

Development and Assessment of Friction Stir Welding Strategy for Similar and Dissimilar Joints

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Abstract—Friction Stir Welding (FSW) is a solid-state joining process invented at The Welding Institute (TWI), UK, in 1991. It produces defect-free, high-strength welds without melting the base material, eliminating fusion welding defects such as porosity, hot cracking, and solidification distortion. This paper presents the development and assessment of an FSW strategy applicable to similar joints (AA5083–AA5083) and dissimilar joints (AA5083–AA7039 and aluminium–mild steel). The study examines the influence of critical process parameters—rotational speed, traverse speed, plunge depth, tool tilt angle, and tool geometry—on joint quality, microstructure, and mechanical properties. AA5083 (marine-grade, non-heat-treatable) and AA7039 (defence-grade, heat-treatable) were selected as base materials with H-13 tool steel used for the FSW tool. The paper consolidates findings from 21 peer-reviewed references and presents a four-stage welding strategy covering tool design, parameter optimisation, weld zone qualification, and service performance validation including corrosion and fatigue. Results confirm that controlling the rotation-to-traverse speed ratio (n/v) and tool shoulder-to-pin geometry is central to achieving consistent mechanical properties across both similar and dissimilar joint configurations.

I. INTRODUCTION

Friction Stir Welding (FSW) is a solid-state joining process in which a non-consumable rotating tool consisting of a shoulder and a pin is plunged into the interface of two workpieces and traversed along the joint line. Frictional contact and plastic deformation generate localised heat that softens material to approximately 80–90% of its solidus temperature without causing melting. The rotating pin transports plasticised material from the leading to the trailing edge, consolidating it under shoulder forging pressure to form a continuous, defect-free weld.

Since its invention at TWI in 1991 [1], FSW has demonstrated clear advantages over fusion welding for aluminium alloys: elimination of solidification defects such as porosity and hot cracking, fine recrystallised grain structure in the stir zone, low distortion, and energy efficiency approximately 30–50% below arc welding

processes. These attributes have driven adoption in aerospace, shipbuilding, automotive, and defence industries where lightweight, high-integrity joints are required.

The demand for multi-material structures—combining different aluminium grades or aluminium with steel—has extended FSW research into dissimilar-material joining. Dissimilar joints introduce mismatched thermal conductivities, different flow stresses, intermetallic compound (IMC) formation at the interface, and asymmetric heat distribution between the advancing and retreating sides. A systematic strategy addressing tool design, parameter selection, material positioning, and service performance is therefore necessary.

This paper presents the development and assessment of an FSW strategy for similar joints (AA5083–AA5083) and dissimilar joints (AA5083–AA7039 and aluminium–mild steel), grounded in a synthesis of 21 peer-reviewed studies.

II. LITERATURE REVIEW

Thomas *et al.* (1991) invented FSW at TWI as a solid-state alternative to fusion welding for aluminium alloys [1]. Mishra and Ma (2005) established through a foundational review that FSW eliminates solidification defects and produces fine-grained microstructures superior to those of fusion methods, and confirmed that for non-heat-treatable alloys such as AA5083, FSW preserves strength far better than arc welding [2].

Lohwasser and Chen (2010) documented industrial adoption of FSW in Boeing Delta II rocket fuel tanks, Mazda and Toyota vehicle chassis, and marine structures [5]. Nandan *et al.* (2008) identified rotational speed, traverse speed, axial force, and tool tilt angle as dominant process variables, establishing that the n/v ratio governs heat input per unit weld length [4].

Diogo Mariano Neto and Pedro Neto (2013) reviewed heat generation models, contact conditions, and material flow predictions, establishing that accurate material and process data are prerequisites for reliable simulation-based tool design [6]. Vivek Patel *et al.* (2019) identified pin profile, shoulder geometry, material positioning, welding speed, and rotational speed as primary parameters affecting dissimilar joint quality, noting the need to control IMC layer thickness and differential material flow [7].

