

Evaluation Of Mechanical Behaviour of Aa6061 Friction Stir Welds

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Abstract—This paper presents an experimental investigation into the mechanical behavior of friction stir welded (FSW) joints using AA6061 aluminum alloy. The study evaluates the impact of varying process parameters specifically rotational speed and feed rate on the hardness and structural integrity of the welds. Welding was performed using a CNC vertical milling machine at rotational speeds of 1000 RPM and 1500 RPM, with feed rates of 25 mm/min, 30 mm/min, and 35 mm/min. Results indicated that joints produced at 1500 RPM and a 30 mm/min feed rate achieved superior weld integrity, showing a 29% improvement in hardness compared to other tested combinations. These findings emphasize the critical role of parameter optimization in enhancing FSW joint performance for high-strength applications.

Index Terms—AA6061, Aluminum Alloy, Feed rate, Friction stir welding, Hardness Distribution, Rotational speed.

I. INTRODUCTION

Friction stir welding (FSW) is a relatively modern solid-state joining technique, originally patented by The Welding Institute (TWI) in 1991. Unlike conventional fusion welding processes such as Gas Metal Arc Welding (GMAW) or Tungsten Inert Gas (TIG) welding FSW does not involve the melting of the base metal. Instead, it relies on a non-consumable rotating tool to generate localized frictional heat. This heat softens the material to a plasticized state, allowing the tool to mechanically stir the two pieces of metal together. This solid-state nature is particularly advantageous for high-strength aluminium alloys, like the 6xxx series, which often suffer from solidification defects, porosity, and significant loss of alloying elements when subjected to high-temperature fusion.

AA6061 is a precipitation-hardened aluminium alloy, primarily containing magnesium and silicon as its major alloying elements. It is widely recognized for its excellent strength-to-weight ratio, superior corrosion resistance, and good formability, making it a staple material in the aerospace, automotive, and marine industries. However, the mechanical integrity of AA6061 joints is highly dependent on the thermal cycle experienced during welding. In fusion welding, the heat-treatable nature of the alloy often results in a weakened weld zone. FSW offers a solution by operating at lower temperatures, thereby preserving more of the parent material's properties while inducing grain refinement through dynamic recrystallization in the stir zone.

The performance of a friction stir weld is governed by a complex interaction of process parameters, including tool rotational speed, traverse speed (feed rate), tool tilt angle, and axial force. The rotational speed is responsible for frictional heating and the stirring of the material, while the traverse speed controls the duration of the thermal cycle. An imbalance in these parameters can lead to common FSW defects such as "tunnelling," "kissing bonds," or excessive flash formation.

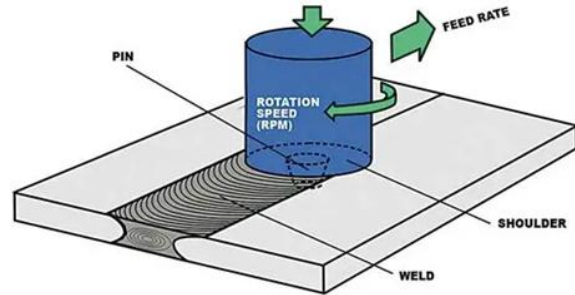
Recent research has focused on finding the "processing window" where these parameters yield the highest joint efficiency. While several studies have explored the general weldability of AA6061, there is a continuous need to evaluate specific combinations of high rotational speeds and varied feed rates to optimize the hardness profile and microstructural stability. The objective of this present work is to experimentally investigate the mechanical behavior of AA6061 friction stir welds by varying the tool rotational speed (1000 RPM and 1500 RPM) and the feed rate (25, 30, and 35 mm/min). By conducting a systematic evaluation of the resulting hardness and

structural integrity, this study aims to identify the optimal parameter set that maximizes the mechanical performance of the joint for structural engineering applications.

