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RESEARCH ARTICLE OPEN ACCESS

Optimising the Welding Parameters of AA6101-T6 Using Friction Stir Welding

Shahid gull[1], Dr Sachin Saini[2,] Simranjit Singh[3]
[1] *Research Scholar, Email Id: shahidgull53@gmail.com, RIMT University, Mandi Gobindgarh, Punjab, India*
[2] *Assistant Professor, Email Id: Sachin.saini@rimt.ac.in, RIMT University, MandiGobindgarh-147301, Punjab,*
[3]*Assistant Professor, Email Id: Simranjitsingh@rimt.ac.in, RIMT University-147301, Mandi Gobindgarh, Punjab, India*

ABSTRACT
Since aluminium has a high weight to strength ratio, non-corrosive behaviour, and thermal and electrical conductivity qualities, it is used extensively in the construction, aircraft, transportation, and electrical industries. Looking at the distinct properties of the aluminium alloys, from that array Aluminium AA6101-T6 alloy was employed in this study using the method of friction stir welding for some experimental investigations. To check the soundness of the butt joint during experimental observations, different combinations of feed (mm/min), rotating speed (rpm), tool offset alternately on advancing and retarding sides were used. The joints were made by single pass welding with a tapered pin shape. The impact on weld quality of combining high rpm and extremely low feed speeds was investigated. Looking closely into how different welding settings affected the quality of the weld. Combining a feed of 25 mm/min, a pin offset of 0 mm, and a rotating speed of 2280 rpm produced finer grains and enhanced mechanical properties. ANOVA and S/N ratio show that rotational speed has the greatest influence on tensile strength and hardness, and tool offset has a significant impact on the joint's impact strength**.**

Keywords: Friction stir Welding (FSW), Aluminium alloy AA6101-T6, Advancing side (AS), Retarding sides (RS), Tensile strength, Micro hardness, Impact test.

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I. INTRODUCTION

A solid state joining method called friction stir welding allows a variety of materials to be joined below their melting point. In 1991, the Welding Institute (TWI) devised friction stir welding (FSW) [1].

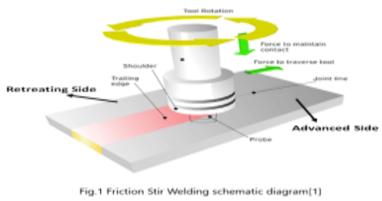

Fig no. 1: Schematic Diagram of Friction stir welding

From the several findings it has been clearly indicated that the traditional welding process has several drawbacks, such as substantial distortion, huge residual strains, hydrogen cracking, welding fumes, and microstructural embrittlement brought on by strong post welding thermal gradients. However, as solid state techniques weld below the melting temperature, they can reduce or eliminate these disadvantages to a minimum. One benefit of friction stir welding is that it saves extra weight gain in the finished product because it doesn't require any filler material during the welding process. In conventional welding, heat is generated by an external heat source to melt the material; in friction stir welding, heat is generated by friction between the rotating tool and the work piece. The forging pressure applied to the metal pieces by the tool shoulder and the tool's rotational and translational motion cause the two work pieces to mechanically intermix in FSW. The term "advancing side" refers to a plate whose tangent direction in the direction of tool rotation matches the welding direction, and the term "retreating side" refers to a plate whose tangent direction is against the welding direction. The production of many types of joints, such as butt joints, lap joints, T-welds, L-welds, etc., is now accomplished via friction stir welding. At first, friction stir welding was primarily created for aluminium alloys, however, these days;

