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A Parametric Study on the Influence of Welding Speed and Axial Force in Friction Stir Welding of High-Strength Aluminum Alloys

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Abstract- Friction Stir Welding (FSW) offers a promising solid-state joining method, particularly for high-strength aluminum alloys like AA7075-T6, which are prone to welding defects under conventional fusion methods. This research evaluates how variations in welding speed (50–100 mm/min) and axial force (4–10 kN) influence mechanical performance and microstructural features of FSW joints. Using a systematic design of experiments, joints were evaluated via tensile testing, Vickers microhardness, and optical microscopy. Optimal results were found at 60 mm/min and 6 kN, yielding a tensile strength of 420 MPa and refined, defect-free grains. These findings provide actionable insight into parameter selection for advanced aerospace and automotive applications.

Key Words: Friction Stir Welding (FSW), Welding Speed and Axial Force, tensile strength, etc.

1. INTRODUCTION

Tungsten Friction Stir Welding (FSW) is a solid-state joining process that has revolutionized the way engineers and manufacturers approach the welding of non-ferrous metals, especially aluminum alloys. Developed by The Welding Institute (TWI) in 1991, the technique involves the use of a specially designed rotating tool with a pin and shoulder that is plunged into the abutting edges of the workpieces to be joined. As the tool traverses along the joint line, frictional heat and plastic deformation soften the material without reaching its melting point. The softened material is stirred and forged under axial pressure, resulting in a high-integrity, fully consolidated weld. This method eliminates common fusion welding defects such as solidification cracking, porosity, and metallurgical discontinuities.

High-strength aluminum alloys such as AA7075-T6, which are precipitation-hardened and belong to the 7xxx series, are essential in high-performance applications due to their excellent strength-to-weight ratio, fatigue resistance, and corrosion behavior. These alloys are widely used in aerospace structures, automotive crash components, defense systems, and marine applications. However, their inherent weldability issues pose significant challenges. Traditional arc welding techniques often degrade the mechanical properties of these alloys by dissolving strengthening precipitates and inducing defects such as hot cracking and voids due to their high thermal conductivity and low solidus temperature.

FSW provides an effective solution by joining the material in the solid state, preserving its metallurgical integrity and reducing heat-affected damage. Nevertheless, the mechanical and microstructural quality of the FSW joint is highly sensitive to process parameters. Among the critical variables in FSW, welding speed (traverse speed) and axial force (downward pressure) play vital roles. These parameters control heat input, material flow, tool-workpiece interaction, and recrystallization behavior, all of which influence the final joint strength and quality.

i. Welding speed affects the time available for frictional heat generation and plastic flow. Higher speeds reduce heat input, potentially leading to defects such as tunnel voids due to inadequate stirring. Conversely, slower speeds increase heat, which can cause grain coarsening or excessive flash.

ii. Axial force governs the depth of tool penetration and material consolidation. Insufficient axial force may lead to incomplete bonding or void formation, while excessive force can cause flash defects and increase tool wear.

While previous studies have addressed these variables independently, limited research has examined their combined effects on the FSW of AA7075-T6, especially under industrially relevant conditions. Moreover, the interaction between these parameters remains underexplored in terms of how they affect joint efficiency, hardness gradients, and microstructural transformation zones, such as the nugget zone (NZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ).

The present study aims to bridge this gap by conducting a comprehensive parametric investigation into how varying welding speeds and axial forces influence the mechanical properties and internal structure of AA7075-T6 FSW joints. Through systematic experimentation and analysis—including tensile testing, Vickers microhardness profiling, optical microscopy, and defect inspection—this work provides insight into the optimal parameter combinations that maximize joint strength and quality. The outcomes are expected to contribute significantly to the development of optimized process protocols for the FSW of high-strength aluminum alloys, thereby enhancing their reliability and efficiency in critical structural applications.

2. LITERATURE REVIEW

Friction Stir Welding (FSW) has been the subject of extensive research since its introduction by The Welding Institute (TWI) in 1991. Its ability to produce high-quality joints in difficult-to-weld materials, especially aluminum alloys, has driven considerable interest in both academic and industrial settings. Numerous studies have explored the influence of key process parameters—including welding speed, tool rotation speed, axial force, and tool design—on joint performance, mechanical properties, and microstructural features. However, the combined effect of welding speed and axial force, particularly in high-strength aluminum alloys like AA7075-T6, remains insufficiently addressed in the current body of literature.

