TECHNICAL CONSIDERATIONS ON FRICTION STIR PROCESSING OF DISSIMILAR ALUMINUM ALLOY WELDED JOINTS

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Abstract: The paper presents a critical and integrated analysis of Friction Stir Processing (FSP) applied to dissimilar welded joints of aluminum alloys from the 5xxx, 6xxx, and 7xxx series. Based on more than 30 recent primary sources and the author's own experimental data, the effects of FSP on the microstructure, mechanical properties, and corrosion behavior of joints produced by TIG, MIG, FSW, or hybrid TIG + FSP methods are evaluated. Optimal technological windows (800–1000 rpm, 40–70 mm·min^{-1}, tilt angle 1.5–2°) are detailed, together with the influence of the number of passes, tool geometry, and micro-alloying additions (Sc, SiC/Gr, B_4 C, Fe foil). The summarized results show that FSP reduces grain size in the stir zone to 2–6 µm, increases tensile strength by 20–35%, doubles elongation, and eliminates porosity and solidification cracks. For AA6061/AA7075 joints treated by the TIG + FSP sequence, fatigue life improves by 40%, while for AA5083 welds, intergranular corrosion resistance becomes comparable to the base material. The paper provides a practical guide to FSP parameters and highlights relevant industrial applications - naval repairs, lightweight ballistic structures, cryogenic heat exchangers, and wear-resistant surface layers. Future research directions are also identified, including multiscale thermomechanical modeling, tool wear in Zn-rich alloys, and evaluation of ballistic impact behavior. The overall conclusion emphasizes that FSP is a green, robust, and efficient method for enhancing the performance of dissimilar aluminum alloy welded joints, with strong potential for large-scale implementation in aerospace, naval, automotive, and defense industries.

Key words: FSP, dissimilar aluminum alloys, corrosion resistance, mechanical properties, microstructure refinement, welded joints

1. INTRODUCTION (HEADING 2STYLE)

Welding is an essential process in the manufacture of large and complex components in various industries, including automotive, aerospace, petrochemical, power generation, and shipbuilding [1]. However, conventional welding techniques often lead to problems such as coarse-grained structures and common defects such as cracks, porosity, inclusions, lack of penetration, and incomplete fusion [2–3]. The demand for high-quality welds has led researchers to explore innovative welding techniques and post-weld treatments [4].

Friction Stir Welding (FSW), a solid-state joining process, operates below the melting point of the base material, which enables it to efficiently join dissimilar and hard-to-weld materials [5–6]. Based on the principles of FSW, Mishra et al. introduced Friction Stir Processing (FSP) as a method for microstructural modification rather than joint formation [7]. As a thermomechanical process, FSP induces intense plastic deformation and generates lower heat, facilitating grain refinement and reducing defects and residual stresses typically associated with fusion welding and casting processes [8].

Friction Stir Processing (FSP) is a solid-state method that enhances material properties through localized heat and mechanical deformation. It affects the material in four main zones:

- Parent Metal (PM): remains unaffected in structure and properties, despite minor heat exposure;
- Heat-Affected Zone (HAZ): experiences thermal changes but no deformation;
- Thermo-Mechanically Affected Zone (TMAZ): undergoes both deformation and heating, often without full recrystallization;

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• Stir Zone (SZ) / Nugget Zone: undergoes complete recrystallization due to the tool's action, resulting in fine grains and improved strength [9].

Together, these zones demonstrate FSP's effectiveness in refining materials without melting, offering improved structural performance (Figure 1).

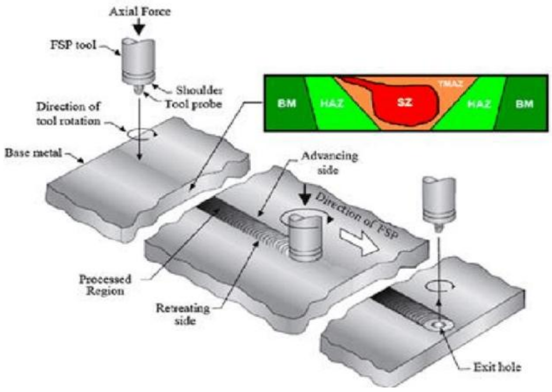


Figure 1 – Process and the mechanism of FSP [9].

