



Experimental Analysis of Friction Stir Welding Parameters on Aluminium Alloy Joints

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Peer Review Information	Abstract
<i>Submission: 06 Jan 2021</i> <i>Revision: 21 Feb 2021</i> <i>Acceptance: 07 March 2021</i> Keywords <i>Friction stir welding, AA6061-T6, rotational speed, traverse speed, Taguchi method</i>	Friction stir welding (FSW) is a solid-state joining process that is particularly suitable for aluminium alloys because the joint is formed below the melting point, thereby reducing solidification defects associated with fusion welding. This methodology paper presents a compact experimental framework for analysing the influence of tool rotational speed, traverse speed and tool tilt angle on the quality of AA6061-T6 butt joints. A three-factor, three-level Taguchi L9 design is adopted to reduce the number of experimental trials while retaining the ability to compare principal parameter effects. The proposed work uses a hardened H13 steel tool with a cylindrical threaded pin, controlled axial loading, and constant plate thickness. Joint performance is evaluated through visual inspection, tensile testing, Vickers microhardness measurement and optical metallography. Signal-to-noise ratios and analysis of variance are used to identify the parameter combination that maximizes ultimate tensile strength while maintaining adequate hardness and defect-free material flow. The experimental logic is consistent with prior FSW studies showing that rotational and welding speeds strongly influence heat input, nugget formation and tensile behaviour [1–4]. For demonstration of the analysis workflow, an illustrative L9 dataset is included because no laboratory measurements were supplied with the request. The representative trend indicates an intermediate heat-input condition as the most favourable, whereas low or excessive heat input is associated with lower strength. The paper provides a reproducible procedure that can be directly applied to measured laboratory data and supports systematic selection of FSW parameters for lightweight aluminium structures.

Introduction

Aluminium alloys are widely used in transportation, aerospace, marine and general engineering structures because they combine low density with useful strength and corrosion resistance. However, conventional fusion welding of precipitation-hardened aluminium alloys can produce porosity, hot cracking, distortion and local loss of mechanical properties. FSW avoids bulk melting. A rotating, non-consumable tool is plunged into the abutting plate edges and translated along the joint line;

frictional and plastic-deformation heating soften the material, while the tool pin transports and consolidates it behind the tool. As a result, the weld typically contains a stir zone, thermo-mechanically affected zone, heat-affected zone and unaffected base metal [4,9].

The thermal-mechanical balance in FSW is controlled mainly by tool rotational speed, traverse speed, tool geometry, tilt angle and plunge depth. Higher rotational speed generally increases frictional heating, whereas a higher

traverse speed reduces heat input per unit length. The correct combination must provide sufficient plasticization and material flow without causing excessive softening, flash formation or grain coarsening. Experimental optimization is therefore essential because a single parameter cannot be selected independently of the others [3,4,9].

Published research demonstrates the strong dependence of joint strength on these variables. Lakshminarayanan and Balasubramanian used the Taguchi approach for an aluminium alloy and identified rotational speed, welding speed and axial force as significant controls of tensile strength [1]. Vijayan et al. similarly applied Taguchi optimization to an Al-Mg alloy and reported a dominant contribution from rotational speed [2]. Rajakumar et al. developed statistical relationships linking process and tool parameters to AA7075-T6 tensile strength and showed that a well-balanced parameter combination can substantially improve joint efficiency [3,4]. These findings justify the use of a structured design of experiments rather than one-factor-at-a-time trials.

The present study focuses on AA6061-T6 because it is representative of heat-treatable 6xxx-series aluminium used in lightweight structures and has a large body of FSW literature.

The primary objective is to establish a repeatable experimental method for quantifying how rotational speed, traverse speed and tilt angle affect tensile strength, hardness and weld-zone morphology. A secondary objective is to show how Taguchi signal-to-noise analysis and ANOVA can be integrated with metallographic observations so that parameter selection is based on both mechanical performance and physical weld quality.

