

Tensile Strength, Hardness, and Joint Efficiency of Similar AA2024 and AA7075 Friction Stir Welded Joints with Post-Weld Treatment

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ABSTRACT

Although Friction Stir Welding (FSW) reduces defects associated with conventional fusion welding of high-strength aluminium alloys such as AA7075 and AA2024, the resulting joints may still exhibit microstructural heterogeneity, residual stresses, and reduced joint efficiency. Limited studies have investigated cryogenic treatment as a post-weld technique to enhance the performance and structural integrity of similar AA7075 and AA2024 joints. Therefore, this study investigates the effects of cryogenic treatment on the thermal behavior, mechanical properties, and joint efficiency. Similar joints were fabricated using FSW parameters with three different shapes of pin tools. The joints were exposed to cryogenic treatment in liquid nitrogen. The mechanical characteristics of the weldments were evaluated using Vickers microhardness and tensile tests. Thermal imaging indicated that the maximum welding temperatures persisted significantly lower than the melting temperatures of both alloys, with a peak registered temperature of 311.1 °C for AA7075, thereby promoting dynamic recrystallization within the stir zone. Mechanical testing displayed that cryogenic treatment greatly improved the ultimate tensile strength, increasing from 430 MPa to 485 MPa for AA7075 joints and from 360 MPa to 405 MPa for AA2024. Furthermore, in the stir zone, the hardness was upgraded by 15%, reaching 220 HV for AA7075 and 150 HV for AA2024. The joint efficiency was also enhanced by 12.5–12.7%, reaching 83.52% for AA2024 and 82.96% for AA7075. The findings show that the combination of FSW and cryogenic treatment is a simple method to improve the mechanical reliability and structural integrity of aluminium alloy.

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Introduction

Overview of solid-state welding and high-strength aluminum alloys

The high-strength aluminum alloys like AA2024 and AA7075 have long been used for marine, automotive industry, and aerospace applications in large quantities (Fakhri et al., 2022). Such alloys are essentially difficult to weld by conventional fusion welding processes, which yield to defects including porosity, hot cracking, and brittle intermetallic compounds occurring at the welded joint interface that jeopardize weldment efficiency and structural integrity (Fakhri et al., 2024a).

To mitigate these challenges, solid-state welding (SSW) has developed as a vital bonding method that creates a robust structural bond between the joining parts while keeping the base materials strictly in solid form (Beghdadi et al., 2025; Iqbal et al., 2025). As a result, it does not face many of the severe flaws associated with fusion welding, which include residual stresses, macro-porosity, and other metallurgical imperfections generated during phase solidification (Wu et al., 2026; Ojetoye et al., 2024). Because solid-state welding keeps the peak processing temperature safely below the melting point of the materials, it significantly helps reduce thermal distortion, minimizes residual stresses, and successfully retains the inherent mechanical properties of parent alloys. Moreover, lower heat input and higher material utilization mean that such solid-state manufacturing is highly energy-efficient and environmentally friendly. Of these methods, resistance welding and friction welding are widely used in industrial applications due to their localized heating effectiveness and operational reliability (Meng et al., 2023; Behrens et al., 2021).

Friction stir welding (FSW) and microstructural challenges

Friction stir welding (FSW) is a friction-based solid-state welding procedure that is often used for aluminum alloys. In this method, a metallic non-consuming tool rotates and induces very high plastic deformation and material flow to make phase-connecting joints without melting (Thavasilingam et al., 2025; Yadav et al., 2025). It is extremely efficient for generating fine-grained microstructures and reducing defects, compared to traditional fusion welding techniques requiring lower energy and material. Friction stir welding has proven to be a viable alternative to conventional welding and also addresses most of these limitations by eliminating many common weld defects while producing refined microstructures (Çam et al., 2023; Sun et al., 2022; Khedr et al., 2023).