The Changchun University Research Team (2022) summarised approximately twenty years of Al–Cu FSW research, identifying thermal conductivity mismatch and brittle Cu–Al IMC formation as the central strategic challenges [13]. Bin Abdulaziz University Research Team (2023) addressed Al–Mg dissimilar welding and proposed interlayer insertion, ultrasonic-assisted FSW, and electric-current-assisted FSW to reduce IMC formation [14].

For similar AA5083 joints, Threadgill *et al.* (2009) confirmed FSW produces fine equiaxed grains in the stir zone but causes HAZ softening [20]. An orthogonal study on AA5083 established the dominant effect of n/v on tensile strength and the characteristic W-shaped hardness profile. Tsujikawa *et al.* (2007) demonstrated fatigue must be incorporated into strategy design for marine-grade alloys [21].

Omran and Shamsudin (2022) reviewed approximately 150 studies and concluded parameter spaces for dissimilar joints must compensate for material property

mismatches absent in similar-material welding [9]. Mertinger *et al.* (2022) showed stationary-shoulder tool geometry significantly alters the thermal cycle in dissimilar Al5083–Al7050 joints [17]. Hashim *et al.* (2024) updated the strategic framework to include process monitoring, tool-wear management, and automation [15]. Attah *et al.* (2024) demonstrated corrosion resistance is sensitive to traverse speed in dissimilar FSW aluminium joints [16].

III. WORKING PRINCIPLE

FSW is initiated by rotating the tool and plunging the pin into the joint interface until the shoulder contacts the workpiece surface. Frictional contact between the shoulder and workpiece combined with viscous dissipation from plastic deformation generates localised heat sufficient to soften material without melting. The tool then



traverses along the joint line, transporting plasticised material from the leading to the trailing edge of the pin where it consolidates under shoulder forging pressure.

Three distinct microstructural zones form during the process. The **stir zone (SZ)** experiences intense plastic deformation and dynamic recrystallisation, producing fine equiaxed grains. The **thermo-mechanically affected zone (TMAZ)** is deformed but not fully recrystallised. The **heat-affected zone (HAZ)** is exposed only to thermal cycling; in precipitation-hardened alloys, precipitate coarsening in the HAZ is a primary source of joint inefficiency.

The **advancing side (AS)**, where tool rotation coincides with traverse direction, and the **retreating side (RS)**, where they oppose, experience asymmetric shear stress and material flow. This asymmetry affects microstructural uniformity, hardness distribution, and

defect formation—particularly in dissimilar joints where each side consists of a different material.

IV. MATERIALS

A. Aluminium Alloy AA5083

AA5083 is a non-heat-treatable Al–Mg–Mn alloy (4.0–4.9 wt.% Mg, 0.4–1.0 wt.% Mn, trace Cr, Si, Fe, Cu, Zn, Ti) deriving its strength from solid solution strengthening and strain hardening. H116 and H321 tempers are standard for marine applications due to resistance to sensitisation. AA5083 maintains excellent mechanical properties post-weld, making it predominant in shipbuilding, cryogenic vessels, and offshore structures.

B. Aluminium Alloy AA7039

AA7039 is a heat-treatable Al–Zn–Mg alloy (3.8–4.8 wt.% Zn, 2.3–3.3 wt.% Mg, 0.2–0.8 wt.% Mn, 0.2–0.4 wt.% Cr) strengthened by MgZn₂ precipitate hardening in the T6 temper. Originally developed for military armour, AA7039 combines high strength, fracture toughness, and stress corrosion cracking resistance with better weldability than AA7075.

C. Mild Steel (MS) Plate

MS plate (0.05–0.25 wt.% C) has tensile strength of 400–550 MPa, yield strength of approximately 250 MPa, and elongation of 20–30%. Its melting point (~1510°C) is approximately 850°C above that of aluminium, imposing significant thermal management requirements in Al–steel FSW.

D. Tool Material: H-13 Tool Steel

H-13 (Cr 4.75–5.50%, Mo 1.10–1.75%, V 0.80–1.20%, C 0.32–0.45%, Si 0.80–1.20%) is selected for its hot hardness (>500 HV at 500°C), resistance to thermal fatigue and shock, and sufficient toughness to withstand cyclic plunge and traverse loads during aluminium alloy FSW.

