



## Parametric Optimization for Tensile Strength of Friction Stir Welded Aluminium Alloy AA1100 using Taguchi Method

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### ABSTRACT

Friction stir welding of AA 1100 was conducted across a defined parameter range, leading to the establishment of optimal settings for Tensile Strength (TS). The tensile tests, performed using an Instron Universal Testing machine, yielded TS values ranging from 48 MPa to 98 MPa. Employing the higher-is-better criterion for maximum TS, the Taguchi experimental method was applied to optimize various process parameters and identify dominant factors. The optimal parameters were determined as a rotational speed of 900 rpm, traverse speed of 25 mm/min, and tilt angle of 2 degrees. Through analysis of variance, it was revealed with 90% confidence that rotational speed exerted the most significant influence on tensile strength, contributing over 72%. Additionally, the tilt angle contributed over 24%. Conversely, the traverse speed demonstrated an insignificant effect on tensile strength within the parameter range explored in this study.

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### INTRODUCTION

Friction Stir Welding (FSW), is a solid-phase welding technique enabling the welding of diverse parts and geometries. The fundamental working principle involves the insertion of a non-consumable rotating tool with a specially designed pin and shoulder into the adjacent edges of two plates to be joined. The tool is then traversed along the joint line, generating frictional heat between the wear-resistant welding tool and the workpieces. This heat causes the workpieces to soften without reaching their melting point. Subsequently, the rotating tool mechanically blends the softened material, creating a solid-state bond. FSW offers advantages such as sound welds without complications like cracking and porosity commonly associated with

fusion welding techniques [2]. Among the myriad welding methods for joining metals, particularly low-temperature alloys like aluminum, friction stir welding has emerged as the most suitable method for processing aluminum alloys [3]. This preference is attributed to its numerous merits over conventional fusion welding techniques. Consequently, FSW of aluminum alloys finds extensive applications in aerospace, automobile, and marine industries, leading to plasticization during welding and favorable combinations of mechanical properties, including high strength, light weight, high ductility, and excellent thermal and electrical conductivity, along with high corrosion resistance [4].

Prior studies have investigated FSW of aluminum, such as research that



examined the effects of rotational speed on flow behavior and weld properties in friction stir welding of pure aluminum [5]. Controlling welding parameters, particularly rotation speed and probe design, resulted in defect-free welds with superior strength compared to the base metal. Another study simulated flow stress, temperature, and pressure on friction stir welding of edge joints in similar aluminum alloys [6]. This research aimed to establish FSW parameters for connecting 6061 aluminum alloy sheets to produce welds of the highest strength. Tensile tests revealed that failures occurred near the weld edge line, where the lowest hardness values were observed.

From the existing studies, it is apparent that determining suitable FSW processing parameters for various material systems is crucial. These parameters can help eliminate errors arising from variations in different parameters to achieve an optimal process window. In this work, the aim is to establish optimal parametric settings that result in the highest tensile strength of AA 1100 friction stir weldments. Additionally, the significance of each parameter on the tensile strength of the AA 1100 friction stir weldment will be determined.

## LITERATURE REVIEW

Friction Stir Welding have been studied by several researchers. Bayazid *et al.*[7]. investigated the FSW parameters of 6063-7075 aluminum alloys using taguchi method. They studied the effect of rotational speed, travel speed and plates positions on strength of dissimilar 6063-7075 joint using Taguchi method and ANOVA analysis. It was determined from the results of S/N analysis that the optimal condition for dissimilar 6063-7075 joint is achieved when values of rotational speed, travel speed and plates' positions were 1600 rpm, 120 mm/min and AS-7075

respectively. In such condition, tensile strength of joint was 143.59 MPa. Finally the ANOVA analysis indicated that effectiveness of rotational speed, travel speed and plates' position parameters on tensile strength of joint were 59%, 30% and 7% respectively.

Cavaliere *et al* [8] investigated the effect of different welding speeds of friction stir welding by varying traverse speed from 50 mm/min to 175 mm/min on the metallurgical and mechanical properties of the alloy. During the tensile test, it was found that there is a decrease in ultimate tensile strength with the increase in traverse speed due to the generation of insufficient heat input. On the other hand, higher heat generation occurs at lower weld speed.