Nevertheless, it has been reported that microstructural heterogeneity and gradient mechanical properties remain in most of the FSW joints of high-strength aluminum alloys with similar characteristics, which may disadvantageously affect the whole structural performance and reliability of welded joints. Consequently, various post-weld treatment techniques are required to enhance the mechanical performance and structural stability of friction stir-welded joints.

Recent advances in post-weld cryogenic treatment

Deep Cryogenic treatment (DCT) is also efficiently applied to change the microstructure and minimize residual stress (Al-Mukhtar et al., 2019). It is a thermal treatment process that exposes materials to liquid nitrogen, which has very low temperatures (up to -196°C). This treatment may refine microstructure, precipitation behavior, and improve the mechanical properties of metallic materials. Research has shown that cryogenic treatment caused a significant improvement in the hardness, tensile strength, and wear resistance of metals (Noh et al., 2025; Kothandam et al., 2025).

Recent studies have also validated that friction stir welding can significantly enhance weld quality and minimize common fusion welding defects in high-strength aluminum alloys during grain refinement and dynamic recrystallization mechanisms. In addition, several researchers have reported that cryogenic treatment contributes to the relief of residual stress, microstructural refinement, improved precipitation behavior, and enhanced hardness and tensile properties in various metallic materials (Guo & Sun, 2025).

Furthermore, recent investigations on friction stir-welded aluminum configurations indicated that sub-zero conditioning could improve precipitation uniformity and reduce internal stress concentration fields. Nevertheless, despite these promising developments, limited studies have systematically investigated the combined influence of cryogenic treatment on the thermal behavior, tensile properties, hardness distribution, and joint efficiency of similar AA2024 and AA7075 friction stir welded joints, particularly in relation to different FSW tool pin geometries and material flow behavior.

Research gap, novelty, and specific objectives

Despite previous studies on friction stir welding and cryogenic treatment, systematic literature focused on the exact influence of deep cryogenic treatment as a post-weld optimization technique for similar high-strength AA2024 and AA7075 FSW joints remains limited and insufficiently clarified. Furthermore, the relationship between welding thermal behavior, material flow characteristics, and the resulting mechanical performance after cryogenic treatment has not been comprehensively evaluated.

Therefore, the present study aims to evaluate the effectiveness of cryogenic treatment on thermal behavior, tensile properties, hardness distribution, and joint efficiency of similar AA2024 and AA7075 friction stir welded joints to assess its viability as a post-weld enhancement technique.

To achieve this objective, similar joints were fabricated using selected FSW parameters based on previous literature with three distinct tool pin geometries (tapered cylindrical, cylindrical, and hexagonal) to comprehensively evaluate material flow variations during welding. A thermal imaging camera was used in a coordinated manner to monitor the temperature fields through the welding process, underlining that the dynamic recrystallization process occurred entirely in solid-state conditions. Moreover, the quantitative effects of post-weld cryogenic treatments on ultimate tensile strength (UTS), cross-sectional Vickers microhardness distributions, and joint stiffness were experimentally characterized and statistically verified. The developments that will result from this research are anticipated to benefit sustainable engineering applications through the creation of welded structures with higher strength-to-weight ratios and less material consumption, and increased survivability in aerospace and automotive structural systems.

Experimental Work

Base materials (AA7075 and AA2024)

For their good strength-weight ratio, corrosion resistance, and excellent machinability, aluminum alloys of 6 mm thickness are largely utilized in aeronautics and automotive applications. Mainly composed of zinc as an alloying element, AA7075 is a preferred material in military gearing and airplanes owing to its significantly higher tensile strength and fatigue strength (Sabbar et al., 2021; Shonhai, 2024). Conversely, owing to its moderate strength properties, acceptable thermal conduction capacity, and weldability, AA2024 containing a large composition of copper is suitable for the fabrication of aerospace structures (Kumar et al., 2022). However, in aluminum alloys, some limitations can also be observed in welding processes in terms of degradation of mechanical strength in HAZ, as well as weld defects like pores and fractures (Nopriantoko, 2025). To address such limitations and achieve welds with greater strength, more commonly in the recent era, Friction Stir Welding (FSW), a solid-state joining method, has been introduced that offers higher-quality joints (Qiao et al., 2025).