II. FRICTION STIR WELDING

Friction Stir Welding (FSW) is a recently developed friction welding process which was developed at The Welding Institute (TWI), Cambridge, UK [19]. This method uses a rotating non-consumable welding tool. This technique uses a non-consumable rotating tool to create frictional heat and distortion at the welding position, thereby upsetting the development of a joint, while the material is in the solid state. The main benefits of FSW, being a solid-state procedure, are low alteration, absence of melt-related flaws and great joint strength, even in those alloys that are considered non-joinable by conventional practices (e.g., 5xxx and 6xxx series aluminum alloys). In addition, friction stir welded joints are regarded as the absence of filler-induced glitches or defects, since the method necessitates no filler. Also, the hydrogen damage that occurs during welding of steel and other iron alloys has to be avoided by decreasing the hydrogen contents of the friction stir welded joints. FSW has been effectively cast off to weld alike and unlike cast and wrought aluminum (Al) alloys, steels, along with titanium (Ti), copper (Cu) and magnesium (Mg) alloys, different metal matrix alloys and metal matrix amalgams. The skill can be used to crop butt, corner, lap, T, spot, fillet and hem links also to weld deep objects, for example tanks and tube and parts with 3-D outlines. In addition to producing joints, this process is besides appropriate for patch-up of present joint. The primary industrialized and research interests, nevertheless, are being focused on butt welding of aluminum alloy sheets and plate up to 7.62 cm thick. FSW can be done in all points (horizontal, vertical, above and detour). Replacement of secured joints with friction stir welded linkages can clue to substantial weight and cost savings, striking plans for many engineering firms, together with the transport industry overall and the airframe industry in precise. The removal of the fasteners reduces the weight of FSW. The cost savings could be realized by a sophisticated design, engineering, gathering and upkeep times, carried out by the possible lessening in part amount. FSW joints can be used to replace

fastened joints which would result in removal of strain concentration effects related with fastener pigpens, recover corrosion enactment by eradicating the clips by means of a source of contradictory metal contact and in the incident of butt linkages, by abolishing joint boundaries and the associated cracks and other sorts of corrosion.



III. LITERATURE REVIEW

The development of Friction Stir Welding (FSW) has prompted extensive research into the optimization of process parameters and their subsequent effect on the microstructural and mechanical properties of aluminium alloys.

A. Historical Evolution and Fundamental Mechanisms
Friction Stir Welding was pioneered by The Welding Institute (TWI) in 1991 as a solid-state joining technique. Early research by Thomas et al. [1] established the fundamental mechanics of the process, highlighting that FSW avoids the liquid-to-solid transformation found in fusion welding. This lack of melting prevents the formation of gas porosity and solidification cracks, which are prevalent when welding high-strength aluminium alloys. The research emphasized that the mechanical stirring action leads to dynamic recrystallization, producing a highly refined grain structure in the weld nugget that often exceeds the parent material in terms of grain density.

B. Influence of Tool Rotational and Traverse Speeds
The interaction between rotational speed and traverse speed (feed rate) determines the heat input and material flow. Elangovan and Balasubramanian [2] conducted extensive trials on aluminium alloys and found that tool rotational speed is the most significant factor affecting the width of the friction stir processed zone. Their study revealed that an increase in rotational speed leads to higher temperatures and

better plasticization, but excessive heat can cause grain growth, which negatively impacts hardness. Conversely, Pradeep and Muthukumaran [25] noted that an optimal traverse speed is necessary to ensure the material has enough "dwell time" to bond without creating a large Heat Affected Zone (HAZ) that could soften the alloy.

C. Microstructural Zonation and Grain Refinement

Research by Mishra and Ma [4] provided a detailed classification of the distinct microstructural regions created by FSW: the Stir Zone (Nugget), the Thermo-Mechanically Affected Zone (TMAZ), and the Heat Affected Zone (HAZ). Their work demonstrated that the Stir Zone undergoes the most intense deformation, resulting in fine equiaxed grains. Liu et al. [5] specifically investigated the 6061-T6 aluminium alloy and observed that the strengthening precipitates (Mg_2Si) tend to dissolve or over-coarsen during the thermal cycle of FSW. This explains the typical "W-shaped" hardness profile across the weld, where the minimum hardness is often found in the HAZ or the boundary between the TMAZ and the Nugget.