FSP is recognized as an environmentally friendly, energy-efficient technique with minimal material waste. Its applications are versatile, including the development of superplastic materials [10], surface composites [11], homogenization of composites, microstructural refinement of aluminum castings [12], and post-weld enhancement. Since FSP is derived from FSW, it shares similar process parameters.

The present paper reviews current research on the use of FSP to improve the quality of welds produced by various welding methods. The analysis also highlights areas for future research and development in this field.

2. MATERIALS PROCESSED BY FSP

Recent developments in the marine, automotive, defense, and aerospace industries have driven a significant shift toward the adoption of lightweight metallic materials such as aluminum, titanium, and magnesium, in preference to traditional structural metals. Among these, aluminum alloys from the 5xxx, 6xxx, and 7xxx series are extensively utilized due to their superior combination of mechanical and physical properties. These include a high strength-to-weight ratio, excellent corrosion resistance under harsh environmental conditions, low density, favorable formability, and elevated thermal conductivity [13].

Examples:

- AA6061 (Al-Mg-Si alloy): Good corrosion resistance and moderate strength;
- AA7075 (Al-Zn-Mg-Cu alloy): High strength due to precipitation hardening;
- Both are widely used in aerospace (aircraft structures, rockets), automotive (rims, bumpers), and defense (ammunition hardware).

- Chemical components (wt. %)

The data are taken from ASTM B209/B928 and EN 573-3 specifications, supplemented with experimental reports for the alloys actually used in the analysed studies [13].

Table 1 – Chemical components for aluminum alloy [14]

Types of Al alloy	*Al*	*Si*	*Cu*	*Fe*	*Zn*	*Mg*	*Mn*	*Cr*	*Ti*	*Other elements*
AA5083-F/H321	Bal.	≤ 0,40	≤ 0,10	≤ 0,40	≤ 0,25	4,00–4,90	0,40–1,00	0,05–0,25	≤ 0,15	≤ 0,15 (Ni, V etc.)
AA6061-T6	Bal.	0,40–0,80	0,40–0,80	≤ 0,70	≤ 0,25	0,80–1,20	≤ 0,15	0,04–0,35	≤ 0,15	-
AA6082-T6	Bal.	0,70–1,30	0,70–1,30	≤ 0,50	≤ 0,20	0,60–1,20	0,40–1,00	≤ 0,25	≤ 0,10	-
AA7075	Bal.	≤ 0,40	≤ 0,40	≤ 0,50	5,60–6,10	2,10–2,50	≤ 0,30	0,18–0,28	≤ 0,20	-

- Mechanical properties and influence of the treatment condition

Table 2 – Basic mechanical properties and influence of the treatment condition [14]

Alloy (state)	*Rm (MPa)*	*Rp0,2 (MPa)*	*A_5 (%)*	*Hardness HBi*	*Remarks*
AA5083-F	275	125	18-22	75	As fabricated condition, excellent resistance to marine corrosion
AA5083-H321	305	215	12-16	85	Stress corrosion stabilization by controlled rolling + H321
AA6061-T6	310	275	10-12	95	Good specific strength, easy to weld; β″ precipitates provide strengthening
AA6082-T6	310	260	8-10	95	High Mn content → better thermal stability than 6061
AA7075	570	505	11	150	Ultra-strong alloy; susceptible to weld cracking

- Weldability features:
  - AA5083: Excellent weldability with TIG/MIG; however, it is sensitive to sensitization (β-Mg_2Al_3) after exposure above 65 °C [14];
  - AA6061/6082: Good weldability, but ~40% strength loss occurs in the heat-affected zone due to dissolution of β″ precipitates [15];
  - AA7075: Poor weldability (hot cracking, porosity, Cu-Zn-Mg segregation) [16];
  - Filler 5356: Preferred for 5xxx/6xxx alloys to avoid cracking; not recommended for 7xxx alloys [17].