Chemical composition of base materials (AA7075 and AA2024)

The sheets in this study are AA7075 and AA2024 aluminum alloys. To identify the exact composition of elemental materials in these samples, we depend on chemical analysis performed by an ARL 3460 photoelectron emission spectrometer (Thermo Fisher Scientific, Ecublens, Switzerland). The composition analysis results for each utilized alloy are provided in Tables 1 and 2, respectively (The Aluminium Association, 2007).

Table 1. Al-2024 chemical compositions test results and standard data reference

Aluminum 2024	Element %							
	Si	Fe	Cu	Mn	Mg	Zn	Ti	AL
Actual [Test]	0.047	0.4	4.2	0.83	1.2	0.22	0.148	92.95
Nominal (The Aluminium Association, 2007)	≤ 0.50	≤ 0.5	3.8-4.9	0.3-0.9	1.2-1.8	≤ 0.25	≤ 0.15	90.7 – 94.7

Table 2. Al-7075 test chemical compositions and standard reference data

Aluminum 7075	Element %							
	Si	Fe	Cu	Mn	Mg	Zn	Ti	AL
Actual [Test]	0.09	0.465	1.91	0.15	2.75	5.99	0.185	88.5
Nominal (The Aluminium Association, 2007)	≤ 0.40	≤ 0.50	1.2-2	≤ 0.3	2.1 – 2.9	5.1 – 6.1	≤ 0.2	87.1 – 91.4

Tensile test of base materials (AA7075 and AA2024)

In accordance with the ASMT E8/E8M-13a standard, CNC machinery was used to machine the sheet metal specimens in their original state. As seen in Fig. 1, the specimens measured 100 mm in total length, 25 mm in gauge length, 6 mm in fillet radius, and 6 and 10 mm in width (ASTM E8/E8M, 2013).

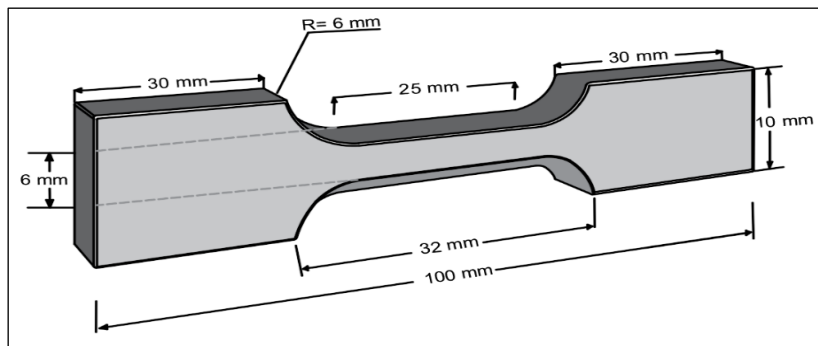


Fig. 1. Schematic of the tensile test specimen with dimensions.

Because grain elongation along this axis typically produces slightly better tensile characteristics, the specimens have been cut in line with the rolling direction to assess the ultimate tensile strength (Lin et al., 2023). For each case, three samples of the substrate material underwent tensile testing, and the average of

the values obtained was used. The ultimate tensile strength and yield strength of the joints were evaluated at room temperature using a Computer Control Electronic Universal Testing Machine (Model UE3450/UE34100, Laryee Technology Co., Ltd., Beijing, China) equipped with a 100 kN load cell, under a precisely maintained crosshead speed of 1 mm/min. Fig. 10 illustrates the stress-strain curves for the two substrate materials, AA7075 and AA2024 (Gara et al., 2023).