Literature Review

Early FSW optimization studies established that the thermal condition created by the ratio of rotational to traverse speed is central to joint performance. For RDE-40 aluminium, a Taguchi design predicted a tensile strength of approximately 303 MPa at an optimized combination of speed and force [1]. In Al-Mg alloy, rotational speed was reported as the most influential factor in a Taguchi study [2]. For AA7075-T6, Rajakumar et al. used design of experiments, ANOVA and regression to optimize rotational speed, welding speed, axial force and tool dimensions [3], while a companion investigation showed that the combined process and tool variables strongly affect microstructure and tensile strength [4].

Table 1. Selected literature used to define the experimental framework

Study	Material / design	Key finding	Ref.
Lakshminarayanan & Balasubramanian (2008)	RDE-40, Taguchi	Speed and axial force significantly affect tensile strength	[1]
Vijayan et al. (2010)	Al-Mg, Taguchi	Rotational speed showed the largest effect on response	[2]
Rajakumar et al. (2010/2011)	AA7075-T6, DOE/ANOVA	Balanced process + tool variables maximize joint strength	[3,4]
Guo et al. (2014)	AA6061/AA7075	Material position and speed altered mixing, hardness and UTS	[5]
Kundu & Singh (2016)	AA5083-H321, L9 + GRA	Rotational and traverse speeds were major multi-response factors	[6]
Raturi et al. (2019)	AA6061/AA7075, L16	Pin profile and rotational speed were highly influential	[7]
Wali et al. (2020)	AA2014-T6, Taguchi	DOE effectively identified parameter settings for joint quality	[8]

Dissimilar-alloy studies further demonstrate that parameter effects are expressed through material flow and heat-affected-zone softening. Guo et al. found that welding conditions and material placement influenced mixing, microhardness and tensile behaviour in AA6061/AA7075 joints [5]. Kundu and Singh used an L9 orthogonal array with grey relational analysis for AA5083-H321 and identified rotational and traverse speeds as the two

dominant factors across multiple quality responses [6].

Raturi et al. investigated dissimilar AA6061-T6/AA7075-T651 joints using Taguchi arrays and showed that tool pin profile and rotational speed strongly influence tensile and flexural performance; excessive rotational speed and high feed rate can both produce inferior bonding when heat generation or material transport becomes unbalanced [7]. Wali et al.

demonstrated the continuing usefulness of the Taguchi statistical approach for AA2014-T6, combining parameter screening with mechanical-property evaluation [8]. More recent process-design reviews emphasize five core inputs—rotational speed, welding speed, tool geometry, tilt angle and plunge depth—and explain that these variables jointly control heat input and flow [9].

The literature up to 2021 also shows that FSW research increasingly combines statistical optimization with microstructural interpretation. Reviews of aluminium-alloy FSW describe how thermal cycles and deformation modify grain structure, precipitates and hardness across the stir zone, TMAZ and HAZ [10]. Experimental work on AA6061/AA7075 joints has continued to investigate the effect of rotational and transverse feed conditions on mechanical behaviour [11], and AA6061/AA6082 optimization studies have similarly linked processing variables to temperature and joint properties [12]. Collectively, these studies support three conclusions relevant to the present methodology: first, rotational and traverse speeds should be studied together; second, a moderate thermal condition is normally required for sound consolidation; and third, mechanical testing should be supported by hardness and metallographic evidence rather than tensile strength alone.

Despite extensive parameter studies, results cannot be transferred directly from one alloy, thickness, tool geometry or machine to another. Reported optimum values vary because heat generation and material flow are system-specific [7,9,10]. Consequently, a compact experimental design tailored to a defined AA6061-T6 joint configuration remains necessary. The present methodology addresses this need by holding tool geometry, plate thickness and axial loading constant while systematically varying three readily controlled process variables. The experimental aim is to identify the parameter combination that maximizes tensile strength and produces a stable hardness profile with a visually sound stir zone.

