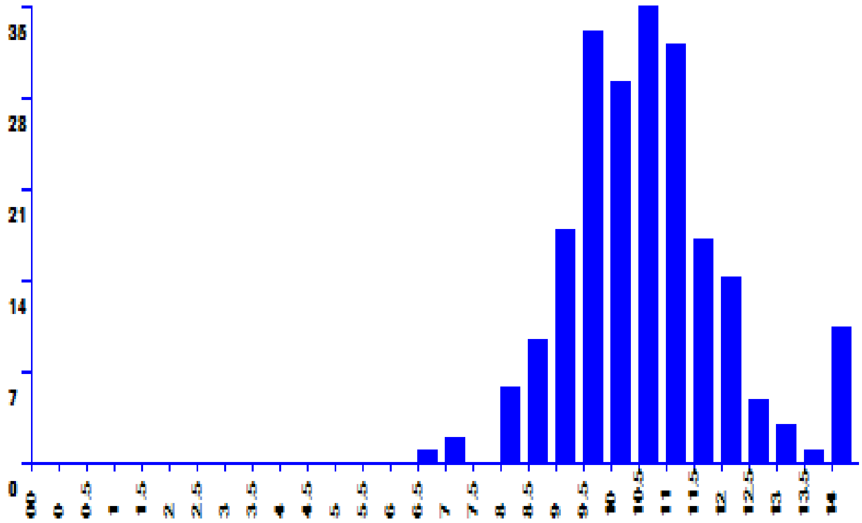


Figure 8. Grain Distribution of Base Metal (AA 6063 Aluminium alloy)

3.2 Input Parameters Obtained from Response Surface Methodology (RSM)

The spindle speed limit ranges of 800, 1000, and 1200 rpm, the feed rates of 20 mm/min, 25 mm/min, and 30 mm/min, and the three tool profiles listed in Table 1 are used to tabulate the input parameters from RSM. The spindle force is 8 KN and the weld length is 115 mm. The first profile number for the tools is 1.Tapered Threaded (TTH). 2. Hexagonal (HEX) 3. Square Cylindrical (SQC).

Table 1. Input Parameters from RSM.

Sample Number	Tool Profile	Spindle Speed (RPM)	Feed Rate (mm/min	Sample Number	Tool Profile	Spindle Speed (RPM)	Feed Rate (mm/min
1	1	800	20	15	2	1000	30
2	1	800	25	16	2	1200	20
3	1	800	30	17	2	1200	25
4	1	1000	20	18	2	1200	30
5	1	1000	25	19	3	800	20
6	1	1000	30	20	3	800	25
7	1	1200	20	21	3	800	30
8	1	1200	25	22.	3	1000	20
9	1	1200	30	23	3	1000	25
10	2	800	20	24	3	1000	30
11	2	800	25	25	3	1200	20
12	2	800	30	26	3	1200	25
13	2	1000	20	27	3	1200	30
14	2	1000	25				

According to *Devanathan Chockalingam's* observations, spindle speed and axial force have the greatest effects on the tensile strength of the welded connections, followed by welding speed [15].

The goal of the current effort was to optimize the weld strength by welding parameter adjustments. The result was interpreted as the weld joints' ultimate tensile strength, and statically engineered combinations were suggested using the Box Behnken design of tests with 28 inputs. Three factors were found to be experimentally correlated with ultimate strength; the highest ultimate strength was achieved with a tapered threaded cylindrical tool profile, 1000 rpm spindle speed, and 20 mm/min Y-axis feed. Maximum values of strength are 133.576 N/mm^2 with a desirability factor of 1. These findings are summarized.

ANOVA was used by *A. Pradeep and S. Muthukumaran*[1] to predict the ideal tensile strength of friction stir –welded low alloy steel plates [16]. The p-value of the present quadratic model, which was less than 0.0001, indicated that the model was significant in predicting ultimate tensile strength (UTS). The produced model appears to be accurate based on the high degree of fitness between the actual UTS and the one predicted by the response surface methodology (RSM), as indicated by the R-squared value of 0.9785. The adequacy of the experimental data for the proposed model is further supported by the agreement between the adjusted and anticipated R-squared values.

Additionally, the sufficient precision value of 15.934 was higher than 4, demonstrating the model's ability to distinguish between the important and trivial effects of process parameters on UTS. As a result, it seems that the created model is very appropriate for describing the friction stir welding (FSW) process parameter circumstances. Table 2 provided a summary of these results. The following is a summary of these findings.

Table 2. ANOVA Quadratic Model for Tensile Strength

Source	Sum of Squares	df	Mean Squares	F-Value	P-Value
Model	7120.06	9	791.12	34.51	<0.0001 Significant
A-Tool Profile	3000.8	1	3000	130.9	<0.0001
B-Spindle Speed	13.18	1	13.18	0.5751	0.473
C-Y Axis Feed	76.82	1	76.82	3.35	0.1099
AB	15.09	1	15.09	0.6584	0.4438
AC	1.84	1	1.84	0.0801	0.754
BC	23.62	1	23.62	1.03	0.3439
A^2	3761.11	1	3761.11	164.07	<0.001
B^2	334.64	1	334.64	14.6	0.0065
C^2	5.57	1	5.57	0.2429	0.6372

With a correlation coefficient of 0.95782, the ideal combination demonstrated the selected model's fitness for assessing the experimental data utilizing *Maanvizi Muthukumar*[1]*'s* Box Bhenken design of experiments [17]. The current statistical parameters for ultimate tensile strength in the FSW process are as follows, which were derived from the model generated above. The high degree of fitness between the actual and projected values of UTS is indicated by the R-Squared value of 0.9785. With the number of predictor variables in the model taken into account, the corrected R-squared is 0.9526. It suggests that around 95% of the variability in UTS can be explained by the independent variables.

The model has a predicted R-Squared, or ability to predict, of 0.8253 based on the validation data set. It suggests that the model has a respectable level of accuracy for predicting UTS. The model's ability to navigate the design space is deemed adequate, as indicated by its score of 15.934. The study conducted by *R. Adalarasan* [1] investigates the effectiveness of response surface methodology and desirability analysis in determining the ideal combination of machining parameters to achieve the desired surface quality when working with Al6351/20%Al2O3 composite [18].