Friction stir welding process and joint preparation

The friction stir welding procedure is a common and growing bonding process in the solid state that relies on the principles of unifying and homogenizing the grain structure in aluminum plates (Hirata et al., 2023). The process utilizes a rotating pin tool that is pushed into a workpiece while maintaining contacting the surface and moving across the weld line (Sunnapu & Kolli, 2021). This contact generates friction and mechanical energy that does not melt the metal but rather softens it. These mechanical distortions and mixing can stimulate an intense flow of plastic materials into the softened region (Akbari et al., 2023; Rathinasuriyan et al., 2024). This causes dynamic recrystallization in the treated region, resulting in a microstructure with small, homogenous grains. The FSW samples were prepared using a wire-cut machine. The test samples were prepared using a 6 mm thick aluminum plate of type AA7075 and AA2024, with a length of 200 mm, and a width of 75 mm, as shown in Fig. 2.

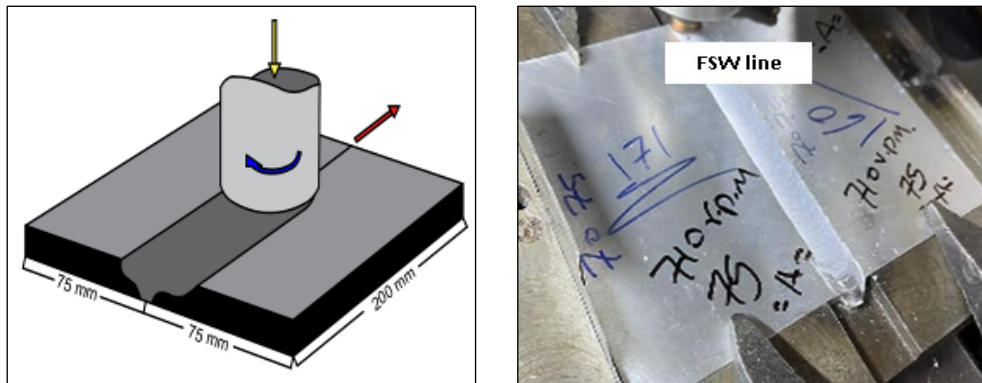


Fig. 2. Friction stir welding process.

Tool geometry (pin shape and dimension) is another governing parameter in friction stir welding (FSW), as it has a great impact on heat generation, material flow, and the quality of the weld joint. Different forms of pin profiles have been comprehensively studied to determine their effects on the weld strength, nugget formation, and microstructural attributes for different aluminum alloys. Some of the tool geometries that have been widely used are cylindrical, tapered cylindrical, hexagonal, square, and triangular profiles (Arumugam et al., 2025). These instruments are typically designed with various dimensions according to the welding configuration and the thickness of the welded plate.

The design parameters of the tool for this study were selected in line with an established empirical correlation between shoulder diameter and plate thickness given by Equation 1 (Muhayat et al., 2025):

$$D_s = (2.5 \sim 3) t \quad (1)$$

where D_s stands for shoulder diameter, and t is the plate thickness. For a plate thickness of 6 mm, the shoulder diameter was selected as 18 mm, which falls within the recommended range.

An FSW tool with dimensional parameters, including shoulder pin diameter, pin length, and plate thickness, is used for performing the respective experiments. The overall geometry and key components of the FSW tool are presented in Fig. 3.

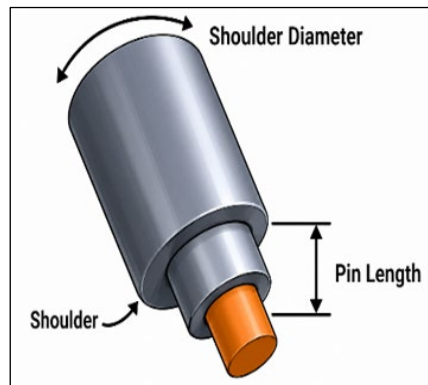


Fig. 3. FSW tool geometry.

Table 3 summarizes the detailed geometrical parameters of the friction stir welding pin used in this work. The three distinct tool pin profiles (tapered, cylindrical, and hexagonal) were evaluated for their effect on material flow characteristics and mechanical performance of welded joints, as shown in Fig. 4.