Similarly, W.B Lee *et al* [9, 10] analyzed the friction stir welding for AA1100-T6 and AA2024 using five different pin profiles. By examine the triangular pin, flat cylindrical pin and cylindrical threaded profile, the cylinder with taper tool pin diameter are the significant parameters responsible for the better tensile strength. They also found that at the range of 300 to 700 rpm, 15 to 35 mm/min and axial force of 4 to 8 kN produced defect-free welds

Peel *et al* [11, 12, 13 ] used AA1100 aluminum alloy for FSW by varying the welding conditions like tool design, rotation speed, and translation speed. The results of microstructural, mechanical property and residual stress investigations of four aluminum AA1100 specimens revealed that welding properties are influenced by the thermal input rather than the mechanical deformation by the tool.

A. Baumann *et al* [14, 15] studied the influence of the FSW process parameters on the microstructure, mechanical properties and low cycle fatigue behavior of AA1000 series aluminum alloy plates by selecting three different rotations and welding



speeds. It is found that the most of the specimens broke in the region between Heat Affected Zone (HAZ) and Thermo-Mechanically Affected Zone (TMAZ) during the tensile test. It is observed that the 70 % of the welding properties is based on the base metal. Also, there is 40 % decrease in low cycle fatigue life in the welded specimens.

## MATERIALS AND METHODS

The material used in this work was aluminum alloy, AA1100. It is a relatively light alloy with a minimum of 99.0% aluminum. The plate was cut into dimensions of 100 × 60 × 3 mm. The chemical composition of the base metal is given in Table 1. The list of equipment used are presented in Table 2.

**Table 1:** Chemical composition (wt.%) of the aluminums AA 1100

Elements	Al	Be	Si/Fe	Zn	Cu	Mn	Fe	Zr
AA 1100	99	0.0008	0.68	0.10	0.05-0.2	0.05	0.95	0.003

### List of Equipment used

The equipment used in this work are shown in Table 2;

**Table 2:** List of equipment

S/N	Equipment Specification	Model	Capacity
a	Milling machine	Gambin S.2.	2800rpm
b	Universal Testing Machine	3380 Series	100 kN
c	Jigs	Customized	-
	Cutting tool	ASTM A600	-
	Bench vice	BH-QT-200	360-Degree Swivel Base

## METHODS

### Experimental procedure

Care was taken to ensure that the milling machine was in good working condition and properly calibrated. The FSW tool was selected and installed appropriately (tool shoulder and tool pin) into the milling machine's spindle. The already prepared aluminum AA1100 plates, were properly aligned, and positioned under the FSW tool assembly. The work pieces were set up by a clamping system to secure the materials to be welded on the milling machine's worktable was rigidly held. The tool pin was positioned so that it extends below the tool shoulder to configure the milling machine to rotate the FSW tool at the desired rotational speed, and the feed rate was adjusted (traverse

speed) to control how fast the FSW tool moves along the joint line. Trials were made until stable stir welding conditions were achieved. The FSW process of the specimens was then commenced. Upon contact with the workpiece, the FSW tool generated frictional heat, causing material softening without reaching the melting point of AA1122 aluminum alloy. The tool was methodically plunged into the joint interface and moved along the joint line, effectively creating the weld as it progressed.

Throughout the FSW process, key parameters such as spindle speed, feed rate, and axial force were continuously monitored and adjusted as necessary to achieve optimal welding conditions. To manage the heat generated during FSW and

safeguard the tool from overheating, coolant was utilized to cool and lubricate the process. The FSW process unfolded along the entire length of the joint line until the desired weld formation was achieved. Upon completion of the welding process, the tool was meticulously retracted from the workpiece. This comprehensive experimental procedure ensured precision and control throughout the Friction Stir Welding operation.

A cylindrical tool made of high-speed steel (HSS) was used. The tool has a shoulder diameter of 20 mm, a pin diameter of 10mm, and a pin length of 4.5mm. The rotating tool was specially designed such that the pin inserts into the abutting edges of plates to be joined and

traversed along the line of the joint, also the shoulder exerts external pressure and also generates enough heat from friction between the shoulder and workpiece to form a strong joint. A total of 18 plates were used to produce nine (9) similar FSW butt joints at varying parameters edges of sheared faces were ground to obtain a good surface finish and checked and ensured for perpendicularity. Taguchi method, a technique used to find the most effective parameters with a few number of experiments was used to design an L9 orthogonal array for the process conditions. Table 2 presents the Taguchi array for the process conditions utilized in the FSW process.