According to recent research, the model may be able to distinguish between noise and significant process parameter impacts on UTS. Together, these values suggest that the constructed model fits the process parameter circumstances in FSW well and can be utilized to predict UTS. The Model F-value of 34.51 indicates that the produced model may be statistically significant. The F-value obtained indicates that the model terms have a significant impact on the response variable, with noise accounting for only 0.01% of the total F-value. The p-values for the individual terms indicate that the only significant terms in the model are A (tool profile), A^2 (square of tool profile), and B^2 (square of spindle speed).

This suggests that these factors have the biggest effects on the tensile strength. The ideal set of process parameters for a friction stir welded tool profile of tapered threaded (TTH) was determined to be a spindle speed of 1000 rpm and a table feed of 20 mm/min. This combination yielded the maximum tensile strength of 133.576 N/mm^2 with a percentage error of 1.455%. The desirability graph below makes it easy to see the optimal value of the results.

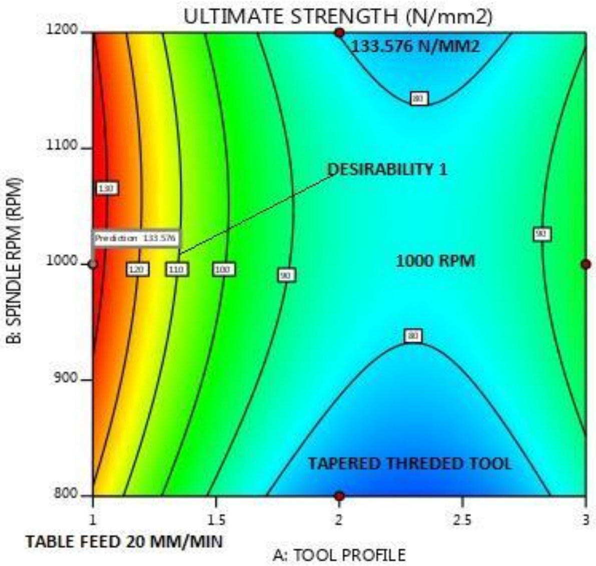


Figure. 9: Desirability Graph

Table: 3. Results of confirmation experiments.

Measured outputs	Objective	RSM output	Exp. output	% of error

Yield strength (MPa)	Maximize	108.25	120.35	10.05
Ultimate tensile strength (MPa)	Maximize	126.33	131.66	4.04
% Elongation	Maximize	5.35	4.96	-7.86
Microhardness(HV)	Maximize	76.5	84.5	9.46

3.3 Micro Tensile Test

Tensile testing is done on the base material (175.61 N/mm^2) and on each of the 27 weld samples on their nugget zone. Peak load, peak stress, displacement at peak load, and strains at peak stress are all measured during this test. Figure 7 illustrates how the tensile strength of different samples varies in response to feed changes. When compared to other welds, the base material has a higher tensile strength. Tensile strength variation is displayed on the graph for spindle speeds of 800, 1000, and 1200 rpm with feed rates of 20, 25, and 30 mm/min. The findings were displayed for various tool profiles, including hexagonal (HEX), square cylindrical (SQC), and tapered threaded (TTH).

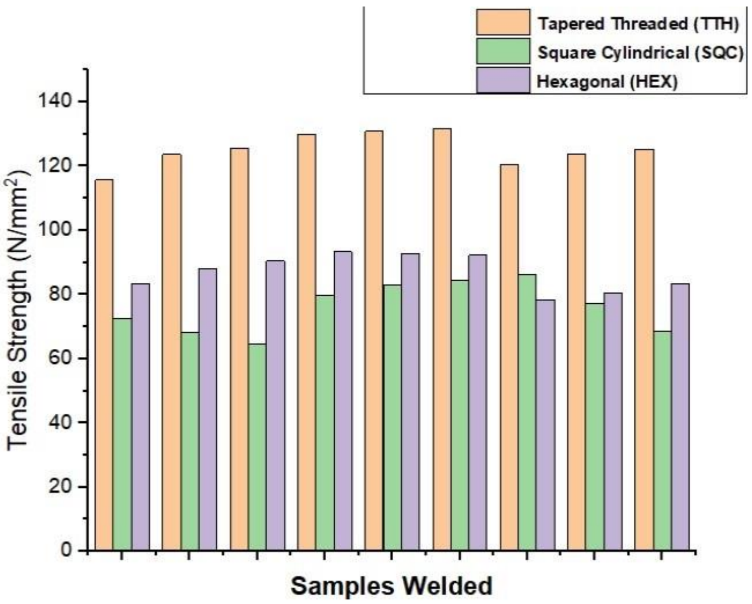


Figure 10. Tensile strength vs Samples welded.

As can be seen from the above findings, different tool profiles, spindle speeds, and table feed rates all had an impact on the tensile strength. The tapered threaded profile with a feed rate of 30 mm/min and a spindle speed of 1000 rpm corresponds to the highest value of tensile strength, which was measured at 131.66 N/mm^2. For more research to examine the impact of feed rate and spindle speed on tensile test, the tapered threaded profile with the highest tensile strength is selected. In order to examine the weld penetration of a chosen sample and its impact on tensile strength, a radiography test was also performed. In fact, tool profiles can be impacted by the tensile strength of friction stir welded (FSW) aluminum 6063 alloy, especially with regard to wear and deformation.

The tool experiences considerable mechanical loads as a result of material flow and heat cycling during FSW. The tapered threaded tool profile yields the best welds with the highest tensile strength out of the three tool profiles employed in this application: hexagonal, square cylindrical and tapered threaded. *Daniel F.O. Braga*[1] concentrated on identifying the most significant FSW parameters on UTS for all joints and how they interacted with one another[19].The Box Behnken design of studies suggests that the ultimate strength (response) for the statically determined combinations (28 inputs) matches to the three variables that were also established through experimentation. With a spindle speed of 1000 rpm and a Y axis feed of 20 mm/min, the sample characteristics of a tapered threaded cylindrical tool profile yielded the maximum ultimate strength value of 133.576 N/mm^2. It was discovered that every single variable affected the final strength differently. The final strength rises to a significant range when the table feed value, which matches the tapered threaded profile, climbs from 20 mm/min to 30 mm/min. As a result, the tool with the tapered threaded profile is the more important one and has a greater weld strength value.

