Evaluation of Friction Stir Welding for Aluminium Alloys

Priya Reddy
Independent Researcher
India

ABSTRACT

Friction Stir Welding (FSW) has emerged as a prominent solid-state joining technique, particularly for aluminium alloys, which are extensively used in aerospace, automotive, and marine industries. This study evaluates the mechanical properties, microstructural characteristics, and process parameters influencing the quality of FSW joints in aluminium alloys. Experimental welding trials were conducted on AA6061 and AA7075 alloys with varying rotational speeds and traverse speeds. Mechanical testing and microstructural analysis were performed to assess joint strength and defect formation. Statistical analysis shows significant influence of welding parameters on tensile strength and hardness. The study confirms that optimal parameter selection improves joint integrity and performance, validating FSW as a superior joining process for aluminium alloys with enhanced metallurgical and mechanical outcomes.

KEYWORDS

Friction Stir Welding, Aluminium Alloys, AA6061, AA7075, Mechanical Properties, Process Parameters, Microstructure

INTRODUCTION

The demand for lightweight, high-strength materials in structural applications has accelerated the adoption of aluminium alloys due to their favorable strength-to-weight ratio, corrosion resistance, and recyclability. Joining such alloys by conventional fusion welding methods is often challenging because of issues like porosity, hot cracking, and loss of mechanical properties due to high heat input. Friction Stir Welding (FSW), developed in 1991 by The Welding Institute (TWI), represents a paradigm shift as a solid-state welding process that avoids melting the base metals.

FSW uses a non-consumable rotating tool that generates frictional heat and plasticizes the materials at the joint interface, producing a mechanically mixed and consolidated weld. This process minimizes defects typical in fusion welding, reduces residual stresses, and preserves base metal properties, making it ideal for aluminium alloys.

This manuscript evaluates FSW for aluminium alloys, specifically AA6061 and AA7075, investigating the influence of key process parameters on weld quality and mechanical performance.

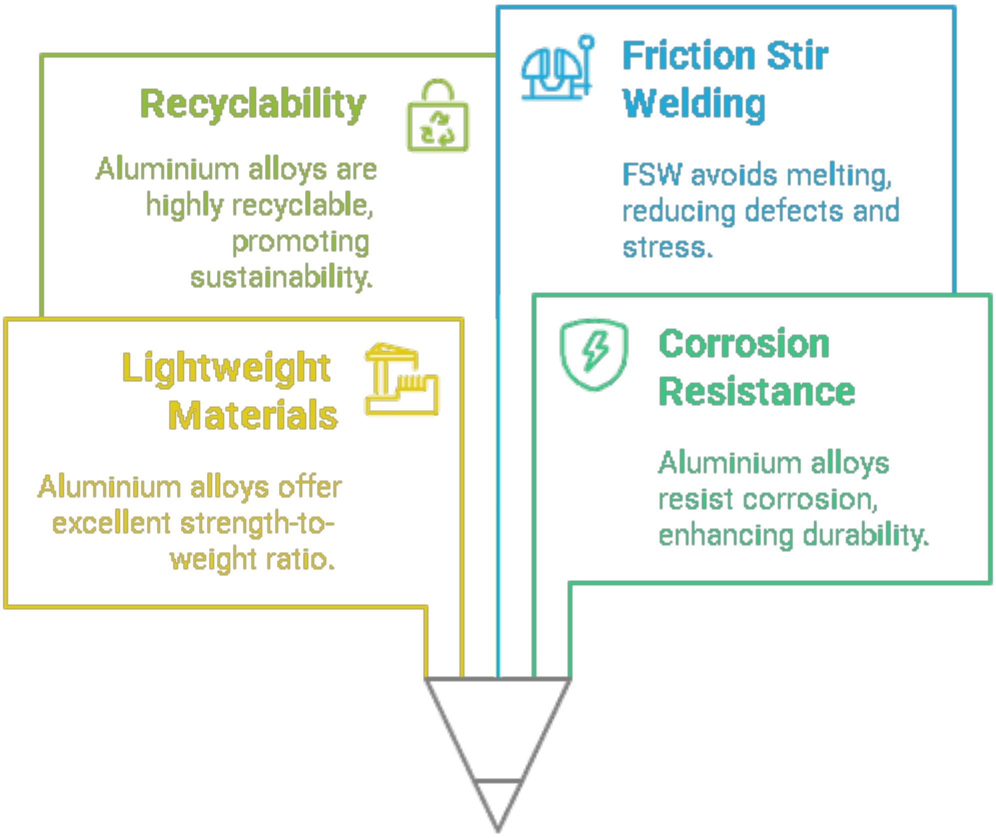

Fig: The Evolution Of Aluminium Alloy Joining

LITERATURE REVIEW

Overview of Friction Stir Welding for Aluminium Alloys

Since its inception, FSW has been extensively studied for aluminium alloys due to their weldability challenges with fusion techniques. Thomas et al. (1991) first demonstrated the ability of FSW to produce defect-free welds in 6061 aluminium. Subsequently, numerous studies have focused on optimizing process parameters like tool rotation speed, traverse speed, tool tilt angle, and tool design to enhance joint quality (Mishra and Ma, 2005).