it is utilized for materials with great strength, such as titanium, SS alloys, etc. For this experiment, we employed aluminium alloy AA6101. There are numerous applications for friction stir welding, including the shipbuilding, automotive, and aerospace industries. These days, a great deal of research is being done to create joints that are flawless [2]. to find these flaws, a variety of tests can be performed, including visual inspection, macro structural analysis, and micro hardness testing of welded joints. Three different kinds of flaws were observed during the macroscopic analysis. Defects in the tunnel, joining line, and incomplete fusion. These flaws are brought about by improper welding parameter selection, which leaves the welding line zone with insufficient heat generation. A number of experiments were conducted to determine the impact of welding parameters on the quality of the weld, including welding speed, transverse speed, tool design (pin geometry, pin diameter, shoulder diameter, etc.), and axial force[3,4]. The flaws in FSW can also be found using techniques including radiography, phased array ultrasonography, and conventional ultrasonography. The friction stir welding region has a stronger wearing resistance than the base material, according to a test conducted on a grinding machine. [5]. When lap welding an aluminium alloy that has been friction stir welded, a flaw known as interface lifting occurs. This defect can cause a defect production site under pressure and fade an FSW joint while it is in use [6].The intermediate lifting flaw of FSW arises when the weld piece part is fastened wrongly on the milling machine bed. Deformation results from an uneven or loose setup when the tool shoulder spins quickly. This deformation results in rising of the plate, weakening of the joint region, and an increased chance of metallurgical bonding between the plates. The micro hardness study at optimized welding parameters revealed the variations in micro hardness distribution in different regions [7]. When Saini et al. (2021) evaluated the FSW joint of the magnesium alloy AZ61a, they discovered that the maximum micro hardness and tensile strength were seen at 1800 rpm and 2000 rpm, respectively, at a welding speed of 20 mm/min. Microscopic analysis of the joints revealed that the dynamic recrystallization resulted in the development of equiaxed Grains in the stir zone and TMAZ [8]. When 6061 Al was welded to copper, the researchers discovered that a complex, intercalated microstructure was also formed via dynamic recrystallization [09, 10].

This study examines the impact strength, tensile strength, and micro hardness of weld nuggets produced in FSW of AA6101-T6 alloy. The analysis of variance, signal to noise ratio, and Taguchi L9 orthogonal array techniques were used to calculate the relative effects of various parameters on welded joints.

II. EXPERIMENTATION

A. Problem Formulation

Bus bar conductors and structural constructions like commercial and maritime structures are among the uses for AA6101-T6 material. Through friction stir welding; AA6101-T6 will be able to be used together. Analysing the joint's micro hardness, impact strength, and tensile strength after connecting AA6101-T6 presents a problem.

B. Research Objectives

1) To determine and evaluate the AA6101-T6 joint's tensile strength using FSW.
2) To determine and evaluate the AA6101-T6 joint's Impact strength using FSW.
3) To determine and evaluate the AA6101-T6 joint's micro hardness using FSW.

C. Material, Tool and FSW Parameters

The basic metal in this experiment were AA6101-T6 alloy with dimensionsof 15.0 cm x 15.0 cm x 0.6 cm, Tables 1 and 2 demonstrate the chemical compositions and mechanical properties of AA6101-T6 alloy respectively.

Table 1. Chemical compositions (wt. %)

Material	Al	Zn	Mn	Be	Cu	Fe	Si	Ti	Mg	Cr
AA 6101-T6	98.10	0.09	0.09	-	0.11	0.33	0.65	0.09	0.88	0.09

Table 2. Material properties

Name of material	**Ultimate Tensile Strength, MPa**	**Strain,%**	**Impact Strength,Mpa**	**Hardness,Hv**
AA6101-T6	145.6	**37.99**	28.8	66.9

Both advancing and retreating sides were of AA6101-T6 alloy, the advancing side is the side on which the tool rotates and travels in the same direction. The term "retreating side" refers to when they are moving in the other direction. Proper clamping were provided on CNC vertical milling machine (FANUC CNC 2014) The machine's Info, are as follows: –
Device Name: **FANUC CNC** vertical milling machine
Axis Limit: x = 2500, y = 1500, z = 1000
Rotation: 30-36000 rev/min
Weight recommended: 3000 kg
To avoid any misalignment and distortion of any kind due to large forces that apply during this process, and this way sound welding was done in single tool travel means single pass welding. The ideal tool profile was previously identified to be a tapered pin profiled high speed steel (HSS) tool with a 24 mm shoulder diameter, 6 mm pin diameter, and 5.9 mm pin length, which was used to manufacture all butt welded joints [11]. The axial stress was maintained throughout the welding process so that the tool pin's tip was consistently 0.1 mm from the lower surface of the base metal. The welding was done utilizing a 4-axis computer-controlled friction stir machine that had an accuracy of 6 microns. The traversal speed, tool offset, and tool rotation speed were selected as the welding parameters for friction stir welding. The tilt angle against the welding direction of a 4-axis FSW machine can be adjusted from 0° to 2°. Because of this, the welding settings used in this study are selected so as to achieve a suitable joint efficiency [12, 13].