54.27% represents the difference between the weld strength and the minimum and maximum range. Furthermore, 74.85% is the joint efficiency.

3.3.1 Effect of Tensile Strength on Feed Rate and spindle speed

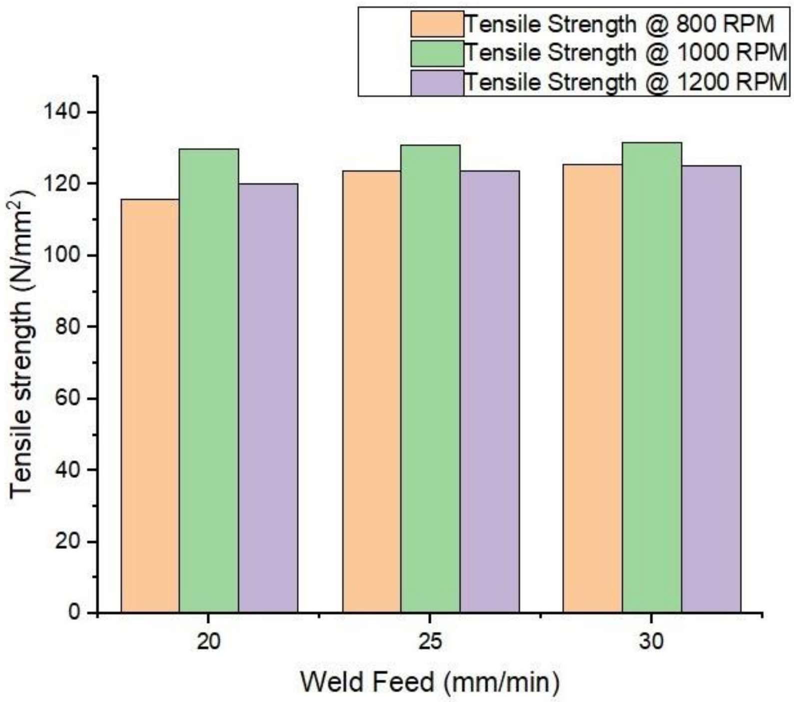


Figure 11. Tensile strength vs Table Feed corresponds (800 -1200 rpm) with TTH tool profile

Figure 8 illustrates how feed rate and spindle speed affect the tapered threaded sample's tensile strength. Table feed was shown to be impacted by tensile strength, with a little increase in spindle speed at lower feed rates. Tensile strength was shown to have an effect on spindle speed; it rose somewhat for each tool profile variation and as feed rate dropped. In this case, the highest value is 131.66 N/mm^2, which is consistent with a 20 mm/min feed rate, a 1000 rpm spindle speed, and a tapered threaded tool profile (TTH). Through its effects on material properties, residual stresses, tool wear, surface finish requirements, and machining technique, weld quality indirectly influences spindle speed.

3.4 Micro Hardness Test

Vickers micro hardness measurements were performed on the specimens situated at the centerline across the joint. A force of 100 g was applied, and the loading time was 10 s. Figure 9 displays the hardness profiles that match the TTH tool profile obtained from the welded joints. The picture shows how each joint's weld zones experience an increase in hardness. All joints formed at all transverse speeds exhibit a remarkably similar rise in hardness. Nonetheless, there was a small loss of hardness in the stir and heat-affected areas. In the stir zone, the joints produced at a weld feed rate of 30 mm/min exhibited the lowest hardness value. When a 20 mm/min weld feed was used, the welding hardness rose. The base metal's Vickers hardness rating is roughly 90HV.