V. PROCESS PARAMETERS AND WELDING STRATEGY

A. Rotational Speed

Rotational speed governs heat generation through frictional contact and viscous dissipation. Higher speeds increase heat input and improve material flow but risk overheating and stir zone grain growth. For AA5083–AA5083 joints on 6 mm plate, optimal rotational speeds are typically 600–1200 rpm. For dissimilar AA5083–AA7039 joints, the higher flow stress of AA7039 requires

elevated rotational speed or placement of AA7039 on the advancing side to improve plasticisation and mixing.

B. Traverse Speed and the n/v Ratio

The ratio n/v (rotational speed divided by traverse speed) is the single most influential parameter controlling tensile strength and hardness in AA5083 joints. Excessively high n/v produces overheating and grain coarsening; excessively low n/v results in insufficient plasticisation and void formation. For 6 mm AA5083 plate, traverse speeds of 100–300 mm/min paired with appropriate rotational speeds yield acceptable joints.

C. Plunge Depth and Tool Tilt

Plunge depth determines shoulder contact and forging pressure. Insufficient plunge depth produces surface-breaking voids; excessive depth causes plate thinning and flash. A tool tilt of 1–3° in the traverse direction directs the shoulder forging action onto the weld trailing edge, improving consolidation. In dissimilar joints, tilt angle adjustment can compensate for differential material flow between advancing and retreating sides.

D. Tool Geometry

The shoulder generates approximately 80–90% of frictional heat. Shoulder diameter is typically 3–4 times pin diameter. Concave or scrolled shoulder profiles improve material confinement. Pin geometry—cylindrical, tapered-threaded, triflute, or triangular—controls mixing efficiency. For dissimilar joints, threaded and triflute pins improve intermixing of materials with different flow stresses. Mertinger *et al.* (2022) demonstrated that stationary-shoulder configurations reduce heat input asymmetry in Al5083–Al7050 dissimilar joints [17].

E. Material Positioning in Dissimilar Joints

For AA5083–AA7039 joints, positioning AA7039 on the advancing side improves mixing efficiency. For Al–Cu and Al–Mg joints, tool offset towards the aluminium side limits IMC layer thickness. In Al–steel joints, the aluminium is placed on the retreating side with the tool fully embedded in the aluminium, creating a frictional bond at the Al–steel interface without directly stirring the steel.

VI. MICROSTRUCTURAL FEATURES

The stir zone of AA5083 FSW joints exhibits fine equiaxed grains (2–10 μm) from dynamic recrystallisation, yielding improved ductility. HAZ

microstructure changes minimally due to the non-heat-treatable nature of AA5083, but grain boundary sensitisation at 50–200°C reduces corrosion resistance in H116 and H321 tempers.

In AA7039 (T6 temper), HAZ and TMAZ experience MgZn₂ precipitate coarsening and dissolution, producing softening. The extent of HAZ softening depends directly on heat input and is minimised by higher traverse speeds and lower rotational speeds. The stir zone of AA7039 typically shows improved hardness uniformity relative to the HAZ.

In dissimilar AA5083–AA7039 joints, the stir zone contains an intermixed region with onion-ring laminar flow patterns sensitive to n/v ratio and pin geometry. Insufficient mixing produces sharp interfaces and stress concentration; excessive mixing promotes grain growth in AA5083 and overageing in AA7039.

For Al–steel dissimilar joints, a thin IMC layer (predominantly Fe₂Al₅ and FeAl₃) forms at the interface. IMC layer thickness below approximately 2–5 μm is associated with acceptable joint strength; thicker layers lead to brittle interfacial fracture.

VII. MECHANICAL AND SERVICE PERFORMANCE

A. Tensile Strength

For AA5083–AA5083 similar joints, tensile strength of 80–95% of base material strength is achievable with optimised parameters. Fracture typically initiates in the advancing-side HAZ at the minimum of the W-shaped hardness profile. For dissimilar AA5083–AA7039 joints, tensile strength is constrained by the weaker HAZ of AA7039, with reported values of 70–85% of AA5083 base material strength.