D**. Analysis and Testing**

Mechanical and metallurgical testing was performed on each specimen after welding. Tensile, bending, and hardness tests were used to characterize the mechanical properties of each weld. Mechanical circular saw machine was used to cut tensile and impact specimen's perpendicular to the weld direction, as per ASTM standards, respectively (Fig. 2). Tests were carried out by a computer-controlled universal testing machine(ASTM E8M-04) and impact test machine both were as per Associated Scientific Engineering Works, with an accuracy of 1%.

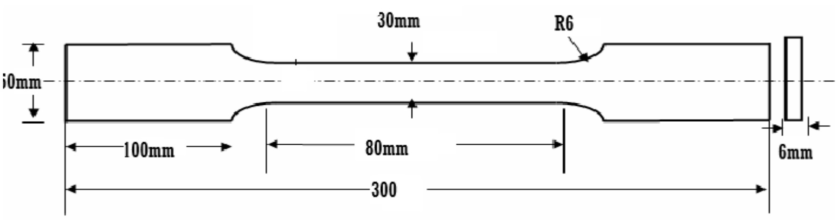

Fig.2 **Images: a tensile sample (per ASTM E8M-04 standard).**

1) Tensile Test

The work specimens generated in accordance with ASTM E8 standards were subjected to a tensile test utilizing the Universal testing machine. The specimens' tensile tests are displayed in the provided image. In comparison to the AA6101-T6 alloy, the tensile strength of the weld samples was lower. Similar behaviour has also been observed using the yield strength values. Together, the efficiencies are lower. It was noted that the sample fracture happened along the weld centre line. The weld centre is where the fracture occurs. Every sample had a ductile fracture. The samples exhibit good mechanical characteristics at 2280 rpm. The tensile strength of the joints produced at 2400 rpm and 20 mm/min feed was lower, and the highest tensile strength was obtained at 2280 rpm and 25 mm/min. The Fine Manufacturing Universal Testing Machine specs are –
Capacity – 15 KN
Maximum crosshead travel – 1200mm
Testing Speed range – 0.001 to 1000 mm/min
Maximum crosshead speed at 5kN – 550 mm/min

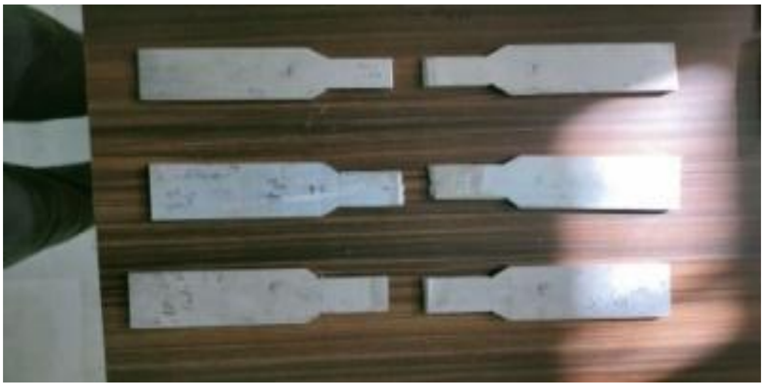

Fig 3. Photograph: –Tensile specimen (after testing).