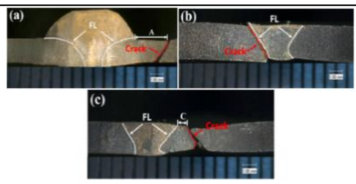
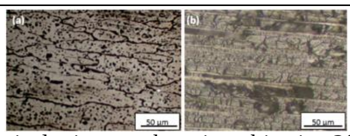
3. FSP PROCESSING OF DISSIMILAR ALUMINUM ALLOYS – APPLICATIONS

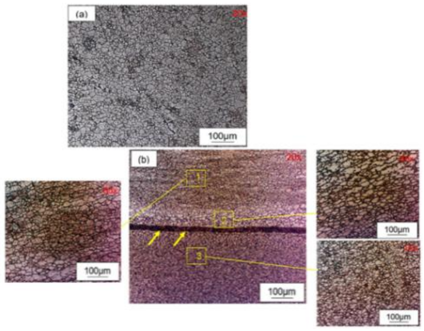
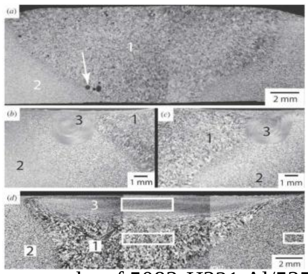
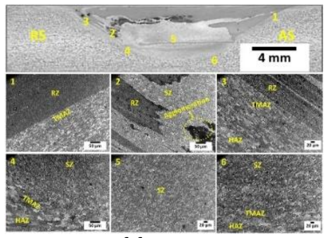
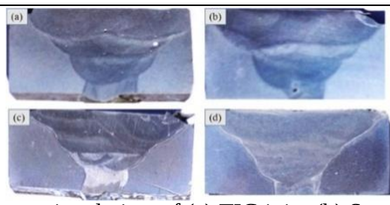
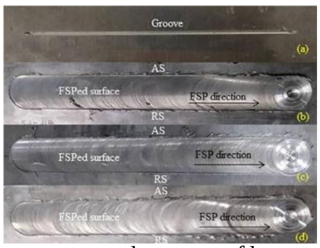
Welding dissimilar aluminum alloys is difficult due to hot cracking, porosity, and loss of strength in the heat-affected zone, especially for high-strength 6xxx and 7xxx series alloys. Traditional fusion welding methods often fail to provide joints with uniform microstructure and stable mechanical properties.

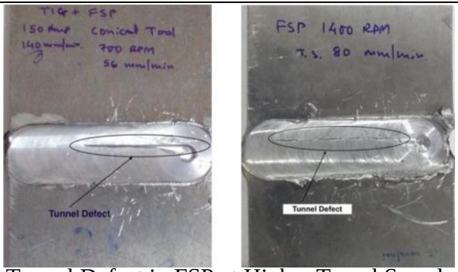
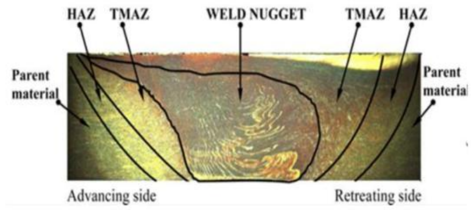
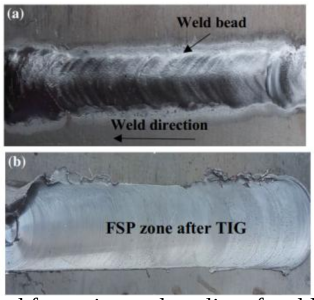
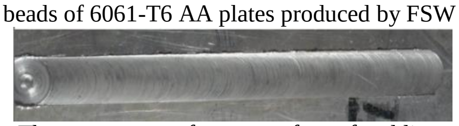
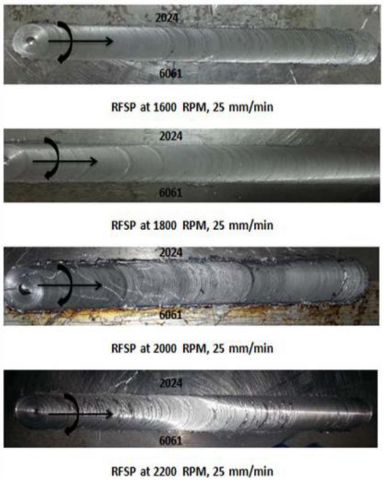
Friction Stir Processing (FSP), derived from Friction Stir Welding (FSW), overcomes these limitations by acting as a solid-state thermomechanical treatment. It refines grains, redistributes intermetallic compounds, eliminates welding defects, and restores or even improves tensile strength, ductility, and corrosion resistance.

