

# Optimization and Characterization of Friction Stir Welding Parameters for Aluminium Alloys 6061 and 6081

Jagjeet Singh Chatha<sup>a,\*</sup>, Simranjit Singh Sidhu<sup>a</sup>, Parminder Singh<sup>a</sup>

<sup>a</sup>Department of Mechanical Engineering, Punjabi University, Patiala, Punjab, India.

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\* Corresponding author:

Jagjeet Singh Chatha   
E-mail: [jagjeet\\_me@pbi.ac.in](mailto:jagjeet_me@pbi.ac.in)

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## ABSTRACT

The research explores the impact of Friction Stir Welding (FSW) parameters on tensile strength and microhardness of AA-6061 and AA-6081 aluminium alloys. Utilizing a vertical milling machine and a cylindrical tool, FSW trials were conducted on 100 x 100 x 6 mm plates, employing various combinations of tool rotation speed, feed rate, and depth of cut. Tensile strength and microhardness were measured post-welding. Analysis revealed that decreasing tool rotation speed improved tensile strength, while decreased feed rates led to reduced tensile strength. Microhardness exhibited a similar trend with lower rotation speed, feed rate, and depth of cut resulting in increased values. Microstructural examination highlighted the dominance of aluminium alloy in the stir zone of welded joints. The study underscores the intricate relationship between FSW parameters and mechanical properties, offering insights for optimizing welding processes in aluminium alloys. These findings contribute to the advancement of FSW techniques and facilitate the development of robust welded joints with enhanced mechanical properties.

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## 1. INTRODUCTION

### Friction Stir Welding

Friction Stir Welding (FSW) is an advanced welding technique developed in December 1991 by Wayne Thomas and his team at The Welding Institute UK [1,2]. Unlike traditional fusion welding methods, FSW operates in the solid state, generating frictional heat and plastic

deformation at the joint area without melting the materials. This process is highly energy-efficient, environmentally friendly, and versatile, particularly suitable for joining high-strength aviation aluminum alloys and other difficult-to-weld metallic alloys. FSW has been hailed as a significant advancement in metal joining over the past decade due to its ability to join large pieces that are not easily heat-treated [3,4]. It involves a non-consumable rotating tool with a specially

designed pin and shoulder, which heats the workpiece and facilitates material movement to create the joint. FSW is considered a green technology as it does not require any consumables like filler material or flux, making it environmentally friendly. Unlike conventional fusion welding, which is limited to small, symmetric parts, FSW can be applied to various joint types such as butt joints, lap joints, and T-butt joints.

### Working principle

The friction stir processing begins with the plunge phase, where a rotating tool is slowly inserted into the workpiece, generating heat at the interface. The material undergoes controlled plastic flow as the tool shoulder makes contact with the workpiece. In some cases, a dwell phase is introduced to reach the desired temperature for plastic flow. The plunge phase can be controlled either by vertical position or force applied under the tool's rotation axis. Once the material is sufficiently heated, the tool traverses in the desired direction, either under displacement or force control. Advanced FSP machines offer additional control modes such as power, temperature, and torque control. Frictional heat generation softens the metal, allowing it to flow around the tool, filling gaps. The process relies on material flow and heat generation, influenced by variables such as tool shoulder diameter and rotational speed. Increasing spindle speed or reducing tool travel speed can enhance heat input, depending on frictional conditions [2,5,6].

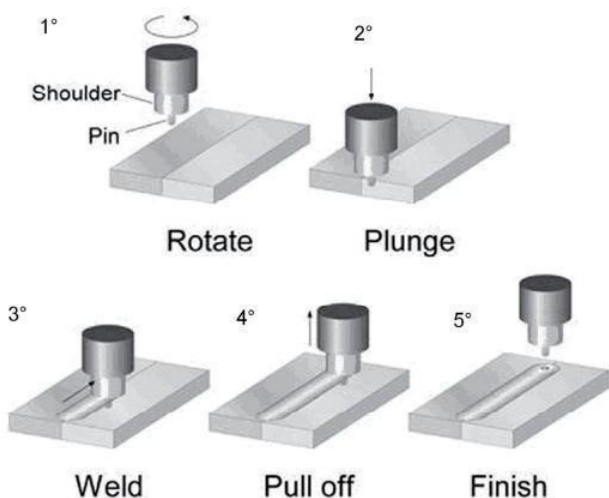


Fig. 1. Step by Step FSW process [7].

### Process Parameters

In friction stir welding (FSW), achieving high-quality, defect-free joints relies on defining several critical process parameters. These parameters, including process rotation speed, tool traverse speed, tool tilt angle, and insertion depth of the tool pin, play pivotal roles in the welding process. By carefully adjusting these parameters, welders can optimize the quality of FSW joints. Among the main process parameters are welding speed (measured in mm/min), which dictates the rate at which the tool travels along the joint line. Another crucial parameter is the tool rotational speed, measured in rotations per minute (rpm), which determines the speed at which the FSW tool rotates during welding. Additionally, the tool pin diameter, typically ranging from 17mm to 20mm, varies based on the thickness of the base metal. This diameter adjustment ensures compatibility with different plate sizes and contributes to achieving desired welding outcomes [8].