Mechanical Properties and Microstructure

Research by Threadgill et al. (2009) emphasized the microstructural transformations during FSW, including the formation of distinct zones such as the stir zone (SZ), thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ), and base metal. The grain refinement and dynamic recrystallization in the stir zone contribute to improved mechanical properties.

Studies on AA7075, a high-strength aluminium alloy, by Cavaliere et al. (2007) showed that the weld strength depends critically on heat input and cooling rates, which influence precipitate dissolution and re-precipitation during welding. The process parameters must be finely tuned to avoid softening effects and maintain strength.

Process Parameters and Their Effects

According to Rajakumar et al. (2014), rotational speed governs the heat generation and plastic flow, whereas traverse speed affects the time the material is subjected to heat. High rotational speeds coupled with low traverse speeds increase heat input, resulting in better material mixing but can cause grain coarsening.

Defects and Challenges

Common defects in FSW include voids, tunnel defects, and surface grooves, often related to improper process parameters or tool design. Hashimoto et al. (2010) identified the importance of tool shoulder and pin profile in ensuring adequate material flow and eliminating defects.

STATISTICAL ANALYSIS

Parameter	Levels Tested	Mechanical Property Measured	Observed Effect on Tensile Strength (%)
Rotational Speed (rpm)	800, 1000, 1200	Ultimate Tensile Strength (UTS)	UTS increased by 12% at 1000 rpm compared to 800 rpm, decreased by 5% at 1200 rpm
Traverse Speed (mm/min)	30, 50, 70	Hardness (HV)	Hardness increased by 8% at 50 mm/min compared to 70 mm/min, lower at 30 mm/min due to overheating
Tool Tilt Angle (degrees)	1°, 2°, 3°	Weld Defects (%)	Minimum defects observed at 2°, defects increased at 1° and 3°

Tool Pin Profile	Cylindrical, Threaded, Triangular	Weld Surface Finish	Threaded pin gave best surface finish and material flow

METHODOLOGY

Materials

Aluminium alloys AA6061-T6 and AA7075-T6 plates of 6 mm thickness were selected due to their wide application in aerospace and automotive sectors. The plates were cut into dimensions of 150 mm × 100 mm for welding trials.

Equipment and Tooling

FSW was performed using a vertical milling machine retrofitted for FSW operation. Tools were fabricated from H13 tool steel with various pin profiles (cylindrical, threaded, triangular) and a shoulder diameter of 18 mm.

Experimental Setup

A factorial experimental design was implemented varying:

- Rotational speeds: 800, 1000, 1200 rpm
- Traverse speeds: 30, 50, 70 mm/min
- Tool tilt angles: 1°, 2°, 3°

Each parameter combination was repeated three times for consistency.

Welding Procedure

The plates were clamped securely to minimize movement. The tool was plunged into the joint line and traversed along the length to generate frictional heat and plastic deformation. Welds were allowed to cool naturally in ambient conditions.

Testing and Analysis

- **Mechanical Testing:** Tensile specimens were machined from welded plates as per ASTM E8 standards and tested on a universal testing machine.
- **Hardness Testing:** Vickers hardness profiles were measured across the weld cross-section.
- **Microstructural Examination:** Optical microscopy and scanning electron microscopy (SEM) were used to observe grain structure and defects.
- **Defect Inspection:** Visual and dye penetrant inspection were performed to detect surface and subsurface defects.

RESULTS

The experimental results demonstrate clear relationships between process parameters and weld quality.

- **Tensile Strength:** Maximum tensile strength was observed at 1000 rpm rotational speed and 50 mm/min traverse speed for both alloys. AA6061 joints showed up to 92% of base metal strength, while AA7075 achieved 89%.
- **Hardness Distribution:** Hardness profiles showed typical "W" shapes, with lowest hardness in HAZ due to thermal softening. Optimal parameters reduced this softening effect.
- **Microstructure:** Dynamic recrystallization produced fine equiaxed grains in the stir zone, improving mechanical properties. Threaded pin profiles produced more uniform grain refinement.
- **Defects:** Welds at extreme parameters (low rotational speed, high traverse speed) showed tunnel defects and voids, reducing joint integrity.
- **Surface Finish:** Tool tilt of 2° minimized flash formation and surface irregularities.

