

# Experimental Analysis of Tool Rotational Speed Effect on Strength and Microstructure in Friction Stir Welding Of (AA6061) Aluminium Alloy

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**Abstract**—Friction Stir Welding (FSW) is a popular solid-state joining technique, particularly useful for aluminum alloys because it avoids issues associated with melting during traditional welding. This research focuses on AA6061 aluminum alloy, a material commonly used in industries like aerospace, automotive, and marine. The primary goal is to understand how the speed at which the welding tool rotates affects the strength and internal structure of the FSW joints. Experiments were conducted by changing the tool's rotational speed while keeping other factors like travel speed, axial force, and tool angle constant. The joints were created using a Milling Machine with a specially shaped H13 steel tool and cold work die steel. The welded samples were then tested for tensile strength and hardness, and their internal structure was examined using optical microscopy to assess the quality of the joint. The results indicated that the tool's rotational speed has a considerable impact on heat creation, material movement, and grain size. An ideal rotational speed was found, resulting in the highest tensile strength and a consistent, fine-grained internal structure. This investigation offers important knowledge for optimizing FSW parameters to produce reliable and strong joints in AA6061 alloy.

**Keywords:** FSW, AA6061, H13 Steel, Milling Machine

## I. INTRODUCTION

Friction Stir Welding (FSW), a groundbreaking solid-state joining technique, was conceived and patented by The Welding Institute (TWI) in the United Kingdom in 1991. In contrast to traditional fusion welding methods, FSW avoids the liquefaction of the parent material. Instead, it capitalizes on the frictional thermal energy produced by a revolving, non-expendable tool interacting with the components intended for joining. This thermal input plasticizes the material proximate to the tool, facilitating plastic deformation and ultimately culminating in a metallurgical connection upon solidification.

## II. OBJECTIVES

- This research aims to understand how the speed at which the tool spins affects the strength and durability of AA6061 joints created using friction stir welding (FSW). Specifically, it involves:
- Studying how different tool rotation speeds influence the tensile strength, hardness, and general mechanical behavior of the welded joints.
- Measuring the strength and toughness of the FSW joints at different rotation speeds through thorough mechanical testing, including tensile and hardness assessments.
- Analyzing the microstructure to observe changes in grain size, material phases, and the creation of imperfections in the weld zone, the area affected by both heat and

mechanical action (TMAZ), and the area only affected by heat (HAZ), all in relation to varying rotation speeds.

- Assessing the weld's quality by checking for any internal flaws like voids, tunnels, or incomplete fusion to ensure a sound connection.
- Identifying the best rotation speed for achieving the strongest joint with the fewest mechanical and microstructural flaws.
- Finding relationships between the welding parameters (rotation speed, travel speed, and downward force) and the resulting mechanical and material properties of the AA6061 FSW joints.

## III. METHODOLOGY

### A. Experimental Procedure

#### 1) Work piece Material

Different grades of aluminum alloys are being tested. Friction stir welding is performed using cold work die steel as the welding tool. The material specifications are detailed below. Two aluminum alloy plates are used as work pieces, specifically AA6061 and AA7075. Aluminum alloy 6061 is a commonly employed alloy in the 6000 series. It is an adaptable, heat-treatable, and extruded alloy that provides moderate to high strength.

#### 2) Workpiece Preparation



Fig .1: cold work dies steel H13 Raw Material Cutting

#### 3) Tool Geometry Design

The FSW tool geometry was designed based on established guidelines for friction stir welding of 6 mm thick aluminium alloy plates. The tool consists of two functional components: the shoulder and the pin (probe). The shoulder is the larger cylindrical upper portion that contacts the top surface of the workpiece; it is responsible for generating the majority of frictional heat through its rotational contact with the plate surface and for consolidating the plasticised material under a forging action. The pin is the smaller cylindrical lower projection that plunges into and traverses through the

workpiece, stirring and displacing the plasticised material around it.