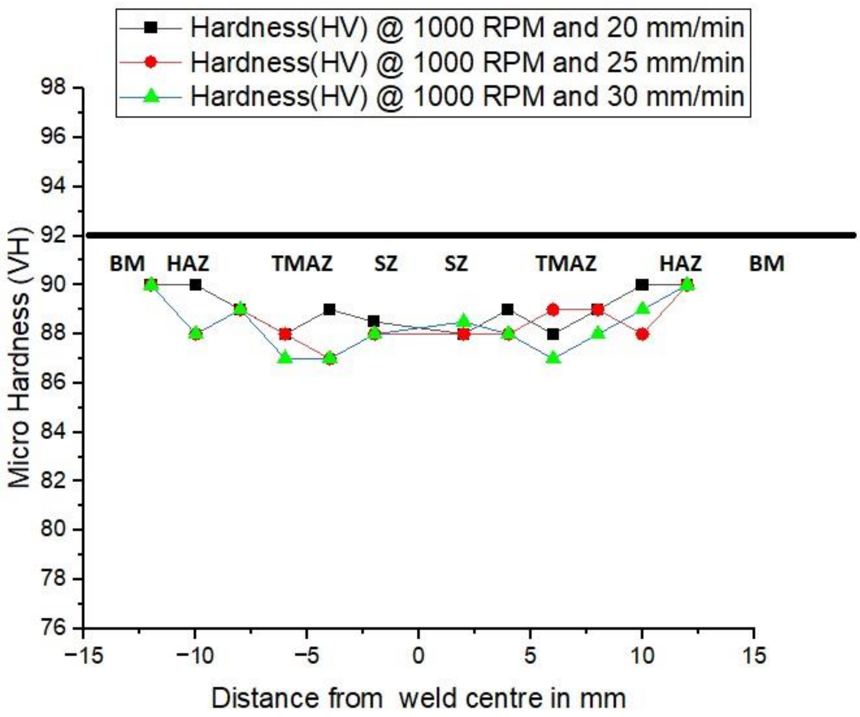


Figure 12. Micro Hardness profile of the weld joints

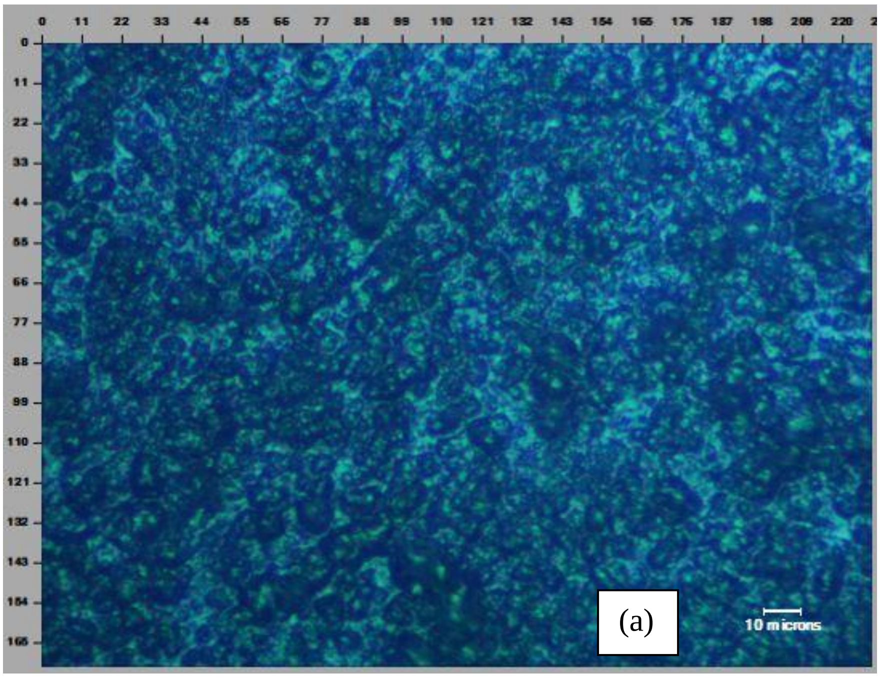
3.5 Microstructure Analysis.

It was determined by *M Ramamurthy*[1] *that* no flaws, cracks, and voids are observed in the weld zone of the specimens and smaller grain sizes are visualized which enhanced the mechanical strength of the aluminum alloy joint [20]. For validating the obtained values of optimal input parameter values and to validate the predicted values, a confirmation experiment is carried out in the considered setup and the obtained outcomes are tabulated in table 3 with % error from RSM predicted values. Observation shows results of confirmation and prediction values are closer enough with an acceptable maximum deviation of 9.46%.

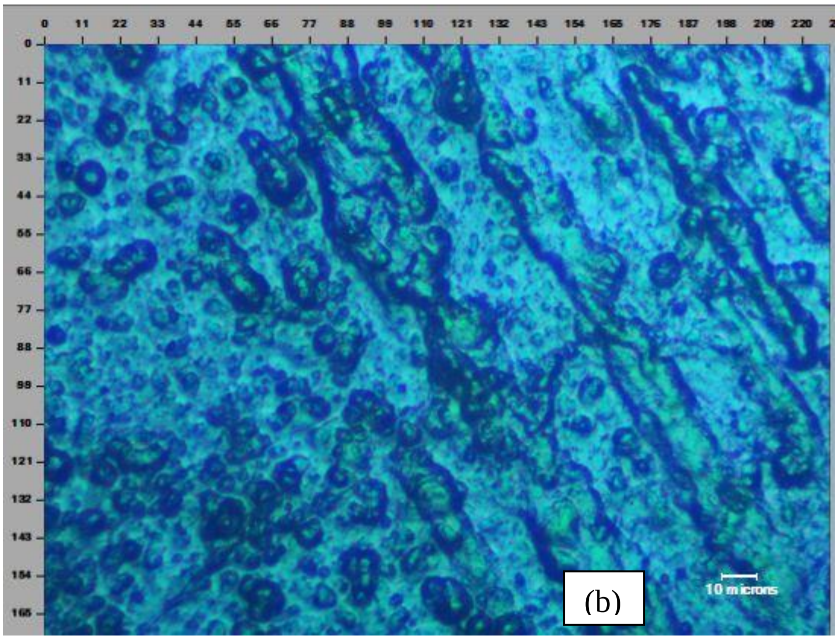
3.6 Optical Micrograph

The optical microstructure of the FSWed specimens corresponding to different experimental trails such as constant feed of 20 mm/min and spindle speed of 800 rpm ,1000 rpm and 1200 rpm corresponds to the optimal tool profile of tapered threaded tool profile is provided in figure 13 (a), (b), (c) respectively. The optical micrographs are captured at a magnification of 10X.

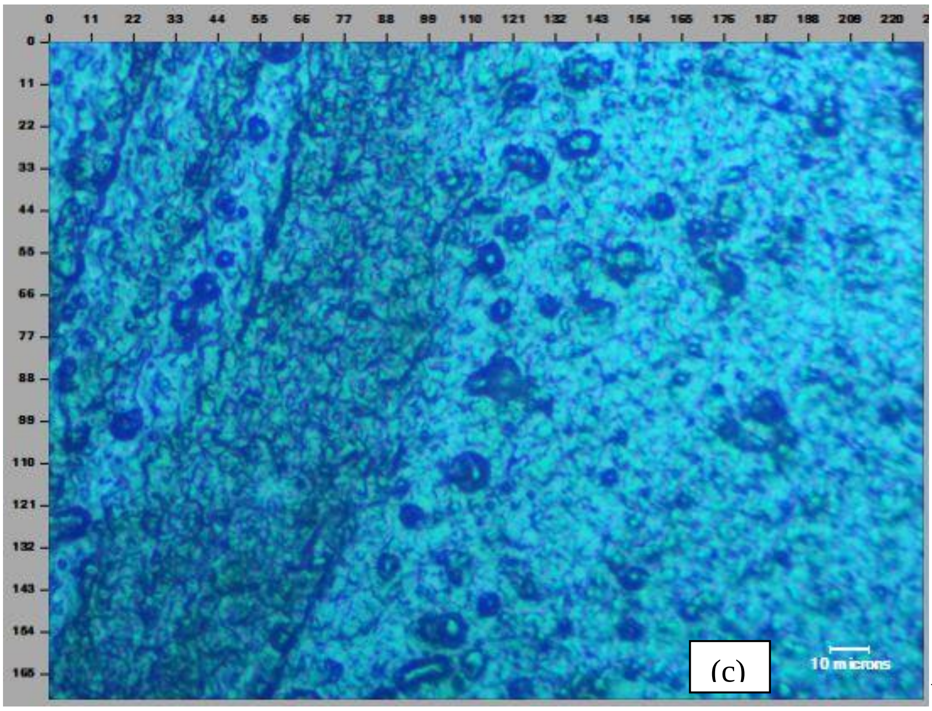
Figure 13: Optical Micrograph of the welded specimen at NZ (Nugget Zone) with Tapered Threaded Tool Profiles



(a) W_1 (with Spindle speed of 800 rpm and Constant table feed of 20 mm/min)



(a) W_2 (with Spindle speed of 800 rpm and Constant table feed of 20 mm/min)



(b) W_3 (with Spindle speed of 800 rpm and Constant table feed of 20 mm/min)

3.7 Grain Distribution Analysis

It can be seen that the grains were more refined, with significant twinning: the average grain size maximum grain size and minimum grain size is measured by linear intercept method. And the grain distribution based on ASTM Standard E112 is shown in figure 14, 15, 16. And the grain analysis was summarized on the table 4 below.