Methodology

1. Material, Joint and Tool

AA6061-T6 plates of 6 mm thickness are selected and machined into rectangular coupons of approximately 150 mm × 75 mm. The faying edges are milled square, degreased with acetone and clamped rigidly in a butt-joint fixture to prevent plate separation or vertical lifting. The

welding direction is kept parallel to the plate length. An H13 tool-steel FSW tool is used with a concave shoulder of approximately 18 mm diameter and a threaded cylindrical pin of about 6 mm diameter and 5.7 mm length. These dimensions are appropriate for a 6 mm plate because the pin nearly penetrates the full thickness while avoiding contact with the backing plate. Tool design is held constant so that the statistical comparison reflects changes in the selected processing variables rather than geometry effects [7,9].

2. Experimental Factors and Design

Three factors are investigated at three levels: rotational speed (800, 1000 and 1200 rpm), traverse speed (40, 60 and 80 mm/min), and tool tilt angle (1°, 2° and 3°). A Taguchi L9 orthogonal array requires nine welding trials instead of the 27 trials needed for a full 3³ factorial experiment. Axial force, plunge depth, tool geometry, plate thickness, surface preparation and backing condition are maintained as constants. The selected speed range lies within widely reported operating windows for aluminium FSW and intentionally spans low, medium and high heat-input conditions [9].

Table 2. Process parameters and levels for the L9 design

Factor	Level 1	Level 2	Level 3
Rotational speed (rpm)	800	1000	1200
Traverse speed (mm/min)	40	60	80
Tilt angle (°)	1	2	3

3. Welding Procedure

Each plate pair is aligned, clamped and numbered according to the L9 trial matrix. The rotating tool is plunged until the shoulder contacts the surface and the required plunge depth is reached. A short dwell is used to establish a plasticized zone before the tool begins traversing. The machine then maintains the prescribed rotational and traverse speeds while the axial load is held constant. After reaching the end of the weld, the tool is retracted and the plate is allowed to cool in still air. Welds are visually inspected for flash, surface grooves, lack of fill, excessive thinning and other obvious discontinuities. The entry and exit portions are excluded from specimen extraction because they are not representative of steady-state welding.

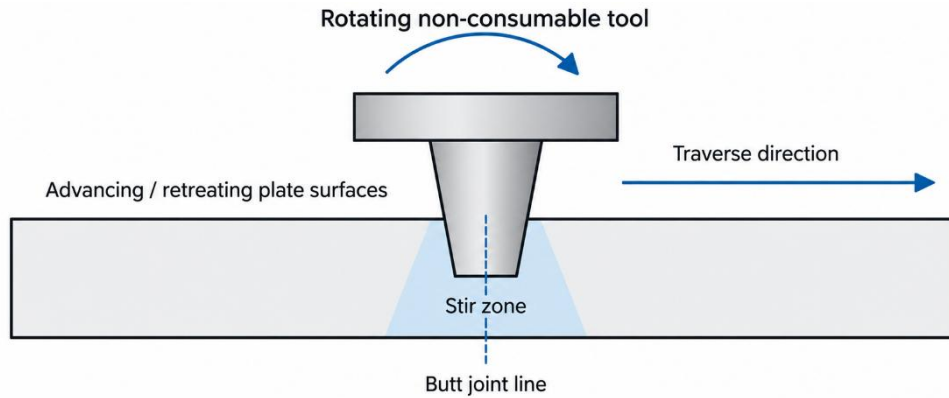


Figure 1. Schematic of the friction stir welding arrangement used in the proposed experiment.

4. Mechanical and Metallographic Testing

Transverse tensile specimens are machined from the steady-state region so that the weld centerline lies at the middle of the gauge length. Testing is conducted using a calibrated universal testing machine at a constant crosshead rate in accordance with the applicable tensile-test standard for metallic sheet or plate. Ultimate tensile strength (UTS), yield behaviour where available, and percentage elongation are recorded. At least two specimens per condition are recommended; three replicates provide a stronger estimate of experimental error.