2) Impact Test

The Impact Charpy test was carried out at room temperature. Indentation strength of the material is determined by measuring the energy absorbed in the fracture. Three different feed rates and rpms were used for the impact test. The work specimens were positioned at the centre line with the weld joint. Because the material was properly mixed to create joints, the impact strength first increased as the tool rotation speed increased. However, when the tool rotation speed climbed further, the impact strength began to decrease because of the high heat that formed that distorted fine grain pattern. During the impact test, the specimens do not break into two pieces, which is because of the high energy absorbing capacity of the joint. The Info, of the impact testing machine are as follows –

PE before striking (Joules) – 300
Hammer angle (degree) – 145
Angle of hammer striking edge – 35
Radius of Striking edge – 9 mm
Distance between supports – 50 mm
Width of hammer tip – 5mm.

Fig 4. Photograph: –Impact specimen

3**) Micro hardness**

Micro Vickers HV testers were used to quantify hardness at several points throughout the welded region. Each specimen was polished and etched using a low concentrated etchant (Nital) chemical before being scanned and observed under microscope for micro hardness investigation, then a micro hardness test was conducted. The preparation of the work specimens complied with ASTM E384 requirements. The diamond-shaped pyramid was used to create the surface deformation. Calculations of hardness were made based on the loads placed on the specimens. For 10 seconds, a load of 200 grams, or 0.2 gm. was applied in the hardness test. The eyepiece's scale was utilized to record the dimensions of the diamond impressions[14,15].

III. RESULTS AND DISCUSSIONS

A. Taguchi Technique

The Taguchi technique was created in 1980 by Genichi Taguchi [16]. This is a simple yet efficient method for maximizing performance attributes within the constraints of a given set of process variables. In order to investigate how process parameters affect particle size and the best milling settings, Aykut Canakci et al. [17] used ANOVA and the Taguchi approach. Koilraj et al. [18] adjusted the welding settings using a Taguchi L16 orthogonal array and ANOVA to increase the tensile strength of the friction stir welded joints between the dissimilar plates.

Table 3. Welding parameters for Optimization.

Welding parameters	L1	L2	L3
a – speed, (rpm)	2000rpm	2280rpm	2400rpm
b– Feed, (mm/min)	30.00mm/min	25.00mm/min	20.00mm/min
c – Tool offset(mm)	0.00mm	1.00mm(AS)	2.00mm(RS)

B. Signal to noise ratio

The intended and unwanted impacts on the output characteristic are indicated by the terms signal (S) and noise (N). The degree to which desired values of quality criteria are not met is indicated by the S/N ratio. The three types of S/N ratio attributes are ranked from best to worst with the higher nominal S/N ratio being the best. This experiment employed the greater the better S/N quality feature because higher bending strength, micro hardness, and tensile strength are desirable qualities. Equation 1 is used to find the S/N ratio. The S/N ratio should be as high as possible.

$$\frac{S}{N} = -10log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \qquad (1)$$

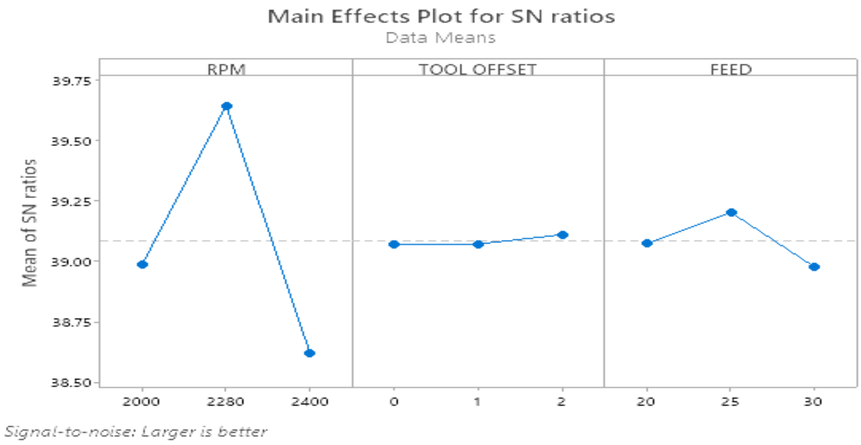

Fig: 5 S/N ratios

C. Testing Results

The work specimens had multiple flaws, including holes and a rough surface, when they were first trail welded on a manual VMM at 500 rpm with manual feed. Fig 6 below shows trial weld setup-

Fig.6 Trail weld setup with cylindrical pin

Subsequently, the parameters were adjusted, producing sound welds with few faults. Tensile tests were performed on the specimens after they had been welded using a CNC VMM at varying RPM and feed rate. Fig 6 below shows CNC VMM and welded joints –

Fig 7: CNC VMM and welded joints

The tensile test results were documented in the provided table 4.