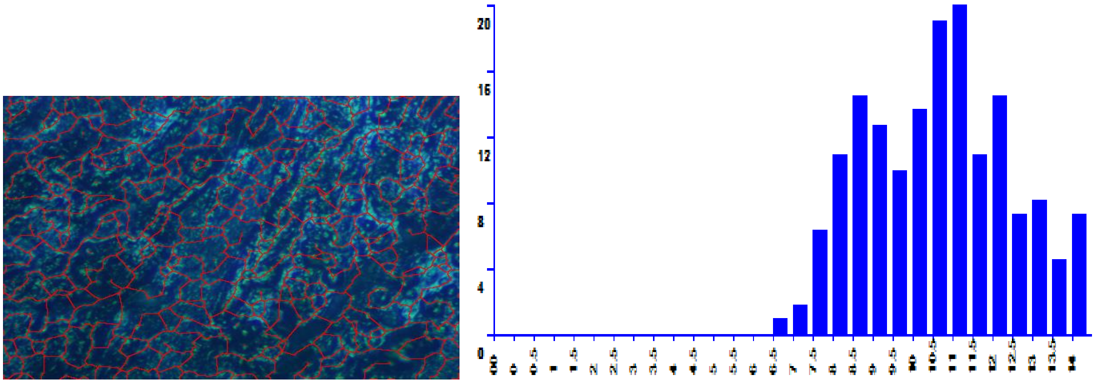


Figure 14. Grain Distribution of Welded Specimen W_1

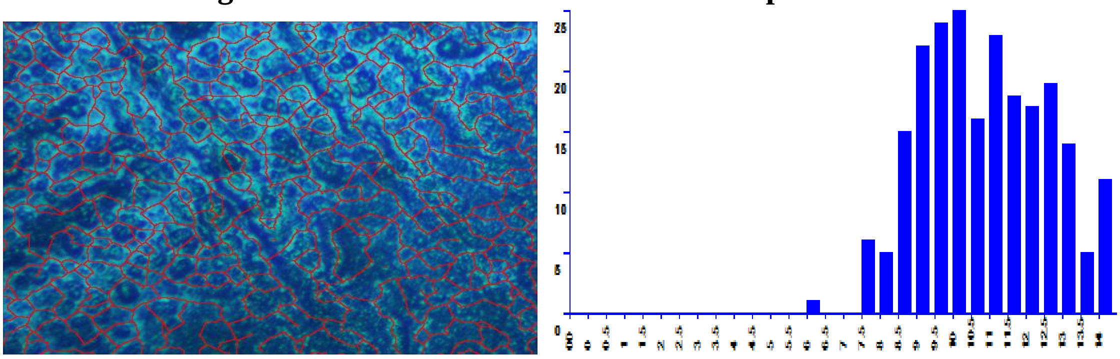


Figure 15. Grain Distribution of Welded Specimen W_2

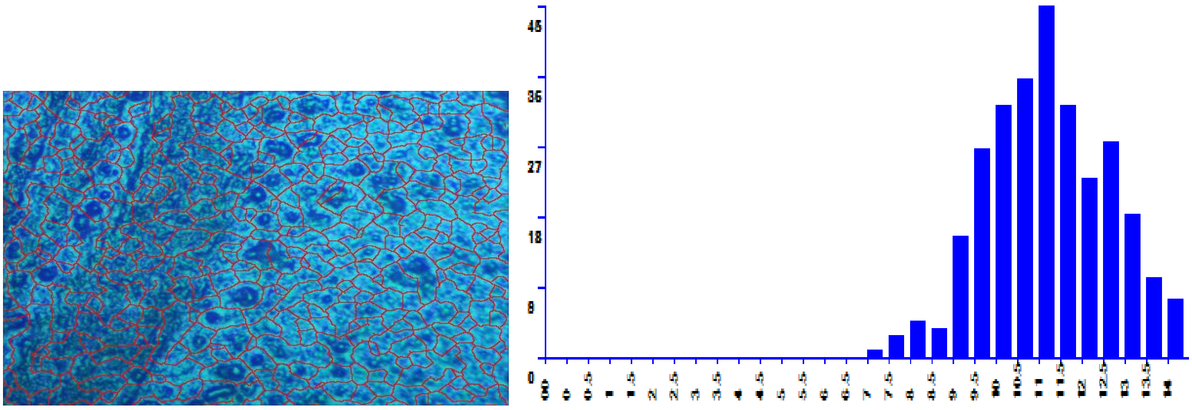


Figure 16. Grain Distribution of Welded Specimen W_3

Table 4: Grain size Analysis summary at NZ (Nugget Zone)

Specimen	Minimum Grain Size(µm)	Maximum Grain Size (µm)	Average Grain Size (µm)	Remarks
Base Metal	14.5	6.5	10	As received
Weld 1	20.5	9.5	14.5	Less Refined Grains
Weld 2	34.5	9	18.5	Maximum Refined grains
Weld 3	25	8.5	16	Medium Refined grains

Itai Mumvenge [1] concluded that the HAZ which is common to all welding processes subjected to thermal cycle with no deformation, has slight changes from the base metal. The TMAZ grain structure was characterized with mixed rotated, elongated and equiaxed grains which reflect grains of partially recrystallized morphology. The NZ has much smaller fine equiaxed grains due to dynamic recrystallization.

The FSW specimen using optimal condition is subjected to micro structural study and the micrographs obtained which shows the heat-affected zone structure (HAZ), interface zone, and nugget zone. HAZ region is characterized for its finer grain structure and is free from voids, oxides, and cracks. The nugget zone has the flow of materials from both the base metals and the flow track is clearly visible. The interface zone shows the distinction between the two base alloy materials separated by a change in the micrograph. The shoulder zone presents the flow of melted metal and their integration for good bonding strength in FSW.