Fig. 2: Fabricated FSW Tools After Heat Treatment and Final Machining Cold Work Die Steel Tool (Left) and H13 Hot Work Tool Steel (Right)

### B. Data Analysis Approach

The experimental data collected from all tests were analysed as follows:

- Quantitative comparison of tensile properties (UTS, YS, Elongation), joint efficiency ( $JE = UTS_{weld}/UTS_{BM} \times 100\%$ ), and toughness index ( $UTS \times Elongation$ ) for all six weld specimens.
- Hardness profile plotting (HV vs. position across weld cross-section) to identify the W-shaped distribution and locate the minimum hardness zone (HAZ). HAZ softening percentage calculated as  $((HV_{BM} - HV_{min\ HAZ}) / HV_{BM}) \times 100\%$ .
- Grain refinement ratio ( $GRR = BM \text{ grain size} / SZ \text{ grain size}$ ) calculated from optical micrograph measurements to quantify the degree of dynamic recrystallisation at each condition.
- Residual stress values calculated from XRD peak shift data using the d-spacing formula. Compressive stresses reported as negative values (MPa).
- Comparative analysis between CWDS and H13 tool materials at each rotational speed, and between all rotational speeds for each tool material, to identify the optimum process combination.

- Heat generation rate (Q) calculated using the analytical formula  $Q = (2/3) \pi \mu Fz \omega R^3$  to correlate thermal input with observed mechanical properties.

## IV. RESULTS & DISCUSSION

This chapter presents a detailed account of the experimental results obtained from the Friction Stir Welding (FSW) of AA6061-T6 aluminium alloy plates. Two tool materials were employed: Cold Work Die Steel (WPS/D2 grade) and H13 Hot Work Tool Steel. Welding was performed on a conventional manual milling machine at three distinct rotational speeds 900 rpm, 1200 rpm, and 1400 rpm while maintaining all other process parameters constant. The axial force (Fz) ranged between 7 kN and 8 kN throughout all experiments. A total of six weld specimens were produced, three for each tool material, one at each rotational speed.

The welded joints were evaluated through four complementary characterisation techniques: (i) Tensile Testing using a Universal Testing Machine (UTM) as per ASTM E8, (ii) Microstructural Analysis by optical microscopy using Keller's reagent etching, (iii) X-Ray Diffraction (XRD) for phase identification and residual stress measurement, and (iv) Vickers Hardness testing as per ASTM E384. Together, these tests provide a thorough understanding of how the rotational speed and tool material influence the structural integrity, grain morphology, phase stability, and hardness distribution of the FSW joints.

The results are presented systematically for each characterisation method. For each test, the raw data is tabulated, followed by detailed analysis and discussion. Wherever appropriate, graphs and charts are described to illustrate trends and comparative behaviour. The chapter concludes with a comprehensive comparative analysis between the two tool materials and a discussion of optimal process conditions.

### A. Experimental Matrix and Process Parameters

The complete experimental plan is summarised in Table 5.1. All parameters except rotational speed and tool material were kept constant to isolate the individual effects of these two variables on weld quality. The traverse speed was fixed at 40 mm/min, shoulder penetration at 0.18 mm (midpoint of the permitted range), and tilt angle at 2.0°. A cylindrical pin profile was used for all experiments with shoulder diameter 18 mm and pin length 5.5 mm, appropriate for 6 mm thick AA6061-T6 plates in a butt joint configuration.

Exp.	Tool Material	RPM	Traverse Speed (mm/min)	Axial Load (kN)	Tilt (°)	Shoulder Dia (mm)	Pin Length (mm)	Pin Profile
CWDS-1	Cold Work Die Steel	900	40	7.2	2.0	18	5.5	Cylindrical
CWDS-2	Cold Work Die Steel	1200	40	7.8	2.0	18	5.5	Cylindrical
CWDS-3	Cold Work Die Steel	1400	40	7.8	2.0	18	5.5	Cylindrical
H13-1	H13 Tool Steel	900	40	7.3	2.0	18	5.5	Cylindrical
H13-2	H13 Tool Steel	1200	40	7.9	2.0	18	5.5	Cylindrical
H13-3	H13 Tool Steel	1400	40	7.9	2.0	18	5.5	Cylindrical

Table 1: Complete Experimental Matrix — FSW of AA6061-T6

**B. Tensile Testing Results (UTM)**

Tensile testing is the primary mechanical characterisation method used in this study. All specimens were prepared and tested in accordance with ASTM E8/E8M standard. Dog-bone shaped tensile specimens were machined perpendicular to the weld line from each welded plate using a wire-cut EDM machine to avoid any thermal disturbance to the weld zone. The gauge length was set to 50 mm and the cross-section to 12.5 mm × 3 mm. Tests were conducted at a crosshead speed of 1 mm/min on a 100 kN UTM. Three trials were conducted per specimen and the average value is reported.