Table 4: Depiction of Tensile Strength (MPa) at various parameters

Weld Joint No	Rotations(rpm)	Welding speed (mm/min)	Tensile Strength (MPa)
01	2000	30	88
02	2000	30	90
03	2000	30	89
04	2280	25	97
05	2280	25	96
06	2280	25	95
07	2400	20	85
08	2400	20	84
09	2400	20	87

The fracture during tensile testing was observed to be inside weld zone propagating almost along the weld centre line(dimple type fracture), hence failure planes were within weld zone making joint weaker than the base metal AA6101-T6.

The tensile strength variation with regard to speed and feed is displayed in the accompanying graph-

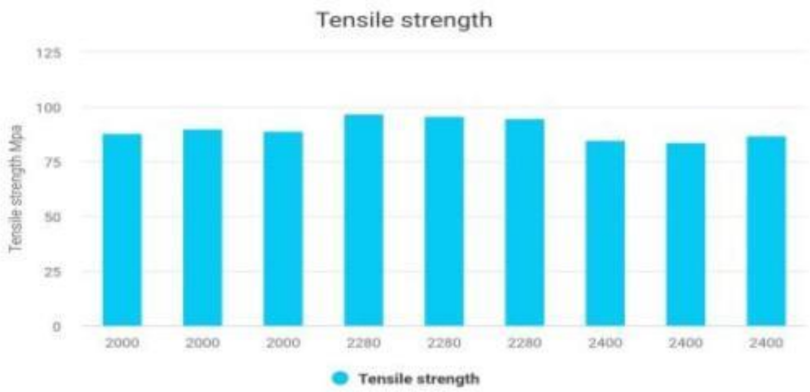

Fig 8: Tensile Strength (in Graphical manner)

Following each specimen's impact test, the impact energy values were noted from the machine scale. The impact strength values were then computed using the cross-section area value. The tensile test findings had been documented in the given table 5.

Table 5: Impact Energy (In Joules)

Weld Joint No	Rotations(rpm)	Welding speed (mm/min)	Impact energy joule
01	2000	30	20
02	2000	30	18.8
03	2000	30	19
04	2280	25	22
05	2280	25	23
06	2280	25	21
07	2400	20	15
08	2400	20	16.2
09	2400	20	17

The Impact energy variation in relation to speed and feed is displayed in the provided graph.

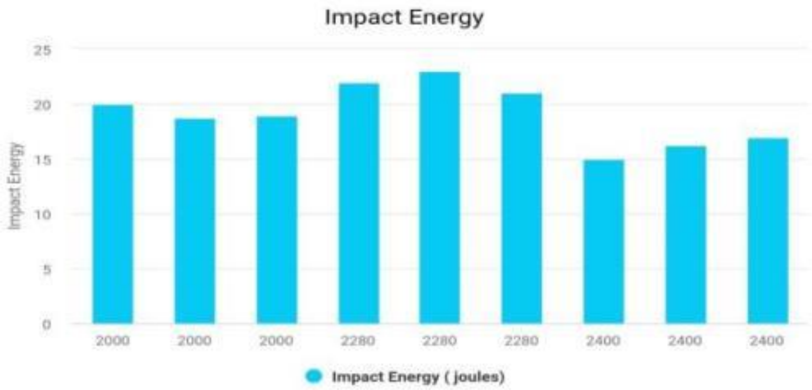

Fig 9: Impact Energy (In Graphical Manner)