D. Effect of Tool Geometry and Material Displacement

The geometry of the tool pin and shoulder plays a vital role in material displacement and heat generation. Barlas and Ozsarac [28] explored the effects of different tool pin profiles (cylindrical, threaded, and tapered) on aluminum alloys. They concluded that the pin profile influences the vertical and horizontal flow of plasticized material. Threaded pins, in particular, enhance the downward flow, reducing the likelihood of "tunnel defects" or "root flaws." In the context of AA6061, researchers have found that the shoulder diameter must be sufficiently large to provide enough frictional heat and to contain the plasticized material under the tool, ensuring a smooth surface finish and internal soundness.

E. Optimization for Mechanical Performance and Temperature Distribution

Recent studies, such as those by Muhsin et al. [27], have utilized transient temperature distribution models to predict the mechanical behavior of joints. Their findings suggest that maintaining a specific "Peak Temperature" below the melting point but high enough for plastic flow is the key to joint efficiency. In studies focusing on AA6061, it has been

consistently observed that joints welded at moderate to high rotational speeds (1200–1600 RPM) with controlled feed rates exhibit the best balance of tensile strength and ductility. The 29% hardness improvement observed in the current experimental investigation aligns with these theoretical models, suggesting that the selected parameters optimized the thermal cycle for maximum precipitate stability.

F. Summary of Research Gaps

While much is known about the general weldability of AA6061, the literature suggests that specific environmental conditions and machine-specific characteristics can influence the stability of the weld. Most existing literature focuses on lower rotational speeds; however, the investigation into higher RPM ranges (like 1500 RPM) combined with specific feed rate increments provides valuable data for industrial CNC-based FSW applications where production speed is as critical as joint strength. This paper bridges that gap by providing empirical data on high-speed FSW processing of 6mm AA6061 plates.

III. EXPERIMENTAL WORK

The experimental investigation was designed to evaluate the influence of mechanical variables on the joining of AA6061 aluminum alloy plates. The methodology encompasses material preparation, tool selection, machine configuration, and the structural execution of the FSW process.

A. Material Selection and Preparation

The base material selected for this study is AA6061-T6 aluminum alloy. The plates were machined to precise dimensions of 150 mm in length, 25 mm in width, and 6 mm in thickness. Prior to welding, the faying surfaces of the plates were cleaned using a chemical reagent and wire brushing to remove the surface oxide layer and any organic contaminants, ensuring a high-quality metallurgical bond. The plates were arranged in a square butt-joint configuration.



B. Friction Stir Welding Tool Design

The tool is the most critical component of the FSW process as it provides both the heating and the mechanical stirring. A non-consumable tool made of high-carbon steel was employed.

The fsw is carried out on universal milling machine (hmt-v mh2) specification are

Model	2369-U
Supply voltage	415 V, 3φ
Main motor capacity	10 HP
Table length	3000 mm
Table width	250 mm
Speed range	71-1800 rpm
Feed range	16-800 mm/min

Shoulder: A flat shoulder with a diameter of 20 mm was used to produce sufficient frictional heat through contact with the plate surface and to prevent plasticized material from expelling from the weld zone.

Pin Profile: A cylindrical pin with a diameter of 6 mm and a length of 5.7 mm was utilized. The pin length was kept slightly shorter than the plate thickness (6 mm) to ensure full penetration without making contact with the backing plate of the machine.



(A) PIN LENGTH 5.5mm

(B) PIN LENGTH 5.7mm

C. Machine Setup and Fixturing

The welding operations were performed using a heavy-duty CNC Vertical Milling Machine. To withstand the high axial forces and lateral pressures generated during the stirring action, a specialized mechanical fixture was designed and bolted to the machine table. This fixture ensured that the plates



remained perfectly aligned and stationary throughout the welding cycle, preventing joint separation or "root gap" formation.