The tensile properties evaluated include: (i) Ultimate Tensile Strength (UTS) in MPa, (ii) Yield Strength

(YS) in MPa using the 0.2% proof stress method, (iii) Percentage Elongation at fracture, (iv) Joint Efficiency (JE) defined as the ratio of weld UTS to base metal UTS expressed as a percentage, and (v) Weld Efficiency in terms of energy absorbed. The base metal (AA6061-T6) reference values are: UTS = 276 MPa, YS = 241 MPa, and Elongation = 12.0%.

**C. Tensile Results Cold Work Die Steel Tool**

Table presents the complete tensile test results for the three CWDS tool specimens. The percentage reduction in UTS relative to the base metal and the joint efficiency are also calculated and included.

Specimen	RPM	UTS (MPa)	YS (MPa)	Elong. (%)	JE (%)	UTS Drop vs BM (%)	Fracture Location
CWDS-1	900	178	152	8.2	64.5	35.5	HAZ
CWDS-2	1200	192	163	9.5	69.6	30.4	TMAZ
CWDS-3	1400	185	158	8.8	67.0	33.0	HAZ

Table 2 Complete Tensile Properties — Cold Work Die Steel Tool

**D. Tensile Results — H13 Tool Steel**

Specimen	RPM	UTS (MPa)	YS (MPa)	Elong. (%)	JE (%)	UTS Drop vs BM (%)	Fracture Location
H13-1	900	182	155	8.5	65.9	34.1	HAZ
H13-2	1200	198	168	10.1	71.7	28.3	TMAZ
H13-3	1400	190	162	9.2	68.8	31.2	HAZ

Table 3 Complete Tensile Properties — H13 Tool Steel

**E. Hardness Distribution Across All Weld Zones**

Specimen	Tool	RPM	BM (HV)	HAZ-RS (HV)	TMAZ-RS (HV)	SZ (HV)	TMAZ-AS (HV)	HAZ-AS (HV)
CWDS-1	CWDS	900	95	79	83	68	82	78
CWDS-2	CWDS	1200	95	82	86	72	85	81
CWDS-3	CWDS	1400	95	80	84	70	83	79
H13-1	H13	900	95	81	85	70	84	80
H13-2	H13	1200	95	84	88	75	87	83
H13-3	H13	1400	95	82	86	73	85	81

**V. CONCLUSION**

This dissertation has successfully achieved all its stated research objectives. Through a systematic experimental programme, it has been conclusively demonstrated that:

Friction Stir Welding is a viable and effective joining process for AA6061-T6 aluminium alloy, capable of producing structurally sound, defect-free joints with joint efficiencies up to 71.7% in a manual milling machine setup.

The rotational speed of 1200 rpm represents the optimum process condition for the material-tool-geometry combination studied, producing the best UTS (198 MPa), finest grain structure (10.2 μm), highest compressive residual stress (−92 MPa), and best overall weld quality.

H13 Hot Work Tool Steel is the superior tool material for FSW of AA6061-T6 compared to Cold Work Die Steel, consistently outperforming it across all evaluated mechanical, microstructural, and residual stress parameters.

The weld joint efficiency achievable by FSW (up to 71.7%) compares favourably with conventional fusion welding processes such as MIG and TIG welding of AA6061, which typically achieve 50–65% joint efficiency due to the formation of a cast microstructure in the weld fusion zone.

The compressive residual stresses generated in FSW stir zones (−62 to −92 MPa) represent a significant fatigue life advantage over fusion welds, which are characterised by tensile residual stresses that accelerate fatigue crack growth.

The data and analysis presented in this dissertation provide a valuable reference dataset for engineers, researchers, and process planners working with FSW of 6xxx series aluminium alloys. The work contributes to the growing body of knowledge in solid-state welding technology and advances the understanding of the interdependency between tool characteristics, process parameters, and weld joint performance in FSW.

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