From the current analysis the welded specimen W_2 has shows maximum refined grains with minimum grain size of 34.5µm, maximum grain size of 8.5 µm and average grain size of 18.5 µm respectively.

As the spindle speed increase with the refinement of grains also increase, up to an optimal speed of 1000 rpm, beyond which the mechanical properties gets reduced due to the gas entrapment during the operation.

It is concluded that with optimal condition and tapered threaded (TTH) tool profile better weld joint can be produced among the similar aluminum joints with enhanced mechanical properties.

Radiography Analysis

It was determined by *Sarafadeen Tunde Azeez* [1] that the welding technique's accuracy, the parent materials' chemistry, and the processing conditions all affect the welds' integrity [21–22]. Using tapered threaded (TTH) tool profiles and a weld feed of 20 mm/min, the most significant samples were subjected to radiography analysis in the current work. The samples had the highest specified values of tensile strengths. The samples are identified by their spindle speeds and tool profiles. The samples correspond to Tapered Threaded Tool profile with spindle speed of 1200 RPM for Weld (W_1), 1000 RPM for Weld (W_2) and 800 RPM for Weld (W_3). Simlliary the samples correspond Square Cylindrical Tool profile with spindle speed of 1200 RPM for Weld (W_4), 1000 RPM for Weld (W_5) and 800 RPM for Weld (W_6) and the samples correspond to Hexagonal Tool profile with spindle speed of 1200 RPM for Weld (W_7), 1000 RPM for Weld (W_8) and 800 RPM for Weld (W_9) respectively. Figure 17, 118, 19 presents these findings.

It is just that the components aren't mixed together. This results from a non-fused root weld. The tool just glues the parts together; it does not weld them; it does not go all the way through the components. This flaw is internal and difficult to perceive with the unaided eye. We focus on the thrust force and the application-specific tool use a longer tool for better penetration to address this flaw of lack of penetration. Additionally, some gasses trapped between the components that need to be welded at a high spindle speed prevent penetration. Because of the low feed rate (20 mm/min), steady axial thrust of 8 KN, and optimal spindle speed of 1000 RPM. Hence, the quality and strength of the weld are impacted by the spindle speed, weld feed, and axial force.

Figure 17. Samples (W_1, W_2, and W_3) welded by Tapered Threaded (TTH) Tool Profiles with Various Spindle Speed and Constant Weld Feed of 20 mm/min.

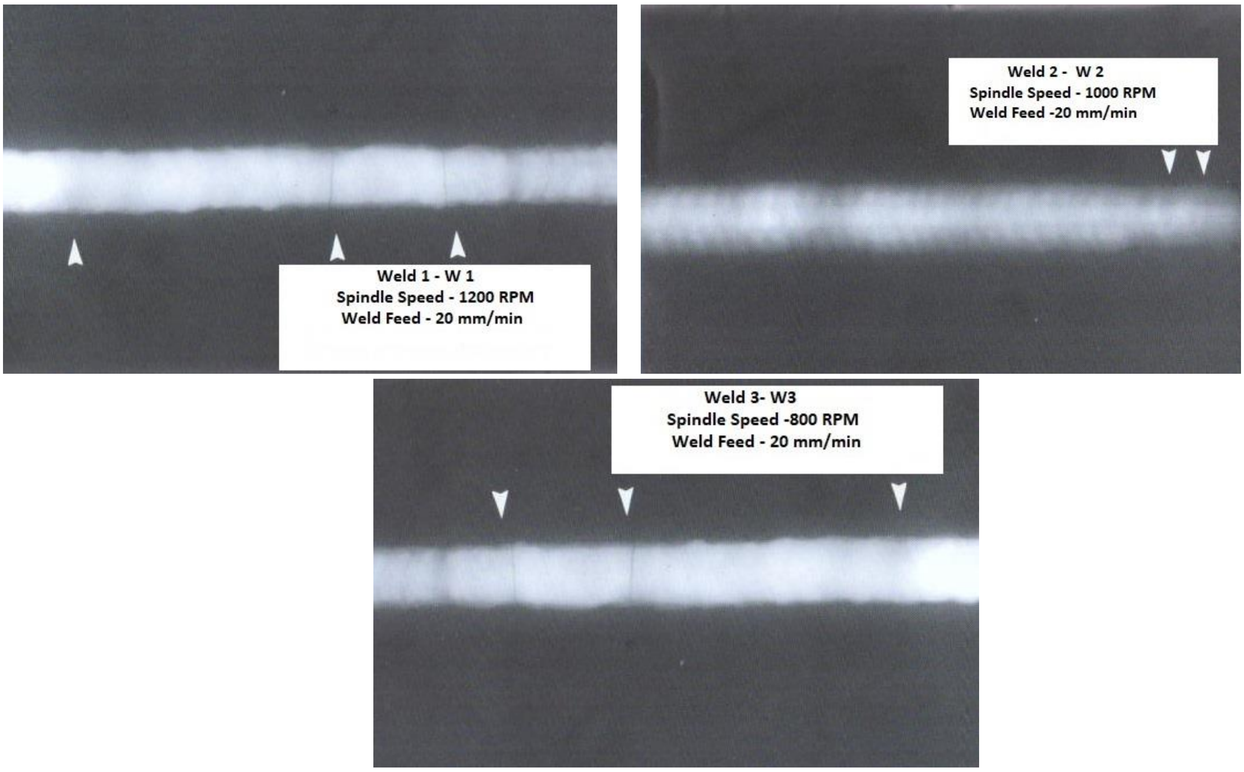


Figure 18. Samples (W_4, W_5, and W_6) Welded by Square Cylindrical (SQC) Tool Profiles with Various Spindle Speed and Constant Weld Feed of 20 mm/min.