**Plate 1:** Experimental setup

#### **Frictional Stir Welding Trials**

These trials were tests carried out on plates prepared for this purpose to ascertain suitable parameters for the stir

welding experiment. The actual welding was then after suitable welding parameters were established.

### Tensile test

The tests were performed using the Universal Testing Machine (UTM). The specimens were prepared according to ASTM E8M-13 standards. Each specimen was fitted in the UTM of capacity 200kN. During the test, the load applied and the displacement readings were recorded to calculate the stress. From the tests, the ultimate tensile stress of the FSW joint was determined. The results were based on the average of three samples.

### Parametric Optimization

The results obtained for the tensile strength (TS) test were used to compute the signal-to-noise ( $S/N$ ) ratio. In this work, a high  $S/N$  ratio for each factor or parameter was selected so as to obtain optimum weld qualities; that is Tensile Strength with minimum deviation. As described in eq. (3.1) below, the  $S/N$  ratios were calculated using a higher-is-better (HB) criterion in order to maximize the response. In Eq. (3.1),  $y$  is the

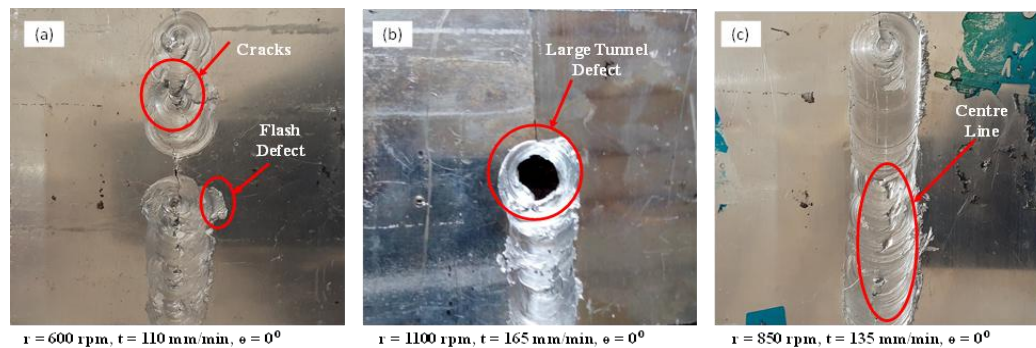
main characteristic considered in this investigation to describe the quality of FSW (i.e. the mean tensile strength), while  $n$  is the number of trials ( $n = 3$ ).

$$S/N = -10 \log_{10} \frac{1}{n} \sum_{i=0}^n \left( \frac{1}{y_i^2} \right) = -10 \log_{10}(MSSQ) \quad \text{Eq. 3.1}$$

Thereafter, the effect of each of the parameters on the weld quality (i.e. tensile shear strength) and optimal setting of the process parameters was determined using Taguchi Method (Minitab Software).

### RESULT AND DISCUSSION

**Result of trials:** These trial runs aimed to pinpoint the suitable range of parameters conducive to achieving high-quality weld. Throughout the trial experiment, notable physical defects such as surface cracks, flash defects, and large tunnels were observed, as depicted in Plate 2. Additionally, discernible continuous lines along the centerline of the joint were evident, suggesting the formation of a robust bond



**Plate 2:** Photographs of FS weldment showing defects during trial experiment

These defects typically stem from an inadequate combination of process parameters, notably an excessively low rotational speed ( $< 700$  rpm) coupled with a high traverse speed (163 mm/min). This parametric combination falls short in generating the necessary heat for effective bonding. This results in insufficient material

mixing and stirring, ultimately leading to the formation of tunnel defects. The presence of tunnels significantly impacts the mechanical properties of the Friction Stir Welding (FSW). Another potential cause for tunnel defects is poor penetration, where the tool shoulder fails to confine materials within the weld line. Flash defects, on the



other hand, occur when the workpiece undergoes extremely hot processing conditions, typically as a consequence of the tool rotating at very high speeds. This heightened rotational speed generates significant heat, thermally softening the material near the tool shoulder boundary and expelling a substantial volume of material in the form of flash. The excessive frictional heat generated by the tool shoulder is another factor contributing to flash formation. Following the trial

experiments, an appropriate range of parameters that yielded minimal defects was identified. These selected parameters were then combined using the L9 Taguchi orthogonal array, featuring four columns and nine rows shown in Table 2. The application of the Taguchi technique, with its specific design of an orthogonal array, facilitated the identification of the most effective parameters in the overall execution with a minimal number of experiments.