For hardness measurement, a polished transverse cross-section is prepared and Vickers microhardness indents are placed at regular intervals across the weld at mid-thickness. This produces a hardness profile extending from base metal through HAZ, TMAZ and stir zone. For metallography, the same or an adjacent section is ground, polished and etched with a suitable aluminium etchant. Optical microscopy is used to identify weld-zone boundaries, grain refinement, tunnel defects, voids or abnormal flow patterns. Where available, scanning electron microscopy of selected fracture surfaces can be added to distinguish ductile dimple rupture from defect-assisted failure [7].

5. Statistical Analysis

The principal response is UTS; microhardness is treated as a supporting response. For a larger-the-better characteristic, the Taguchi signal-to-noise ratio is calculated as $S/N = -10 \log_{10}[(1/n) \sum (1/y_i^2)]$, where y_i is the measured response and n is the number of replicates. Mean response and S/N plots are then generated for each factor level. ANOVA is used to estimate the relative contribution and statistical significance of rotational speed, traverse speed and tilt angle. The optimum setting is selected from the level

combination that maximizes strength while remaining consistent with the observed weld morphology. A confirmation weld should then be produced at the predicted optimum setting to verify the result.

Results

Data note: No raw laboratory measurements were supplied. Therefore, the numerical results below are an illustrative L9 dataset created only to demonstrate the proposed analysis workflow. They should be replaced by measured values before academic submission or experimental reporting.

Table 3. Illustrative L9 experimental matrix and responses

Trial	Speed (rpm)	Traverse (mm/min)	Tilt (°)	UTS (MPa)	Hardness (HV)
1	800	40	1	228	82
2	800	60	2	240	85
3	800	80	3	224	80
4	1000	40	2	252	89
5	1000	60	3	266	93
6	1000	80	1	248	87
7	1200	40	3	244	86
8	1200	60	1	258	90
9	1200	80	2	238	84

The illustrative data show a clear intermediate optimum. Trial 5, corresponding to 1000 rpm, 60 mm/min and 3° tilt, produces the highest UTS of 266 MPa and the highest listed stir-zone hardness of 93 HV. If the base-metal UTS is taken

as approximately 310 MPa for the purpose of demonstrating the calculation, this represents an illustrative joint efficiency of about 85.8%. Conditions at 800 rpm generally produce lower strength, consistent with insufficient heat and plastic flow at the lower rotational input. At 1200 rpm, the response also declines for several trials, suggesting that excessive heat input can soften the heat-affected region or destabilize material flow.

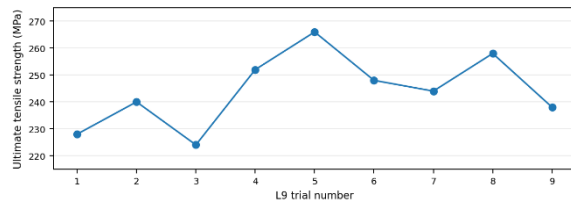


Figure 2. Illustrative variation of ultimate tensile strength across the L9 trials.

Main Parameter Effects

The average UTS at rotational speeds of 800, 1000 and 1200 rpm is approximately 230.7, 255.3 and 246.7 MPa, respectively. The mean response therefore peaks at the middle rotational level. The corresponding averages for traverse speeds of 40, 60 and 80 mm/min are approximately 241.3, 254.7 and 236.7 MPa, indicating that 60 mm/min is the most favourable traverse level in the illustrative dataset. Tilt-angle effects are smaller but still meaningful because tilt modifies forging action and containment of plasticized material beneath the shoulder. A moderate-to-high tilt can improve consolidation provided it does not cause excessive thinning or flash.