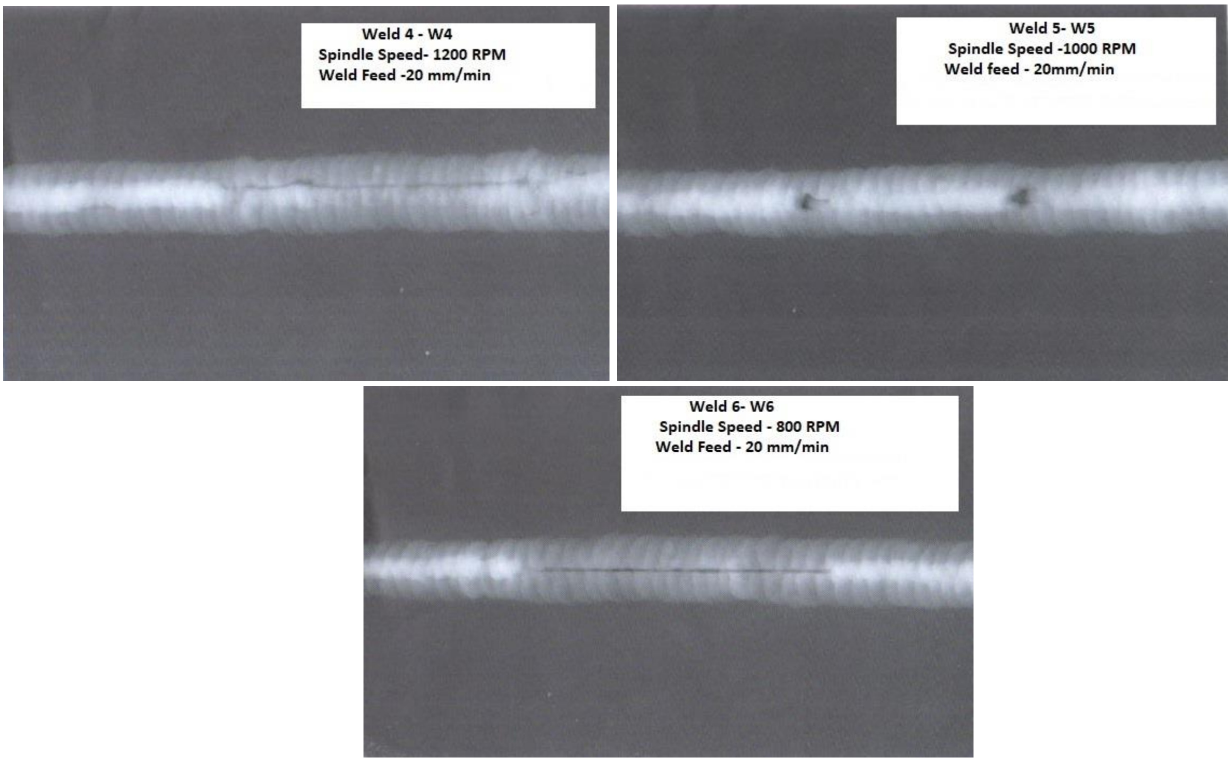
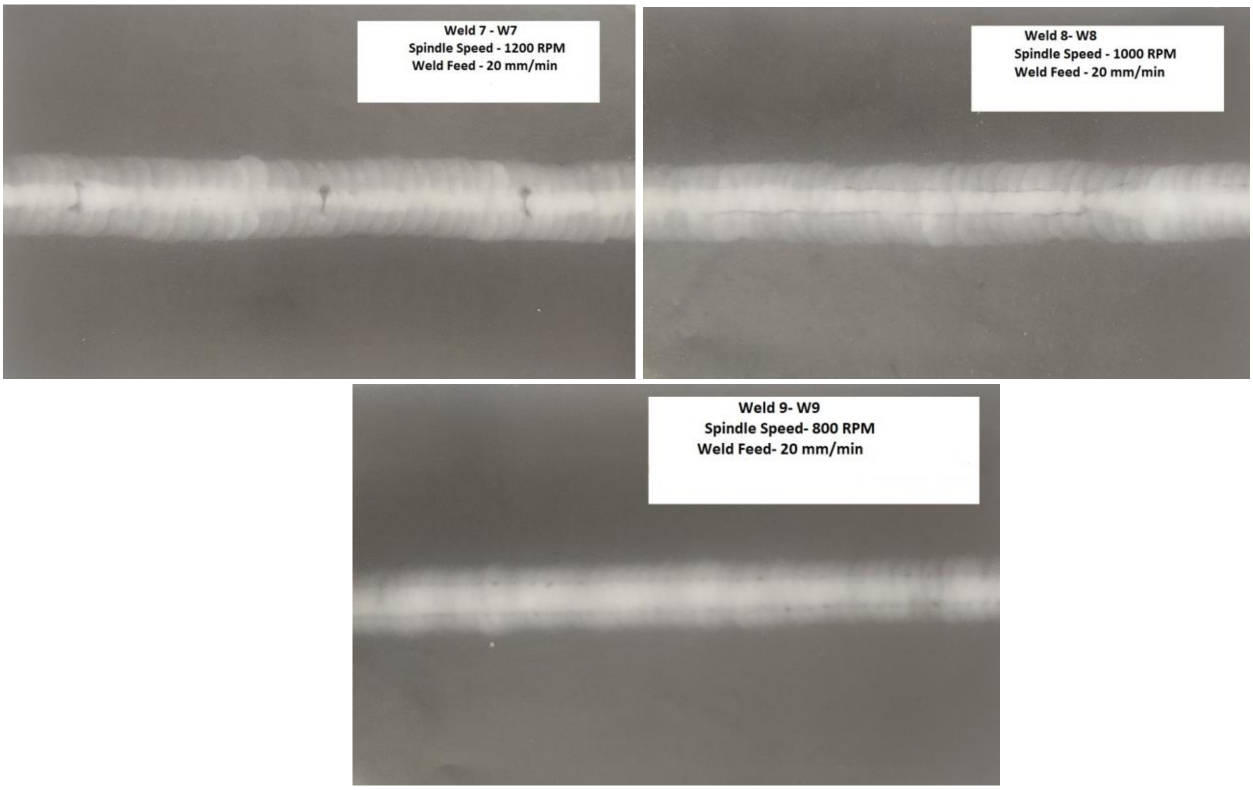


Figure 19. Samples (W_7, W_8, and W_9) Welded by Hexagonal (HEX) Tool Profiles with Various Spindle Speed and Constant Weld Feed of 20 mm/min.



Itai Mumvenge[1] reviewed as, friction stir welds were evaluated by both visual inspection and the X-ray digital radiography method. Evaluation allowed for assessment of the weld integrity by examining for the presence and absence of weld defects. The results indicated that the welds do not have any root defects. The X-rays showed complete penetration as evidenced by the evaluation of micro structural joint interface.[23]

Table 4. Summary of Results from Radiography images.