**Table 3:** L9 Taguchi Array of Process Conditions

No	Rotational Speed (rpm)	Travers Speed (mm/min)	Tilt Angle $\theta$ ( $^{\circ}$ )
1	710	25	1
2	710	40	2
3	710	63	3
4	900	25	2
5	900	40	3
6	900	63	1
7	1400	25	3
8	1400	40	1
9	1400	63	2

#### Result of Tensile Test

The tensile test specimens were subjected to stair welding procedures using the ascertained Taguchi array. The welded

joints are as shown in plate 3. The result of the tensile strength test is presented in Table 4.

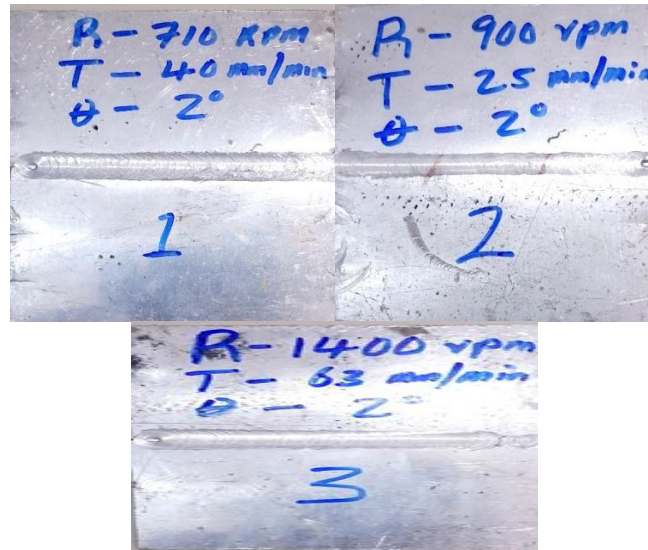


Plate 4: Samples of the Sir Welded Joints

Table 4: Tensile test result

No	r(rpm)	t (mm/min)	θ (°)	TS	SSQ	MSSQ	S/N RATIO
1	710	25	1	67.94	0.0002166	0.000072215	41.41
2	710	40	2	76.52	0.0001708	0.000056928	42.45
3	710	63	3	53.44	0.0003502	0.000116720	39.33
4	900	25	2	98.02	0.0001041	0.000034694	44.60

To decipher the primary effects of the process parameters, mean S/N ratios for each level of the utilized parameters were computed (Eq. 4.2), with results presented in Tables 4.3 for TSS. Figure 3 illustrates the main effects of all three factors on TS. Notably, TS increased with rotational speed from 710 rpm to 900 rpm; further increase to 1400 rpm, however, led to a decrease in tensile strength. The traverse speed exhibited a direct

relationship with tensile strength, decreasing from 25 mm/min to 63 mm/min. Tensile strength increased with an increase in tilt angle from 1 to 2 but decreased from 2 to 3.

$$S/N = -10 \log_{10} \frac{1}{n} \sum_{i=0}^n \left( \frac{1}{y_i^2} \right) = -10 \log_{10}(MSSQ) \quad \text{Eq. 4.1}$$

$$\text{Mean } S/N \text{ Ratio} = \frac{\text{total } S/N \text{ ratio for a factor and for a level}}{\text{number of experiment}} \quad \text{Eq. 4.}$$