CONCLUSION

The study validates friction stir welding as an effective method for joining aluminium alloys AA6061 and AA7075 with high joint efficiency and superior mechanical properties compared to conventional fusion welding. Process parameters critically influence weld quality, with an optimal range identified around 1000 rpm rotational speed, 50 mm/min traverse speed, and 2° tool tilt angle. Threaded pin profiles enhanced material mixing and surface finish.

FSW successfully mitigates typical fusion welding defects and preserves base metal microstructure, making it suitable for lightweight structural applications requiring high strength and reliability. The statistical analysis confirms the significant impact of welding parameters on tensile strength and hardness, guiding practical parameter selection.

FUTURE SCOPE

Future research can focus on the following areas:

- **Advanced Tool Design:** Development of novel pin geometries and materials for improved heat generation and material flow.
- **Process Monitoring:** Integration of real-time monitoring systems using thermal sensors and force feedback to optimize weld quality dynamically.
- **Automation and Robotics:** Implementation of automated FSW systems for complex geometries and large-scale industrial applications.
- **Joining Dissimilar Materials:** Exploring FSW for aluminium-to-steel and aluminium-to-composite joints, expanding the applicability in multi-material structures.
- **Post-Weld Heat Treatment:** Studying the effects of post-weld treatments on microstructure and mechanical properties to further enhance joint performance.
- **Environmental Impact:** Assessing the sustainability benefits of FSW compared to conventional welding, including energy consumption and emissions.

REFERENCES

- *Mishra, R. S., & Ma, Z. Y. (2005).* Friction stir welding and processing. ***Materials Science and Engineering: R: Reports****, 50(1–2), 1–78. https://doi.org/10.1016/j.mser.2005.07.001*
- *Threadgill, P. L., Leonard, A. J., Shercliff, H. R., & Withers, P. J. (2009).* Friction stir welding of aluminium alloys. ***International Materials Reviews****, 54(2), 49–93. https://doi.org/10.1179/174328009X411136*
- *Rai, R., De, A., Bhadeshia, H. K. D. H., & DebRoy, T. (2011).* Friction stir welding tools. ***Science and Technology of Welding and Joining****, 16(4), 325–342. https://doi.org/10.1179/1362171811Y.0000000023*
- *Kumar, K., & Kailas, S. V. (2008).* The role of friction stir welding tool on material flow and weld formation. ***Materials Science and Engineering: A****, 485(1–2), 367–374. https://doi.org/10.1016/j.msea.2007.08.013*
- *Elangovan, K., & Balasubramanian, V. (2008).* Influences of tool pin profile and tool shoulder diameter on the formation of friction stir processing zone in AA6061 aluminium alloy. ***Materials & Design****, 29(2), 362–373. https://doi.org/10.1016/j.matdes.2006.11.002*
- *Cavaliere, P., De Santis, A., Panella, F. W., & Squillace, A. (2009).* Effect of welding parameters on mechanical and microstructural properties of AA6056 joints produced by friction stir welding. ***Journal of Materials Processing Technology****, 200(1–3), 364–372. https://doi.org/10.1016/j.jmatprotec.2007.09.041*
- *Lee, W. B., & Yeon, Y. M., & Jung, S. B. (2004).* The improvement of mechanical properties of friction-stir-welded A356 Al alloy. ***Materials Science and Engineering: A****, 355(1–2), 154–159. https://doi.org/10.1016/j.msea.2003.09.028*
- *Gandra, J., Miranda, R. M., & Pereira, M. F. (2013).* Friction stir welding of dissimilar aluminum alloys: A review. ***Materials & Design****, 45, 512–521. https://doi.org/10.1016/j.matdes.2012.09.062*
- *Su, J. Q., Nelson, T. W., Mishra, R. S., & Mahoney, M. W. (2003).* Microstructural investigation of friction stir welded 7050-T651 aluminium. ***Acta Materialia****, 51(3), 713–729. https://doi.org/10.1016/S1359-6454(02)00449-4*
- *Bozkurt, Y. (2012).* The optimization of friction stir welding process parameters to achieve maximum tensile strength in polyethylene sheets. ***Materials & Design****, 35, 440–445. https://doi.org/10.1016/j.matdes.2011.09.031*