Rotational Speed(RPM) /Feed rate of 20 mm/min	Tool Profile Square Cylindrical	Tool Profile Hexagonal	Tool Profile Tapered Threaded	Comments
800	Evidence of root defects was observed on all the welds produced using the 800-rpm rotation speed and 20mm/min feed rate.	Evidence of root defects was observed on all the welds produced using the 800-rpm rotation speed and 20mm/min feed rate.	No evidence of root defects was observed on all the welds produced using the 800-rpm rotation speed and the respective feed rates. Keyhole observed.	Tapered Threaded tool profile is the optimum tool profile.
1000	Evidence of root defects was observed on all the welds produced using the 1000-rpm rotation speed and 20mm/min feed rate.	Evidence of root defects was observed on all the welds produced using the 1000-rpm rotation speed and 20mm/min feed rate.	No evidence of root defects was observed on all the welds produced using the 1000-rpm rotation speed and the respective feed rates. Keyhole observed.	Tapered Threaded tool profile is the optimum tool profile.
1200	Evidence of root defects was observed on all the welds produced using the 1200-	Evidence of root defects was observed on all the welds produced using the 1200-	No evidence of root defects was observed on all the welds produced using the 1200-	Tapered Threaded tool profile is the optimum tool profile.

	rpm rotation speed and 20mm/min feed rate.	rpm rotation speed and 20mm/min feed rate.	rpm rotation speed and the respective feed rates. Keyhole observed.	

The friction between the tool and the workpiece causes the tool's rotational speed to rise, which in turn increases heat generation. Additionally, the stain rate of the work material will increase with higher tool rotational speed, leading to additional plasticization of the material for transportation. Because there is more time for the tool and workpiece to come into contact, the slower welding pace causes the workpiece to receive more heat. Weld joint 2 has a maximum tensile of 131.6 N/mm^2, according to the results, and the matching radiography image shows full penetration. There is no penetration visible in the radiographic image of weld sample 1, which has the lowest tensile strength (101.93 N/mm^2). It is evident that tensile strength changes in direct proportion to the area of penetration.

By *Santhoshkumar S*, the impacts on welding surfaces after the welding process has been researched and reviewed, tool materials, tool geometry, welding speed, rotating speed, and axial forces are examined [24]. When friction stir welding (FSW), the weld sample with spindle speeds of 1200 rpm and 800 demonstrates a lack of weld penetration. This can be attributed to a number of factors, including tool wear; tool geometry feed rate, heat generation, material flow, and material parameters. One important factor that affects the quality and functionality of the welded joint in friction stir welding (FSW) is the relationship between weld penetration and weld strength with regard to spindle speed.

In conclusion, the strength of the weld joint is influenced by the weld penetration depth, which is largely determined by the spindle speed. The gases trapped during welding will cause lack of penetration, cracks or voids, internal root forms, and ultimately impact the quality and strength of the weld when the spindle speed is increased to its maximum range of 1200 rpm. In addition to controlling heat input to prevent negative impacts on weld quality, finding the ideal spindle speed requires taking into account variables such material type, joint configuration, and intended welding output. The stir zone becomes slightly harder at higher welding speeds. *X. Cao and M. Jahazi* evaluated that the yield strength improves as the Welding speed increases [25-26].As a result, the weld sample W_2, which has a spindle speed of 1000 rpm, has greater weld penetration and strength. The ideal weld speed is therefore this spindle speed.

4. CONCLUSIONS

This study provides a thorough evaluation of the tensile strength and weld quality of AA6063 alloy friction stir welded (FSW) joints through careful examination. The set of input parameters was optimized and tabulated using RSM. Spindle speed, table feed, and tool profiles were the parameters. With the help of this work, AA 6063-like joints' micro tensile strength qualities can be improved by FSW. When it comes to feed rate and spindle rpm, the tapered threaded (TTH) tool performs better than the square cylindrical (SQC) and hexagonal (HEX) tools.

With the greatest spindle speed and feed rate among the range of parameters tested, FSW at 1000 rpm and 20 mm/min demonstrates exceptional micro tensile strength; the value obtained is 131.66 N/mm^2 with a joint efficiency of 74.85%.At a spindle speed of 1000 rpm and a feed rate of 20 mm/min, the average micro hardness values were 84.5 VH in the stir zone, 86 VH in the thermo mechanical zone, and 88.5 VH in the heat-affected zone. Therefore, they have improved mechanical qualities with reduced weld feed. One important factor that affects the quality and functionality of the welded joint in friction stir welding (FSW) is the relationship between weld penetration and weld strength with regard to spindle speed.

As a result, the tapered threaded tool profile of the weld sample W_2, which has a spindle speed of 1000 rpm, displays higher weld penetration and weld strength. Regardless of feed rate, the spindle speed will display a drop in weld strength when it rises above a range of 1000 rpm and trap gasses. Thus, the ideal speed is expressed as a spindle speed of 1000 rpm. The micro structural aspects of friction stir welded AA 6063 joints is crucial for determining their mechanical properties and overall performance. Fine grain structure, controlled precipitation behavior, and minimal defects are desirable outcomes of a well-executed FSW process. Proper optimization of welding parameters is essential to achieve these micro structural characteristics and ensure high-quality welds. Future developments in the areas of residual stress analysis and creep strength are anticipated.

Conflict of Interest

All authors have read and approve this version of the article, and due care has been taken to ensure the integrity of the work. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This paper is our original unpublished work and it has not been submitted to any other journal for reviews.

Author's contribution statement

The authors confirm contribution to the paper as follows: Study conception and design: Pramod Ramakrishnan[1], M.R Radhakrishna Panicker [2]. Data collection: Pramod Ramakrishnan[1]. Experimental analysis and interpretation of results: Pramod Ramakrishnan[1], M.R Radhakrishna Panicker[2], Ajin C Sajeevan[3], Biju N [4]. Draft manuscript preparation: Pramod Ramakrishnan[1], M.R Radhakrishna Panicker[2], Ajin C Sajeevan[3] and Biju N [4]. All authors reviewed the results and approved the final version of the manuscript.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author Pramod Ramakrishnan[1].

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