More frictional heat is produced in the weld zone at higher rotational speeds [19]. More heat was produced as a result of maintaining the tool shoulder's compressive strain on the weld plates [20]. Impact and tensile testing were used to assess the welding bond strength. Combining a traversal speed of 25 mm/min, a zero tilt angle, and zero offset resulted in a sample with the highest impact strength (25 joules) and tensile strength (97 MPa). Higher rotation speeds contribute to the welding process's significant heat input. If you cross at a slower speed, cooling happens more slowly. The tool can interact with the weld plates for a longer amount of time when it rotates faster and traverses slower. A combination of a lower traversal speed of 20 mm/min, a lower rotational speed of 2000 rpm, and a tilt angle of 0° was used to make the sample with the lowest tensile strength (84 MPa). A 0° tilt angle and a decreased rotation speed are used to achieve less heat input during the welding operation. It cools at the same rate as the last one. The reaction between

the components is determined by the amount of heat produced in the stir zone. Particle dispersion and breaking in the weld zone are impacted by inadequate heat generation during the welding process, which

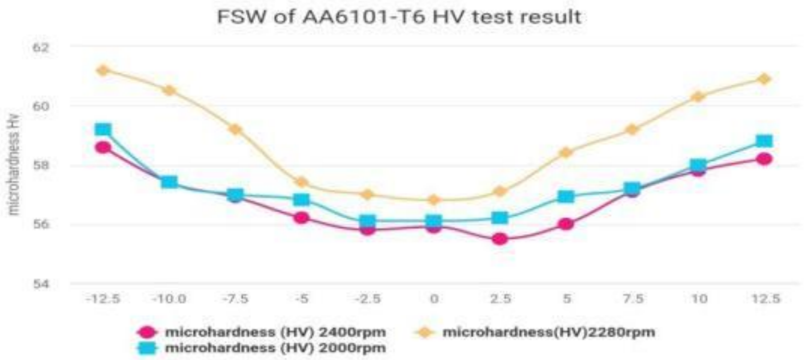

Fig.10 Micro hardness plot for various RPMS

Leads to inadequate material mixing and transportation[21]. Lowering the rotation speed while increasing the traversing speed shortens the tool's interaction time with the weld plates, this influences the degree of consolidation and material transit. Because of this, the weld zone has more discontinuities, which have an impact on the weld joint's impact strength. The hardness tester gives the direct values of the micro hardness because of the calibration done. The variation of the hardness on both sides from the weld zone was calculated and the graph was plotted [22].

One may observe the hardness distribution along the joint. This shows that the joint CL hardness values are lower than those of the advancing and retreating sides [19]. Because of the finer grains and stronger precipitates, the sample with the peak strength shows at the weld centre was produced by combining a higher rotating speed of 2280 rpm, a feed speed of 25 mm/min, and a zero tool offset. Comparable degrees of hardness are seen on the approaching and receding sides [20]. Consequently, during tensile testing, cracks along the weld centre line occurred. The Heat Affected Zone (HAZ) has been determined to have the lowest hardness values; the softening of the Heat Affected Zone (HAZ) is the cause of this. Softening's prevalence is closely associated with the process of annealing. Consequently, the Heat Affected Zone was where all of the fractures on the happened [23].

IV. Conclusions

This study used the Taguchi technique to investigate the outcome of tool offset, feed speed, and rotating speed during friction stir welding of AA6101-T6 alloy. At a Pin rotation speed of 2280 rpm, a traversing speed of 25 mm/min, and a tool offset of 0 mm, a defect-free weld was observed with a tensile strength of 97Mpa. The most crucial parameters for the output were found with the aid of the signal to noise ratio. The amount that each control variable contributed to the output factors was determined. Tensile strength and hardness were mostly determined by the speed at which the tool rotated. The tool offset was the most significant determinant in impact strength. The greatest tensile and impact strength was obtained with finer grains distributed uniformly, according to microstructural study. Weld discontinuities and poor material mixing reduce the tensile and impact strength of the weld. All of the fractures were found in the HAZ during tensile testing.

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