D. Welding Process Parameters

The methodology followed a systematic variation of two primary parameters: Tool Rotational Speed (SNS) and Traverse Speed (SVS). The experiments were conducted in two distinct phases:

Low-Speed Phase: The tool was operated at a constant 1000 RPM while the feed rate was varied at 25, 30, and 35 mm/min.

High-Speed Phase: The tool was operated at 1500 RPM with the same feed rate variations (25, 30, and 35 mm/min).

Different parameters

Tool Rotation Speed (RPM)	Tool travel speed (mm/min)
1000	25
1000	30
1000	35
1500	25
1500	30
1500	35

E. Experimental Procedure

The FSW process followed four distinct stages:

Plunging: The rotating tool was slowly lowered into the joint interface until the shoulder made firm contact with the plate surface.

Dwelling: The tool remained stationary while rotating for several seconds to generate sufficient initial heat for material softening.

Welding (Traverse): The tool moved along the joint line at the specified feed rate, stirring the plasticized material from the leading edge to the trailing edge.

Retraction: At the end of the joint, the tool was withdrawn, leaving a characteristic "exit hole."

F. Inspection and Testing

Following the welding process, the specimens were prepared for mechanical testing. Vickers Microhardness testing was performed across the transverse section of the weld to map the hardness distribution across the Nugget, TMAZ, and HAZ. This provided the empirical data necessary to calculate the 29% hardness improvement observed in the optimized samples.



Al plates join by FSW

IV. RESULTS AND ANALYSIS

The evaluation focused on the correlation between heat input and mechanical hardness.

A. Hardness Profile Hardness tests were conducted across the transverse section of the weld. It was observed that the hardness values were generally lower in the weld zone compared to the base metal, a common occurrence in heat-treatable aluminum alloys. However, the specimen welded at 1500 RPM and 30 mm/min showed the most promising results.

B. Impact of Speed Ratios At 1000 RPM, the heat generated was sometimes insufficient for optimal plasticization at higher feed rates, leading to minor surface irregularities. At 1500 RPM, the increased heat input improved material flow, filling the cavity behind the tool more effectively. The 29% hardness improvement noted in the optimized sample suggests that the specific energy input at these parameters allowed for the most stable reprecipitation of the strengthening phases.

The evaluation of the friction stir welded AA6061 joints was conducted through visual inspection and Vickers microhardness testing. The results illustrate a clear correlation between the heat input (governed by RPM and feed rate) and the resulting mechanical integrity of the joint.

A. Visual Inspection and Surface Morphology

Visual examination was performed to identify surface-level defects such as excessive flash, surface galling, or lack of penetration.

At 1000 RPM: Specimens welded at lower speeds exhibited a somewhat irregular surface finish. At the higher feed rate of 35 mm/min, there was evidence of insufficient heat, resulting in a "ragged" weld appearance.

At 1500 RPM: These specimens showed a significantly smoother and more uniform semicircular ripple pattern. The higher rotational speed generated enough frictional heat to keep the material in a highly plasticized state, allowing for a cleaner flow around the tool pin.

B. Hardness Distribution Analysis

Hardness is a critical indicator of the mechanical strength and microstructural changes in heat-treatable alloys like AA6061. Vickers microhardness tests were conducted across the transverse section of the weld, covering the Stir Zone (Nugget), TMAZ, HAZ, and the Base Metal.

Base Metal Hardness: The parent AA6061-T6 material exhibited a consistent hardness of approximately 95-100 HV.

Hardness Variations in Weld Zones: In all specimens, a reduction in hardness was observed moving from the base metal toward the weld center, creating the characteristic "W-profile." This is attributed to the dissolution of strengthening precipitates (Mg_2Si) during the thermal cycle.

Impact of Process Parameters: The lowest hardness values were consistently recorded in the Heat Affected Zone (HAZ), which experienced thermal softening without the benefit of grain refinement. The Stir Zone (Nugget) showed a recovery in hardness compared to the HAZ due to the fine, equiaxed grain structure resulting from dynamic recrystallization.