2.1 Influence of Process Parameters on FSW Joint Quality

Mishra and Ma (2005) provided one of the earliest comprehensive reviews of FSW, highlighting the influence of tool rotation speed and welding speed on the heat generation and dynamic recrystallization in the nugget zone. Their findings established that increasing tool rotation enhances heat input, while increasing traverse speed reduces it—both of which significantly affect weld morphology and mechanical strength.

Rajakumar et al. (2011) conducted a detailed study on the FSW of AA7075-T6, optimizing process parameters using a statistical design of experiments approach. They found that tool rotation speed and welding speed jointly influence tensile strength, but noted that excessively high or low values could lead to reduced weld quality due to overheating or lack of material mixing. They achieved a maximum joint efficiency of 77% under optimized parameters.

Liu et al. (2013) examined the microstructure and mechanical properties of FSW joints in 7075 aluminum alloy, showing that slower welding speeds lead to larger grain sizes due to increased heat input and prolonged exposure. They also observed that faster traverse speeds improved mechanical strength but increased the risk of tunnel defects if axial force was not adequately controlled.

Esparza et al. (2018) emphasized the need to balance axial force with other parameters. Their work demonstrated that excessive axial force not only leads to flash and tool degradation but can also reduce joint performance due to increased residual stresses. On the other hand, low axial forces cause poor material consolidation and internal voids, negatively affecting tensile and fatigue properties.

2.2 Role of Welding Speed in Heat Generation and Flow Behavior

Zhao et al. (2012) modeled the thermal profiles in FSW and demonstrated that welding speed directly influences the peak temperature in the nugget zone. Higher welding speeds reduce the time for heat accumulation, which can refine grain size but may limit complete material mixing. They recommended a moderate welding speed to balance thermal softening and plastic flow.

Sato et al. (1999) provided detailed observations on microstructural evolution during FSW, revealing that optimal welding speed ensures a well-defined, equiaxed grain structure in the stir zone, which is critical for achieving high strength and toughness. Their work confirmed the importance of maintaining a proper thermal cycle through speed control.

2.3 Effect of Axial Force on Material Consolidation and Defect Formation

Elangovan and Balasubramanian (2008) investigated the effect of axial force on weld defects and found a direct correlation between downward force and material consolidation. Insufficient force led to lack of bonding and wormhole defects, while too much force increased flash formation and wear on the tool shoulder.

Buffa et al. (2009) used numerical simulations to study the influence of process parameters on FSW thermal and material flow fields. They highlighted that axial force is crucial in governing the size of the nugget zone and directly impacts the vertical pressure and frictional heat generation, ultimately affecting the mechanical strength of the weld.

2.4 Research Gaps and Motivation for Current Study

Despite these valuable contributions, most existing studies evaluate welding speed and axial force in isolation, with limited attention to their interdependent effects on joint performance in high-strength precipitation-hardened alloys like AA7075-T6. There is also a lack of comprehensive data linking parameter variations with defect types, grain boundary behavior, and hardness distribution across the weld region. Moreover, optimization studies often rely on empirical trial-and-error approaches rather than systematically designed experiments considering combined parameter variations.

Given the critical importance of AA7075-T6 in aerospace and automotive sectors, where joint integrity and consistency are paramount, there is a compelling need to explore the interactive influence of welding speed and axial force. This study addresses this gap by conducting a parametric analysis, integrating mechanical testing with microstructural examination to derive meaningful conclusions for industrial application.

3. METHODOLOGY

3.1 Material Selection

a) **Base Material:** AA7075-T6, 5 mm thick

Composition (wt.%): Al (Base), Zn (5.6%), Mg (2.5%), Cu (1.6%), Fe (0.5%)

b) **Tool Material:** H13 tool steel, heat-treated for wear resistance

Design: Threaded cylindrical pin (5 mm dia., 4 mm length), concave shoulder (15 mm)

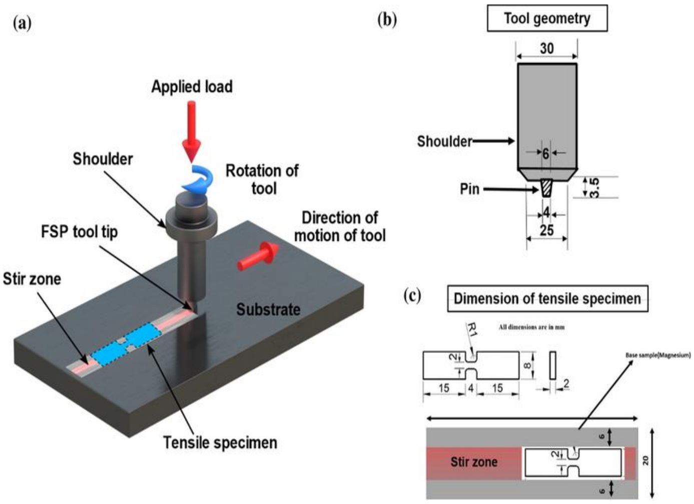

Figure 1: Friction stir welding Process

3.2 Welding Parameters

Table 1: Welding parameters

Parameter	Levels
Welding Speed	50, 60, 75, 100 mm/min
Axial Force	4, 6, 8, 10 kN
Tool Rotation	Constant at 1000 rpm
Tilt Angle	2°