### Advantage/Disadvantage and applications

Friction stir welding (FSW) offers numerous advantages, including the absence of consumables such as filler wires and protecting gases, resulting in lower setup costs and minimal environmental impact. With no melting of the base material, FSW eliminates porosity and reduces energy consumption significantly compared to traditional methods like MIG welding. This process is versatile, capable of welding a wide range of materials including aluminum, copper, zinc, steel, and titanium, making it applicable across various industries. Despite its advantages, FSW does have some drawbacks. It can leave exit holes when the tool is withdrawn from welded plates, and its requirement for stable welding machines may limit its flexibility compared to manual methods. Challenges may arise with thickness variations and non-linear welds, particularly in applications where precision is crucial. The applications of FSW span diverse industries. In the railway sector, it's used for manufacturing high-speed trains, railway tankers, and container bodies. Marine and shipbuilding industries employ FSW for helicopter landing platforms, panels, and offshore structures. In aerospace, it's utilized for wings, fuel tanks, and various aircraft components. Automotive companies explore

FSW for wheel rims, engine supports, and truck bodies, while other industries consider it for electric motor housings, refrigeration panels, and construction equipment. FSW finds applications in construction for structures like bridges, window frames, and heat exchangers. Overall, FSW offers a promising solution for efficient and high-quality welding across a wide array of industrial applications [9-13].

## 2. METHODS

The study comprised four stages: material selection, tool and fixture fabrication experimentation, and testing.

### Material Selection

Aluminum is a widely abundant metal found in the Earth's crust and is typically extracted from bauxite ore. Its alloys, categorized into cast and wrought types, offer diverse properties depending on alloying elements and heat treatment. Heat treatable alloys, like those in the 2xxx series, can achieve high strength through precipitation hardening but may suffer from reduced corrosion resistance. Meanwhile, non-heat treatable alloys, such as those in the 1xxx series, excel in corrosion resistance and

workability. Other series like 3xxx, 4xxx, 5xxx, 6xxx, and 7xxx offer varying properties suited for specific applications, ranging from good formability and weldability to high strength and toughness [14,15]. Each series contains specific alloy compositions tailored to meet particular requirements, making aluminum grades versatile for a wide range of industrial applications. In this experiment the two dissimilar aluminum alloys, 6061 and 6081, were utilized as base materials. The chemical composition of both the materials are shown in table no. 1 and table no. 2. AA 6061 was placed on the advancing side, while AA 6081 was positioned on the retreating side. Aluminum alloy 6081, known for its medium strength and outstanding corrosion resistance, is primarily used in structural applications. It has gradually replaced 6061 in various fields due to its higher strength. Alloy 6081 finds common use in aircraft construction, yacht building, automotive parts, and aluminum can production for food and beverage packaging. AA 6061 is typically processed through extrusion, rolling, or forging to achieve specific shapes. Some alloys, including 6061, can undergo heat treatment or cold working using various methods to enhance their strength, hardness, corrosion resistance, and ease of fabrication [16].

**Table 1.** Chemical Composition of Plate AA 6061.

Element	Si	Fe	Cu	Mn	Cr	Mg	Zn	Al
%content	0.4-0.8	0-0.7	0.15-0.4	0-0.15	0.04-0.35	0.8-1.2	0-0.25	95.85-98.56

**Table 2.** Chemical Composition of Plate AA 6081.

Element	Cu	Mg	Si	Fe	Mn	Cr	Other	Al
% Content	0-0.10	0.60-1.2	0.70-1.3	0-0.5	0.1-0.45	0-0.10	0.3	96.2-98.6

### Tool Material and Design

The experimentation utilized a cylindrical welding tool made of High-Speed Steel (HSS). It is a versatile chromium-molybdenum hot work steel commonly employed in various tooling applications. The tool had a pin diameter of 6 mm, pin length of 6 mm, and shoulder diameter of 20 mm. Table No. 3 displays the chemical composition (%) of the HSS welding tool, while Figure 2 illustrates the welding tool.



**Fig. 2.** Welding tool.

**Table 3.** Chemical Composition (%) of HSS Welding Tool.

Element	C	Mn	Si	Cr	Mo	V
Content	0.40	0.40	1.00	5.25	1.35	1.00

### Experimentation

Friction stir welding (FSW) trails were carried out using vertical milling machine fitted with cylinder shaped tool. The materials taken for investigation were AA-6061 and AA-6081 alloy having dimension of 100 x 100 x 6 mm. The welding was carried out by using a properly designed clamping fixture that allows fixing two plates. The Taguchi method is used to design the experiment to optimize the friction stir welding parameters, considering multiple output parameters. Table no. 4 represents the sets designed for the experimentation and figure no. 3 and 4 shows sample after welding process completed and sample prepared for tensile testing as per standards respectively