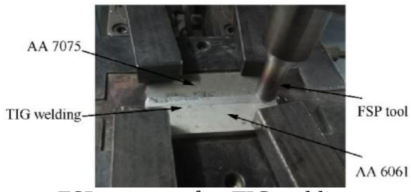
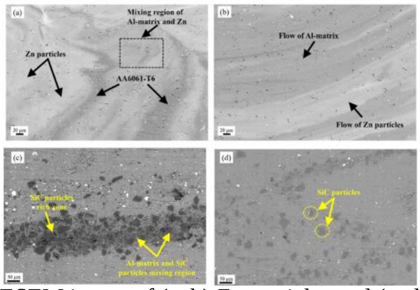
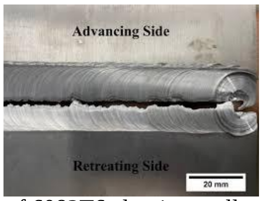
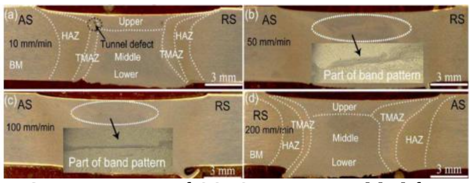
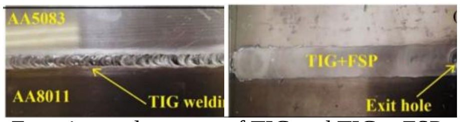
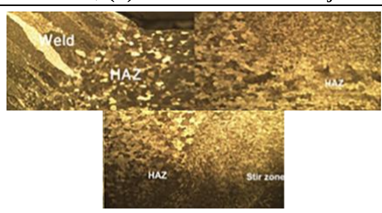
Applied either directly or as a post-weld enhancement for TIG/MIG joints, FSP has proven effective in reducing grain size to 2–6 µm, raising strength by 20–35%, and improving fatigue and wear resistance. These benefits make FSP highly attractive for aerospace, automotive, naval, and defense applications, where lightweight and reliable joints are critical.

Table 3 – Applications of FSP processing of dissimilar aluminum alloys

Al alloy type /configuration	*Initial welding method*	*Parameters*	*Main results „After FSP"*	*Remarks*
AA1050-H14 / AA6082-T6	TIG	1000 rpm; 60 mm min^{-1}; tool W-25 %Re; 1 step	Uniform hardness (±5 HV); equiaxed texture < 5 µm along length [18]	 FSP of dissimilar metals
AA1050 / AA6082 (cordon FSW)	FSW	1000 rpm; 70 mm min^{-1}; 1 step	Nugget hardness ↑18%, wear ↓ 2× [20]	 Optical micrographs using objective 20x magnification 50 mm Friction stir processed FSWed joint (a) AA6082-T6; (b) AA1050-H14

