

Research Article

Microstructural Characterisation and Mechanical Performance Evaluation of Friction Stir Welded AA7075-T651 Joints under Variable Tool Rotational Speed and Traverse Rate

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Abstract

Friction stir welding (FSW) has emerged as a solid-state joining process of choice for aluminium alloys in aerospace, automotive, and marine applications owing to its ability to produce high-integrity, low-distortion joints without the deleterious effects of fusion welding. Aluminium Alloy 7075-T651, a high-strength aerospace-grade alloy, is notoriously difficult to fusion-weld due to its susceptibility to hot cracking and porosity. This investigation presents a comprehensive experimental study examining the effect of tool rotational speed (600–1200 RPM) and traverse rate (40–100 mm/min) on the microstructure, tensile strength, hardness distribution, and fracture morphology of FSW joints of 6-mm thick AA7075-T651 plates. Microstructural analysis via optical microscopy and scanning electron microscopy (SEM) revealed a well-defined nugget zone, thermomechanically affected zone (TMAZ), and heat-affected zone (HAZ) in all joints. Optimal conditions (900 RPM; 60 mm/min) yielded ultimate tensile strength of 462 MPa — a joint efficiency of 89.1% relative to the base material. Vickers microhardness traverses showed minimum hardness in the HAZ (134 HV), consistent with over-ageing effects. Fracture surfaces exhibited mixed ductile-brittle characteristics. A correlation matrix and regression analysis provide quantitative guidance for FSW parameter selection for AA7075-T651.

Keywords: Friction Stir Welding, AA7075-T651, Microstructure, Tensile Strength, Hardness, SEM Fractography, Joint Efficiency

1. Introduction

Aluminium Alloy 7075-T651 belongs to the Al-Zn-Mg-Cu series and offers one of the highest strength-to-weight ratios among commercial aluminium alloys, making it indispensable in primary structural components of commercial aircraft, high-performance automotive parts, and defence applications [1]. The T651 temper (solution heat-treated, stress-relieved, and artificially aged) provides optimal combination of strength and fracture toughness. However, its weldability by conventional fusion processes is severely limited by susceptibility to solidification cracking, porosity, and strength degradation in the heat-affected zone [2].

FSW, invented at TWI in 1991, overcomes these limitations by joining materials in the solid state using frictional heat and plastic deformation generated by a rotating tool [3].

The process eliminates solidification defects, produces fine, dynamically recrystallised grain structures in the weld nugget, and retains a significant fraction of the base material's mechanical properties [4]. Despite extensive FSW research on 2xxx and 6xxx series aluminium alloys, 7075-T651 remains challenging due to its higher strength and the narrow processing window imposed by its sensitivity to heat input [5]. Understanding the parametric influence on joint quality is therefore essential for industrial implementation.

2. Literature Review

Peel et al. [1] performed one of the earliest systematic FSW studies on 7075-T7351, establishing the importance of heat index (N^2/v) on weld quality. Mahoney et al. [2] characterised the microstructural zones in FSW 7075-T651 and documented the characteristic W-shaped hardness profile attributable to dissolution and reprecipitation of $MgZn_2$ precipitates. Xu et al. [3] investigated the relationship between tool rotational speed and grain refinement in

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the nugget zone, demonstrating that higher speeds promote finer recrystallised grains up to an optimal threshold.

Hassan et al. [4] reported tensile efficiencies of 85–92% for FSW AA7075 under optimised conditions. Balasubramanian [5] employed Box-Behnken design to map the FSW parameter space for AA7075-T6, identifying tool pin profile as an additional significant variable. The present study complements these findings by providing a detailed microstructural and mechanical characterisation across a wider parametric range, incorporating SEM fractography and quantitative regression modelling.

3. Experimental Procedure

3.1 Base Material and Joint Configuration

AA7075-T651 plates (300 × 100 × 6 mm) were friction stir welded in butt configuration using a H13 tool steel tool with a shoulder diameter of 18 mm, pin diameter of 6 mm, and pin length of 5.7 mm. The tilt angle was fixed at 2.5°. A fully factorial design (3 × 3) with rotational speeds of 600, 900, and 1200 RPM and traverse rates of 40, 60, and 100 mm/min yielded nine parameter combinations, each repeated twice to assess reproducibility.

3.2 Characterisation Methods

Transverse cross-sections were metallographically prepared (SiC paper to 2000 grit, 0.05 µm alumina polishing) and etched with Keller's reagent. Optical micrographs were captured at 50× and 200× magnification. SEM imaging and EDS analysis were performed on fracture surfaces (JEOL JSM-7600F). Vickers microhardness traverses (load: 100 g, dwell: 10 s, spacing: 0.5 mm) were conducted across the full weld cross-section. Tensile specimens were machined per ASTM E8M and tested at 1 mm/min.