**Table 4.** Design of Experiment.

Sr. No	Tool Rotation Speed (RPM)	Feed Rate (mm/min)	Depth of Cut ( $\mu\text{m}$ )
1	800	20	5.6
2	800	25	5.8
3	800	30	6.0
4	1000	20	5.8
5	1000	25	6.0
6	1000	30	5.6
7	1200	20	6.0
8	1200	25	5.6
9	1200	30	5.8

**Table 5.** S/N ratio for tensile strength and microhardness.

Sr.No	Tool Rotation Speed (RPM)	Feed Rate (mm/min)	Depth of Cut ( $\mu\text{m}$ )	Tensile Strength ( $\text{N}/\text{mm}^2$ )	S/N ratio (Tensile)	Hardness (HV)	S/N ratio (Hardness)
1	800	20	5.6	75.6	37.5704	56	34.9638
2	800	25	5.8	84.2	38.5062	47	33.4420
3	800	30	6.0	80.8	38.1482	42	32.4650
4	1000	20	5.8	70.2	36.9267	54	34.6479
5	1000	25	6.0	76.4	37.6619	43	32.6694
6	1000	30	5.6	81.8	38.2551	45	33.0643
7	1200	20	6.0	67.2	36.5474	48	33.6248
8	1200	25	5.6	74.8	37.4780	50	33.9794
9	1200	30	5.8	77.3	37.7636	42	32.4650



**Fig. 3.** Friction stir welded joint plates.



**Fig. 4.** Typical Tensile Test Specimen.

### 3. RESULT AND DISCUSSION

#### Signal to Noise Ratio analysis for tensile strength and microhardness

The S/N ratio is a quality indicator which represents the effect of changing particular process parameters on the process performance. Higher is better approach was used to calculate the S/N ratio of tensile strength and microhardness. it is calculated by analysing Taguchi design with the help of MINITAB software. Table no. 5 shows values of S/N ratios for tensile strength and microhardness.

**Table 6.** Mean signal to noise (S/N) ratio response for tensile strength.

Level	Tool-Rotation Speed	Feed Rate	Depth of Cut
1	38.07*	37.01	37.77*
2	37.61	37.88	37.73
3	37.26	38.06*	37.45
Delta	0.81	1.04	0.32
Rank	2	1	3

\* indicates higher S/N ratio

Ranks have been given to the different process parameters in the last row of the Table No. 6. Higher is the rank, higher is the significance. It has been found that feed rate has the highest rank 1 and is the most significant factor followed by the tool rotation speed at rank 2. Depth of cut has the lowest rank and is least affecting the tensile strength. The ranks represent the relative importance of each process parameter to the response

**Table 7.** Mean signal to noise (S/N) ratio response for microhardness.

Level	Tool Rotation Speed	Feed Rate	Depth of Cut
1	33.62*	34.41*	34.00*
2	33.46	33.36	33.52
3	33.36	32.66	32.92
Delta	0.27	1.75	1.08
Rank	3	1	2

\* indicates higher S/N ratio

Ranks have been given to the different process parameters in the last row of the Table no. 7. Higher is the rank, higher is the significance. It has been found that feed rate has the highest rank 1 and is the most significant factor followed by the depth of cut at rank 2. Tool Rotation Speed has the lowest rank and is least affecting the micro-hardness. The ranks represent the relative importance of each process parameter to the response.

#### 4. CONCLUSION

The current research investigates the effects of Friction Stir Welding (FSW) parameters on two response variables: tensile strength and microhardness. The study focuses on 6061 and 6081 aluminium alloys. Key conclusions are as follows:

1. Tool rotation speed has a minor effect on both tensile strength and micro-hardness, with S/N ratios ranging from 36.5474 to 38.5062 for tensile strength and 32.4650 to 34.9638 for micro-hardness. The ANOVA results show insignificant p-values for tool rotation speed in both cases, indicating its limited impact.
2. Feed rate is the most significant factor affecting both tensile strength and micro-hardness, with S/N ratios ranging from 37.4780 to 38.7636 for tensile strength and 32.4650 to 34.4100 for micro-hardness. It has the highest rank in both response tables and significant p-values in the ANOVA tables, highlighting its importance.
3. Depth of cut shows a moderate impact on tensile strength, with S/N ratios ranging from 36.9267 to 38.2551, but a more significant effect on micro-hardness, with S/N ratios ranging from 32.4650 to 34.9638. The ANOVA results indicate a moderate significance for depth of cut in tensile strength but a less significant effect in micro-hardness.
4. Optimal process conditions for maximizing tensile strength involve lower tool rotation speeds and higher feed rates, with the highest S/N ratios observed at 30mm/min feed rate and 800 RPM tool rotation speed. However, for micro-hardness, lower feed rates yield higher S/N ratios, suggesting a different optimal parameter combination for this response.
5. Microstructural analysis reveals the presence of various zones in the weldment, with the stir zone exhibiting dynamic recrystallization and smaller defects, particularly in joints created using round tool pin profiles. This indicates the importance of process parameters in achieving defect-free welds.

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