Al alloy type /configuration	*Initial welding method*	*Parameters*	*Main results „After FSP”*	*Remarks*
AA1050-H14 / AA6082-T6	TIG	900 rpm; 50 mm min^{-1}; 1 step; L & T guidance	T samples: +30% $Rp_{0,2}$ vs. L; consistent micro-refining [21]	 (a) FSP+TIG microstructural arrangement of the stir zone sampled (a) transversally, (b) longitudinally
AA5083-H321 / 5356	Arc welding (GMAW)	500 rpm; 203 mm min^{-1}; sculă concavă	Grain size 3–5 µm; Rm ≈ base material; IG corrosion resistance recovered [14]	 Light macrographs of 5083-H321 Al/5356 Al arc weld in the following conditions: (a) as-arc welded, (b) weld toe FSP with arc weld nugget on advancing side, (c) weld toe FSP with arc weld nugget on retreating side, and (d) weld crown FSP
AA5083 + (15 vol %) SiC-Gr surface layer	FSP powder loading	2–4 phase; 900–1000 rpm; 40–80 mm min^{-1}; optimal 950/60/3 phase	Wear ↓2,8×; surface hardness 145 HV (vs. 90 HV) [24]	 Optimization of friction stir processing parameters for improving structural
AA5083-F (filler 5356 + 0,4 % Sc)	TIG	800 rpm; 45 mm min^{-1}; 1 step	Rm 310 MPa (↑32 %); dispersoids Al_3Sc → thermal stability 350 °C [29]	 Cross sectional view of (a) TIG joint (b) Sc added TIG welded joint (c) FSP on TIG welded joint (d) FSP on Sc added TIG welded joint
AA5083 + folie Fe (in-situ Al_3Fe)	FSP as a unique joining method	600–1000 rpm; 30 mm min^{-1}; 1 step; optimal 800	Hardness ↑ la 128 HV; strength without visible embrittlement [30]	 (a) Square groove at the center of base metal and Friction Stir Processed samples at (b) 710 rpm (c) 900 rpm and (d) 1120 rpm

Al alloy type /configuration	*Initial welding method*	*Parameters*	*Main results „After FSP”*	*Remarks*
AA5083 (cordon TIG)	TIG	700, 900, 1100 rpm; 25–75 mm min⁻ ¹	Porosity < 0,5 %; Charpy 7 J (vs. 4 J) la 900/50 [22]	 Tunnel Defect in FSP at Higher Travel Speed
AA6061-T6 (monolith)	FSP as a unique joining method	400–1200 rpm; 20–100 mm min⁻ ¹; optimal 800/40	Hardness 115 HV (de la 95 HV); thermal model < 5 % error [15].	 FSW and FSP zones
AA6061-T6 / AA7075-T651	TIG (150 A, Ar gas)	800–1200 rpm; 40–100 mm min⁻ ¹; pin H13; tilt 2°, 1 pas	Grains 3–6 µm, porosity eliminated; +25 % Rm (≈310 MPa) and doubling of elongation vs. simple TIG [16].	 Weld bead formation and quality of weld, a TIG welding, b TIG+FSP
AA6061-T6 / AA7075-T6	TIG + FSP (in-line)	950 rpm; 45 mm min⁻ ¹; 1 step	Heat flux↓35 %; fatigue resistance↑ 1,4 × [17].	 FSW at 1700RPM,40mm/min The appearance of upper surface of welding beads of 6061-T6 AA plates produced by FSW  The appearance of upper surface of welding beads of 7075-T73 AA plates produced by FSP
AA6061-T6 / AA7075-T6 (without filler metal)	FSP as a unique joining method	600, 900, 1200 rpm; 40–80 mm min⁻ ¹; tilt 1,5–3°	Max. shear at 900/60; micro-grain 4 µm, hardness 118 HV [25]	 Surface of welding line for all (RFSP) specimens