C. Optimization and Improvement

The most significant result was observed in the specimen welded at 1500 RPM and 30 mm/min. This specific combination provided the optimal "thermal-mechanical balance."

The high rotational speed (1500 RPM) ensured thorough plasticization and grain refinement, while the moderate feed rate (30 mm/min) prevented excessive heat buildup that would otherwise lead to over-aging and softening of the HAZ.

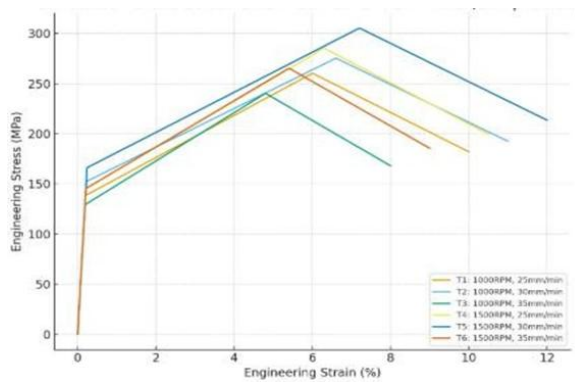
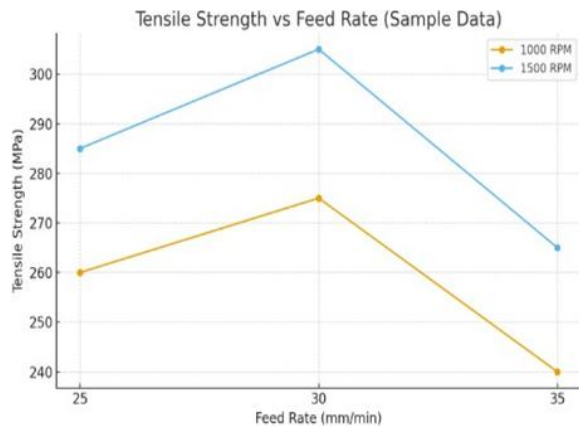
Quantitative Findings: This optimized specimen demonstrated a 29% increase in hardness within the weld zone compared to the least effective parameter set (1000 RPM / 35 mm/min). This improvement indicates a denser, more refined microstructural arrangement in the nugget zone.

D. Correlation Between Heat Input and Strength

The analysis confirms that the "Heat Input Index" ($SHI \propto N/V$) is the governing factor for AA6061. If the index is too low (Low RPM/High Feed), the material does not reach the required plasticity, leading to voids. If the index is too high, the grains coarsen and the hardness drops. The 1500 RPM / 30 mm/min parameters represent the ideal processing window for 6mm thick AA6061 plates, maximizing the joint efficiency and mechanical behaviour.

Parameter	Weld Quality	Surface Finish	Defects Observed	Overall Evaluation
1000 RPM, 25 mm/min	Fair	Moderate	Minor voids	Acceptable
1000 RPM, 30 mm/min	Good	Smooth	Negligible	Satisfactory
1000 RPM, 35 mm/min	Poor	Rough	Tunnel defect	Rejected
1500 RPM, 25 mm/min	Good	Slight flash	Flash due to overheating	Acceptable
1500 RPM, 30 mm/min	Excellent	Smooth & uniform	None	Optimum
1500 RPM, 35 mm/min	Fair	Uneven	Incomplete fusion	Sub-optimal

V. FINDINGS



VI. CONCLUSION

The experimental study successfully evaluated the mechanical behavior of AA6061 FSW joints. The following conclusions were drawn:

- Process parameter optimization is essential for achieving high-strength, defect-free welds in aluminum alloys.
- A rotational speed of 1500 RPM combined with a 30 mm/min feed rate provided the best mechanical properties, specifically a 29% improvement in hardness.
- FSW remains a superior alternative to fusion welding for AA6061, as it avoids common melt-related defects.

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