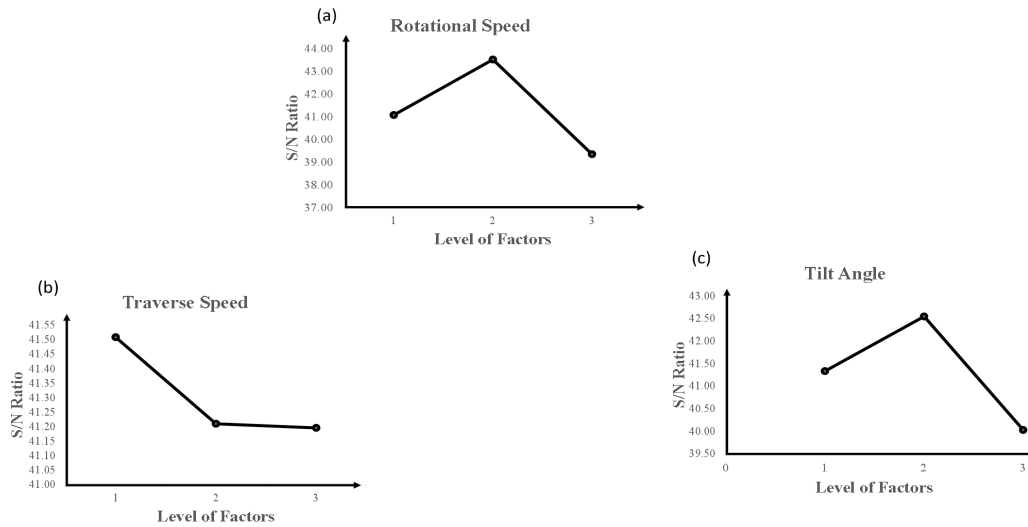
Table 5: S/N Ratio for the Tensile Strength (UTS)

No	r(rpm)	t (mm/min)	θ (°)	TS	SSQ	MSSQ	S/N RATIO
1	710	25	1	67.94	0.0002166	0.000072215	41.41
2	710	40	2	76.52	0.0001708	0.000056928	42.45
3	710	63	3	53.44	0.0003502	0.000116720	39.33
4	900	25	2	98.02	0.0001041	0.000034694	44.60
5	900	40	3	74.88	0.0001783	0.000059449	42.26

6	900	63	1	88.06	0.0001290	0.000042985	43.67
7	1400	25	3	48.66	0.0004223	0.000140778	38.51
8	1400	40	1	51.03	0.0003840	0.000128005	38.93
9	1400	63	2	61.83	0.0002616	0.000087193	40.60

**Table 6:** Main Effects of the Utilized Processing Parameters for the TSS

Column	Factors	S/N Ratio at level 1	S/N Ratio at Level 2	S/N Ratio at Level 3
A	r(rpm)	41.0630	43.5076	39.3459
B	t(mm/min)	41.5086	41.2110	41.1968
C	$\theta$ ( $^{\circ}$ )	41.3361	42.5465	40.0339



**Figure. 3** Main Effects of the Three Factors/Parameters on the Tensile Shear Strength

Based on the higher-is-better criterion (HB), the optimal processing condition for TSS was determined from the main effect plot (Fig. 2) and presented in Table 4. The optimum point is the level at

which the maximum value was attained for each factor, i.e., level 2 for traverse speed (A1), level 2 for rotational speed (B2), and level 1 for tilt angle (C2), as deduced from Table .3 and Fig. 3.

**Table 4:** Optimum Parametric Combination for FSW AA 1100

Factors	Input		
	r(rpm)	t (mm/min)	$\theta$ ( $^{\circ}$ )
Optimal Setting	900	25	2

### CONCLUSION

The friction stir welding of a 3 mm-thick aluminum alloy 1100 was successfully executed, employing parameter combinations such as rotational speed, traverse speed, and tilt angle. The key

findings from the obtained results are summarized as follows:

- i. The optimal process parameters for achieving the highest tensile strength were identified as a rotational speed of 900 rpm,





- traverse speed of 25 mm/min, and a tilt angle of 2 degrees.
- ii. The tensile strength of the weldment, within the established process window, ranged from 48 MPa to 98 MPa.
  - iii. With a confidence level of 90%, the rotational speed emerged as the most influential factor affecting tensile strength, contributing significantly at 70.32%. The tensile strength exhibited an upward trend with increasing rotational speed. Furthermore, the tilt angle demonstrated a substantial impact on tensile strength, contributing significantly at 24.36%. In contrast, the traverse speed appeared to have an insignificant contribution to the tensile strength of the weldment.

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