Al alloy type /configuration	*Initial welding method*	*Parameters*	*Main results „After FSP”*	*Remarks*
AA6061 / AA7075	TIG	900 rpm; 50 mm min^{-1}; pine step 2,5–3,5 mm	Pitch 3 mm: granules 2.7 µm; Rm 310 MPa, A_5 = 12 % [26]	 Various TIG + FSP fabricated joint
AA6061 / AA7075	TIG + thermal monitoring	900 rpm; 50 mm min^{-1}; 1 step	T > 450 °C < 2 s; CFD model ±8 °C of measurements [27]	 FSP process after TIG welding
FSW AA6061-T6 + SiC or Zn powders	FSW	900 rpm; 50 mm min^{-1}; 1 embedding step	SiC: hardness 135 HV; Zn: ductility ↑; selection according to requirements [28]	 FESEM image of (a, b) Zn particles and (c, d) SiC particles reinforced Al-matrix composite, respectively
AA6082-T6 / 6 wt % B_4 C composite	Triple step FSP	3 pase; 900 rpm; 60 mm min^{-1}	Wear ↓3.3×; friction coefficient 0.35 [19]	 FSW joint of 6082T6 aluminum alloy with cold metal transfer (CMT) process
AA6082-T6 (self-support joint)	FSW	conical pin tool, 800–1200 rpm, 80 mm/min	The self-support configuration reduced lateral distortion by 40% and provided Rm 320 MPa, equivalent to the base material [23]	 Cross-sections of SSFSW joints welded for different welding speeds: (a) 10 mm/min, (b) 50 mm/min, (c) 100 mm/min, (d) 200 mm/min
AA8011-H14 / AA5083-H321 (Si-rich)	TIG	1–4 pase; 1000 rpm; 50 mm min^{-1}	Optimum 2 passes: Si homogenization, maximum ductility; 4 passes → elongation ↓ [31]	 Experimental process of TIG and TIG + FSP welded joints, (a) TIG weldment with filler ER4043, (b) TIG + FSP welded joint
Various Al-Al & Al-Cu systems	Various (TIG / FSW / MIG)	Optimal synthesized window: ≈900 rpm / 60 mm min^{-1}, 1–2 passes	Properties ↑ up to 30%; overheating is avoided > 950 rpm [32]	 Microstructure of (a) MIG, (b) FSPed MIG

4. CONCLUSION

This study has demonstrated that Friction Stir Processing (FSP) represents an effective and sustainable method for improving the performance of dissimilar aluminum alloy joints obtained by conventional welding processes such as TIG, MIG, and FSW. The main scientific and practical findings can be summarized as follows:

- FSP significantly improves the mechanical properties (tensile strength, microhardness, ductility) of dissimilar aluminum alloy welds produced by various welding methods, especially TIG and MIG.
- FSP leads to grain refinement, often reducing grain size from ~20 µm in as-welded joints to as low as 2–4 µm in the stir zone, which directly enhances strength and fatigue resistance.
- FSP effectively eliminates common welding defects such as porosity, microvoids, incomplete fusion, and solidification cracks.
- Multiple-pass FSP (2–3 passes) further improves homogeneity, grain distribution, and load-bearing capacity of welded joints.
- Sampling orientation (transverse vs. longitudinal) significantly influences measured properties (UTS, elongation, hardness).
- FSP enhances not only mechanical behavior but also microstructural uniformity, with well-dispersed intermetallic phases and transformation of coarse eutectics into finer particles.
- Optimization of FSP parameters (rotational speed, feed rate, tilt angle, tool geometry) plays a critical role in maximizing performance. Parameters around 900 rpm and ~45–60 $mm \cdot min^{-1}$ have shown the best balance.
- FSP is validated as an energy-efficient, sustainable post-weld treatment for dissimilar aluminum alloys, making it a promising solution for high-performance industrial applications in aerospace, defense, and automotive sectors.

In conclusion, FSP emerges as a green, versatile, and cost-effective technology that not only overcomes the limitations of conventional fusion welding for dissimilar aluminum alloys, but also creates opportunities for developing advanced lightweight structures with superior functional performance. Future research directions should focus on multiscale thermomechanical modeling, tool wear mechanisms in Zn-rich alloys, and the ballistic impact behavior of FSP-processed joints.

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