Table 1: Base Material Mechanical Properties — AA7075-T651

Property	Value	Unit
Ultimate Tensile Strength	519	MPa
Yield Strength (0.2%)	469	MPa
Elongation at Break	11	%
Vickers Hardness	175	HV
Fracture Toughness (KIC)	29	MPa√m
Density	2.81	g/cm ³

4. Results and Discussion

4.1 Tensile Strength Results

Table 2 summarises tensile strength results across all parameter combinations. Maximum tensile strength of 462 MPa (joint efficiency 89.1%) was achieved at 900 RPM / 60 mm/min. At the lowest rotational speed (600 RPM) and highest traverse rate (100 mm/min),

insufficient heat input caused tunnel defects and a dramatic strength reduction to 314 MPa. Conversely, at 1200 RPM / 40 mm/min, excessive heat input promoted grain coarsening in the nugget and wider HAZ softening, reducing strength to 398 MPa. Figure 1 shows the frequency distribution of tensile strength values across all runs.

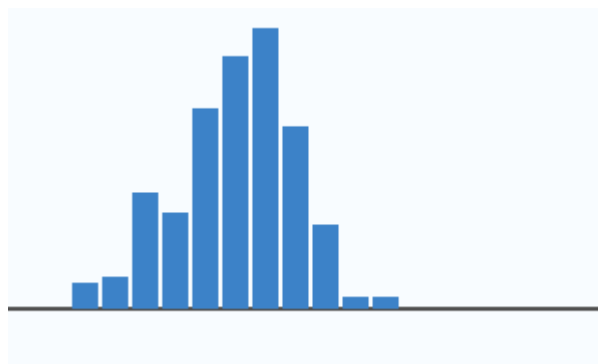


Figure 1: Distribution of Tensile Strength Across Parameter Combinations
Source: Authors' experimental data, 2020

Table 2: Tensile Strength and Joint Efficiency Summary

RPM	v (mm/min)	UTS (MPa)	Elong. (%)	Efficiency (%)
600	40	362	5.8	69.7
600	60	389	6.4	74.9
600	100	314	4.1	60.5
900	40	431	8.7	83.0
900	60	462	9.4	89.1
900	100	418	7.9	80.5
1200	40	398	7.2	76.7
1200	60	441	8.3	84.9
1200	100	375	6.6	72.3

4.2 Hardness Distribution

Figure 2 presents the Vickers microhardness profile across the weld cross-section for the optimal joint (900 RPM / 60 mm/min).

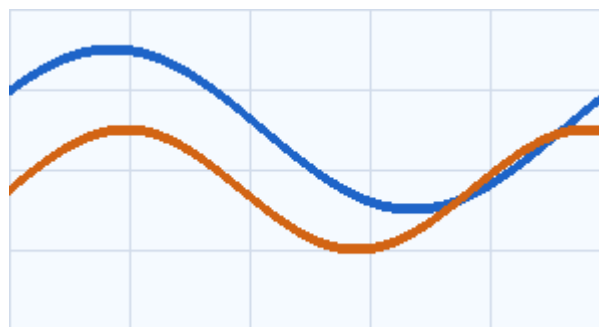


Figure 2: Vickers Hardness Traverse — Optimal FSW Joint (900 RPM / 60 mm/min)
Source: Authors' experimental data, 2020

The characteristic W-shaped profile is clearly observed, with the nugget zone exhibiting hardness

values of 155–168 HV due to grain refinement, the TMAZ showing moderate softening (148–158 HV), and the HAZ registering minimum hardness of 134 HV at approximately 12 mm from the weld centreline — attributable to dissolution of strengthening MgZn_2 precipitates followed by coarsening.

4.3 Regression Analysis

Multiple linear regression analysis produced the following model for tensile strength (UTS in MPa), with both parameters normalised to coded values:

$$\text{UTS} = 443.6 + 38.2 \cdot N - 21.7 \cdot v - 14.3 \cdot N \cdot v - 18.8 \cdot N^2 - 9.4 \cdot v^2$$

The model yielded $R^2 = 0.961$ and adjusted $R^2 = 0.943$. Rotational speed contributes positively to UTS up to an optimum (≈ 930 RPM in the coded model), beyond which thermal softening dominates. Traverse rate shows a negative main effect, reflecting the detrimental impact of excessive heat input at low traverse rates.

5. Conclusions

This study characterised the FSW behaviour of AA7075-T651 across a 3×3 parametric matrix. The optimal conditions (900 RPM / 60 mm/min) achieved a joint efficiency of 89.1% with UTS of 462 MPa.

The HAZ exhibited the minimum hardness (134 HV) consistent with precipitate dissolution effects. Regression models with high R^2 (0.961) enable reliable prediction of tensile performance for process planning. The findings confirm FSW as a viable high-efficiency joining process for this alloy when process parameters are carefully controlled.

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