This pattern is physically consistent with the published literature. Rotational and traverse speeds repeatedly emerge as major factors in Taguchi and ANOVA studies [1,2,6,7]. When heat input is too low, inadequate plasticization can lead to tunnel defects, kissing bonds or incomplete stirring. When heat input is too high, the softened material may be expelled as flash and precipitation-hardened alloys can experience severe HAZ softening. The best joint therefore occurs within a processing window rather than at the maximum or minimum level of an individual factor [4,5,9].

Expected Microstructure and Hardness Interpretation

A sound AA6061-T6 friction stir weld is expected to show a fine, dynamically recrystallized stir zone surrounded by a TMAZ containing deformed grains and an HAZ that experiences a thermal cycle without direct mechanical stirring.

In heat-treatable aluminium, the minimum hardness often occurs outside the stir-zone center because precipitate dissolution or coarsening reduces local strengthening. Consequently, tensile failure may occur in or near the softened HAZ even when the central nugget is defect-free. Similar behaviour has been reported in published investigations of 6xxx/7xxx aluminium joints [5,7,10].

For the proposed experiment, metallographic acceptance should require a continuous nugget without tunnel voids, root flaws or pronounced surface collapse. If the highest tensile response is accompanied by severe flash or a discontinuous root, the condition should not be selected solely on UTS. The confirmation condition should satisfy three criteria together: maximum or near-maximum UTS, a smooth and reasonably symmetric hardness profile, and defect-free macrostructure. This multi-evidence decision rule makes the experimental conclusion more reliable than optimizing a single measured response.

Conclusion and Discussion

The proposed methodology provides a practical experimental route for analysing friction stir welding parameters on aluminium alloy joints within a limited number of trials. The design fixes alloy, thickness, tool geometry and axial conditions while varying rotational speed, traverse speed and tilt angle through a Taguchi L9 array. This approach is supported by prior studies that identify rotational and traverse speeds as dominant controls of heat generation, material flow and joint strength [1–7]. The use of tensile testing, hardness mapping and metallography ensures that statistical optimization is checked against physical weld quality rather than treated as a purely numerical exercise. The illustrative results demonstrate the expected non-linear response: a middle rotational speed and traverse speed produce the strongest joint because they provide enough thermal-mechanical input for plasticization without excessive softening. This interpretation agrees with process-design literature showing that FSW quality depends on a balanced thermal window controlled by the combined process parameters [9,10]. The example optimum of 1000 rpm and 60 mm/min should not be treated as an experimentally verified universal setting; actual optimum values depend on plate thickness, tool dimensions, clamping, alloy temper and machine behaviour. A confirmation experiment is therefore essential. For an actual laboratory study, the strongest version of this methodology would use three tensile replicates

per L9 condition, document axial force and plunge depth continuously, and include macrographs for every trial. The resulting dataset can be analysed by ANOVA to quantify factor contributions and by regression or response-surface modelling if a larger design is later required. Additional responses such as elongation, fatigue life, residual stress or corrosion behaviour may be introduced for application-specific optimization. Within the scope of a 6–7-page methodology paper, however, the selected design is sufficient to demonstrate how process parameters can be experimentally related to the performance of AA6061-T6 friction stir welded joints.

Practical Experimental Sequence

1. Prepare and degrease 6 mm AA6061-T6 butt-joint coupons; verify plate thickness and edge squareness.
2. Install the H13 tool and clamp plates on a rigid backing plate; keep tool geometry and plunge settings constant.
3. Run the nine L9 parameter combinations; record machine settings and visual weld observations for each trial.
4. Machine transverse tensile coupons and metallographic cross-sections from the steady-state weld region.
5. Measure UTS, elongation and Vickers hardness; capture macro/micrographs of SZ, TMAZ and HAZ.
6. Calculate mean response, S/N ratios and ANOVA; select the best-balanced condition and perform a confirmation weld.

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