3.3 Experimental Setup

- CNC-controlled FSW machine ensured consistent force and travel rate.
- Thermocouples monitored in-situ temperatures in the nugget zone.
- 12 samples were produced to cover all parameter combinations.

3.4 Testing Procedures

i. **Tensile Testing:** ASTM E8 sub-sized specimens, tested at 2 mm/min

ii. **Hardness:** Vickers hardness across the cross-section (HV0.1)

iii. **Microstructure:** Etched samples (Keller's reagent) observed under OM & SEM

iv. **Radiography:** X-ray analysis for tunnel/void defects

4. RESULT AND DISCUSSION

4.1 Welding Speed

Table 2: Effect of Welding Speed on UTS at Constant Axial Force (6 kN)

Speed (mm/min)	UTS (MPa)	Hardness (HV)	Defects
50	385	142	Minor Flash
60	420	150	None
75	400	147	Minimal
100	375	138	Tunnel Defects

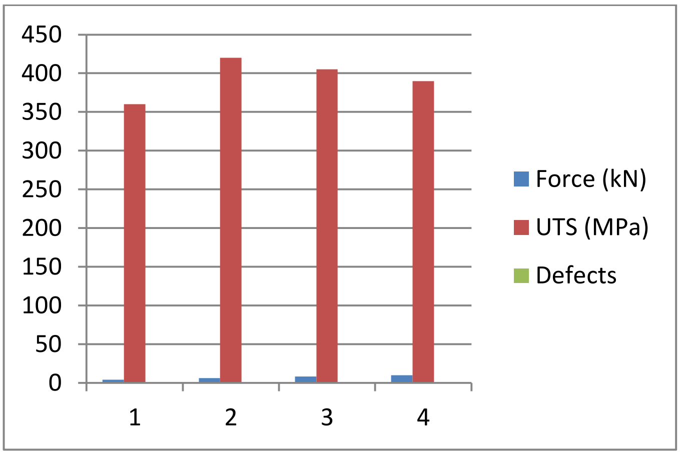

Figure 2: Speed, UTS and Hardness of welding

i. **Low speeds** (50 mm/min): Excessive heat input led to grain coarsening.

ii. **Optimal speed** (60 mm/min): Balanced heat input promoted dynamic recrystallization.

iii. **High speeds** (100 mm/min): Inadequate material flow resulted in voids and tunnel defects.

4.2 Axial Force

Table 3: Axial Force vs. Tensile Strength at Constant Speed (60 mm/min)

	UTS (MPa)	Defects	Flash Formation
4	360	Voids	None
6	420	None	Minimal
8	405	None	Moderate
10	390	None	Excessive

i. **Lower force** (4 kN): Insufficient consolidation → voids.

ii. **Higher force** (10 kN): Induced flash and thermal softening, lowering strength.

iii. **Best balance** at 6 kN: Full consolidation, low flash.

4.3 Microstructural Analysis

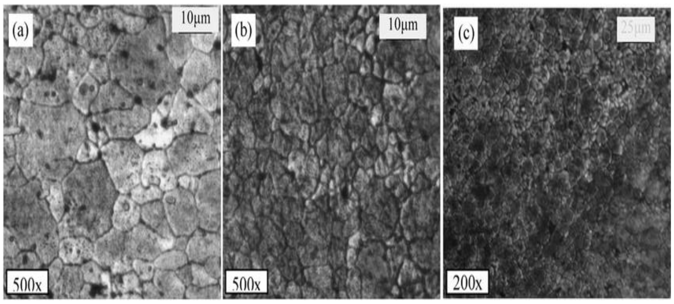

Figure 3: Microstructure of welded joints

Figure 3 described the following points-

a) **Stir Zone (SZ):** Fine, equiaxed grains (~10 μm) due to dynamic recrystallization.

b) **Thermo-Mechanically Affected Zone (TMAZ):** Elongated grains, minor coarsening.

c) **Heat Affected Zone (HAZ):** Grain growth with softened microstructure (loss of precipitates).

d) SEM revealed no porosity or voids in optimal samples; tunnel defects were visible at high welding speeds.