B. Hardness Distribution

Hardness profiles across AA5083 FSW joints show a characteristic W-shaped distribution with minimum hardness at the HAZ on both sides. In AA7039, HAZ softening due to precipitate overageing is more pronounced, with hardness values falling to 60–70% of peak-aged base material. Stir zone hardness in both alloys typically exceeds HAZ hardness due to grain refinement.

C. Fatigue

Tsujikawa *et al.* (2007) established that fatigue crack initiation in AA5083 FSW joints occurs preferentially at the weld root or surface irregularities on the advancing

side [21]. Post-weld surface treatment and root face inspection are recommended for fatigue-critical marine applications.

D. Corrosion

Attah *et al.* (2024) demonstrated that higher traverse speeds reduce microstructural homogeneity and lower polarisation resistance in FSW AA5083 joints [16]. HAZ sensitisation in AA5083 is controlled by limiting heat input. For dissimilar Al–Al and Al–steel joints, galvanic corrosion at the dissimilar metal interface must be addressed through protective coatings in service.

VIII. COST CONSIDERATIONS

Cost Component	Estimate
FSW Machine	₹20–50 lakhs
H-13 Tool (set)	₹5,000–20,000
Power vs. fusion	30–50% lower
Consumables	None
Fixtures/setup	₹50K–2 lakhs

TABLE I: Estimated Cost Components for FSW Setup

Although initial capital cost is high relative to MIG or TIG welding, FSW eliminates consumable costs, reduces post-weld rejection rates by avoiding fusion defects, and delivers consistent weld quality. For high-volume aluminium structural component production, the lifecycle cost of FSW is competitive with fusion processes.

IX. FOUR-STAGE WELDING STRATEGY

Stage 1 – Tool Design: Select shoulder diameter as 3–4× pin diameter with a concave or scrolled profile. For similar AA5083 joints, a cylindrical or tapered threaded pin is adequate. For dissimilar AA5083–AA7039 joints, a triflute or threaded tapered pin improves intermixing. For Al–steel joints, tungsten carbide or PCBN tool material is recommended.

Stage 2 – Parameter Selection: Set n/v within the optimal window for the material pair and plate thickness. Apply 1–3° tool tilt. For dissimilar joints, place the harder alloy on the advancing side and apply tool offset towards the softer alloy to limit IMC thickness.

Stage 3 – Weld Zone Qualification: Characterise the joint using tensile testing, Vickers hardness mapping, optical and SEM microscopy of SZ, TMAZ, and HAZ, and non-destructive inspection (radiography or PAUT) for internal defects. For dissimilar joints, confirm IMC

layer thickness below the critical threshold by cross-sectional SEM-EDS analysis.

Stage 4 – Service Performance Validation: Conduct salt spray or potentiodynamic polarisation testing for corrosion-sensitive applications. Perform fatigue S-N testing for cyclic load applications. Adjust traverse speed and post-weld surface treatment based on service environment requirements.

X. CONCLUSION

This paper has developed and assessed a systematic FSW strategy for similar (AA5083–AA5083) and dissimilar (AA5083–AA7039 and Al–mild steel) joints. The following conclusions are drawn:

- (1) The n/v ratio is the dominant process variable controlling tensile strength and hardness distribution in AA5083 FSW joints. Both excessively high and low n/v ratios degrade mechanical properties.
- (2) In dissimilar AA5083–AA7039 joints, material positioning, pin geometry, and tool offset must be optimised simultaneously. AA7039 on the advancing side and a triflute pin geometry improve mixing and reduce interfacial defects.
- (3) For Al–steel dissimilar joints, IMC layer thickness must be maintained below 2–5 μm through strict heat input control. Tool material must be upgraded to WC or PCBN to manage wear.
- (4) Service performance—corrosion resistance and fatigue life—must be integrated into parameter selection. Higher traverse speeds reduce corrosion resistance and must be balanced against their benefit in limiting HAZ softening.
- (5) The proposed four-stage strategy—tool design, parameter selection, weld zone qualification, and service performance validation—provides a structured framework for developing FSW procedures for new material combinations in industrial applications.

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