5. CONCLUSIONS

This study confirmed that welding speed and axial force significantly influence the quality of FSW joints in AA7075-T6. The best combination—60 mm/min welding speed and 6 kN axial force—yielded:

- High tensile strength (420 MPa)
- Uniform hardness (150 HV0.1)
- Defect-free, recrystallized microstructure

These findings support precise tuning of process parameters for demanding applications like aerospace fuselage joining and automotive crash components.

6. FUTURE SCOPE

To advance this research:

a) Incorporate finite element modeling (FEM) to simulate temperature and strain distribution.

b) Extend studies to dissimilar materials and multi-pass welding.

c) Investigate tool wear and lifetime at different forces for industrial scaling.

REFRENECES

[1] Buffa, G., Hua, J., Shivpuri, R., & Fratini, L. (2009). A continuum based FEM model for friction stir welding—Model development. *Materials Science and Engineering: A*, 419(1-2), 389–396. https://doi.org/10.1016/j.msea.2005.12.007

[2] 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 and Design*, 29(2), 362–373. https://doi.org/10.1016/j.matdes.2006.11.002

[3] Esparza, D., Cabrera, J. M., & Prado, J. M. (2018). Effects of axial force and heat generation in friction stir welding of AA7075 aluminum alloy. *Procedia Manufacturing*, 13, 262–269. https://doi.org/10.1016/j.promfg.2017.09.058

[4] Liu, H. J., Zhang, H. J., Yu, L., & Yu, S. (2013). Effect of welding parameters on microstructure and mechanical properties of friction stir welded joints of 7075 aluminum alloy. *Materials & Design*, 45, 576–582. https://doi.org/10.1016/j.matdes.2012.09.032

[5] 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

[6] Rajakumar, S., Muralidharan, C., & Balasubramanian, V. (2011). Influence of friction stir welding process and tool parameters on strength properties of AA7075-T6 aluminium alloy joints. *Materials & Design*, 32(2), 535–549. https://doi.org/10.1016/j.matdes.2010.08.025

[7] Sato, Y. S., Urata, M., & Kokawa, H. (1999). Parameters controlling microstructure and hardness during friction-stir welding of precipitation-hardenable aluminum alloy 6063. *Metallurgical and Materials Transactions A*, 30(12), 3125–3130. https://doi.org/10.1007/s11661-999-0072-7

[8] Zhao, Y., Zhang, D., & Wang, X. (2012). Numerical simulation of temperature field in friction stir welding of 7050 aluminum alloy. *Materials and Manufacturing Processes*, 27(6), 641–646. https://doi.org/10.1080/10426914.2011.606520

[9] Cavaliere, P., & Squillace, A. (2008). Mechanical properties of 2024 aluminium alloy joints produced by friction stir welding. *Materials & Design*, 29(1), 138–143. https://doi.org/10.1016/j.matdes.2006.11.001

[10] Colegrove, P. A., & Shercliff, H. R. (2005). 3-Dimensional CFD modelling of flow round a threaded friction stir welding tool profile. *Journal of Materials Processing Technology*, 169(2), 320–327.https://doi.org/10.1016/j.jmatprotec.2005.04.120

[11] Hattingh, D. G., Blignault, C., van Niekerk, T. I., & James, M. N. (2008). Characterization of the influences of FSW tool geometry on welding forces and weld tensile strength using an instrumented tool. *Journal of Materials Processing Technology*, 203(1–3), 46–57. https://doi.org/10.1016/j.jmatprotec.2007.09.040

[12] 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.2007.08.018

[13] Lee, W. B., & Yeon, Y. M. (2003). Characteristics of friction stir welded pure aluminum joints by rolled tool. *Materials Science and Engineering: A*, 355(1–2), 154–159. https://doi.org/10.1016/S0921-5093(03)00020-2

[14] Peel, M. J., Steuwer, A., Preuss, M., & Withers, P. J. (2003). Microstructure, mechanical properties and residual stresses as a function of welding speed in aluminium AA5083 friction stir welds. *Acta Materialia*, 51(16), 4791–4801. https://doi.org/10.1016/S1359-6454(03)00319-7

[15] Schneider, J. A., & Nunes, A. C. (2004). Characterization of plastic flow and resulting microtextures in a friction stir weld. *Metallurgical and Materials Transactions A*, 35(8), 2927–2937. https://doi.org/10.1007/s11661-004-0275-y

[16] 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