Table 3. Geometrical parameters of FSW tools for 6 mm plate thickness

Parameter	Value
Diameter of Shoulder	18 mm
Length of Pin	5.7 mm
Tip Diameter (tapered)	4 mm
Hexagon Across Flats	6 mm
Plate Thickness	6 mm

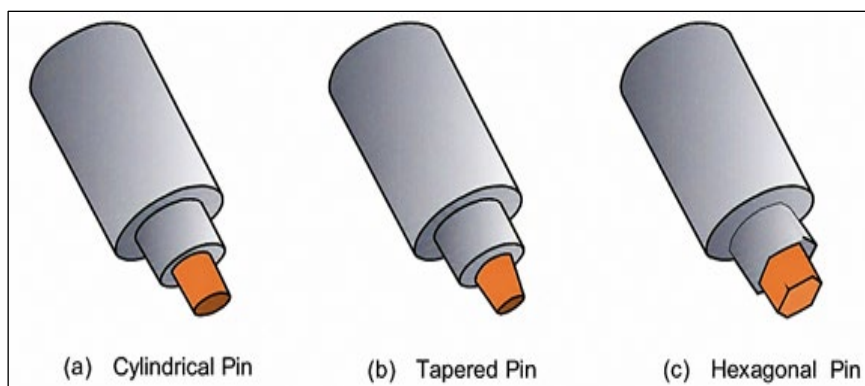


Fig. 4. FSW tool pin geometries: (a) cylindrical shape, (b) tapered shape, and (c) hexagonal shape.

Different of thermal imaging using a camera during FSW of aluminum contributes valuable understanding about heat generation and distribution (Alasdi & Al-Sabur, 2025). FSW uniquely employs a rotating apparatus to generate friction heating and extreme plastic deformation to soften the aluminum without melting it, thereby eliminating typical fusion-welding defects. Thus, thermal imaging is an efficient non-intrusive approach to control process stability, to assess models, and improve FSW settings for high-quality aluminum weld. Experimental work was done using a thermal imaging camera (SMARTSENSOR thermal imaging camera (Model ST9450, Dongguan Smart Sensor Co., Ltd., Guangdong, China), monitoring and recording the temperature distribution throughout the friction stir welding method is seen in Fig. 5. To ensure the reliability and accuracy of the temperature measurements during the FSW process, the thermal imaging camera was securely mounted on a rigid stand to eliminate any machine-induced vibrations. The camera was positioned at a fixed distance of approximately 40 cm from the weld centre. Additionally, an observation angle of roughly 45° was maintained throughout the experiments to provide an unobstructed view of the tool-workpiece interaction zone and to prevent any interference from flash material.



Fig. 5. FSW thermal imaging camera (SMART SENSOR, Model ST9450).

Selected FSW parameters based on previous studies

Welding parameters play an important role in achieving a strong and failure-resistant welded joint. The welding parameters used in this work were selected based on previous studies' parameter settings corresponding to different tool geometries, including cylindrical, tapered, and hexagonal profiles, as summarized in Table 4.

Table 4. FSW parameters used for similar AA2024 and AA7075 joints

Tool Shape	Similar Joint Type	Rotational Speed (rpm)	Welding Speed (mm/min)
Cylindrical	AA7075 - AA7075 (Hussien & Al-Shammari, 2021)	710	25
	AA2024 - AA2024 (Hussien & Al-Shammari, 2021)	110	45
Tapered	AA7075- AA7075 (Gaikwad & Chinchani, 2022)	1000	100
	AA2024 - AA2024 (El-Morsy et al., 2018)	1300	40
Hexagonal	AA7075-AA7075 (Hussien & Al-Shammari, 2021)	1800	77
	AA2024 - AA2024 (Abbass et al., 2016)	1400	35

The dimensions of welded tensile specimens differ from those of the base metal to ensure the weld nugget and heat-affected zone (HAZ) are fully included within the gauge length, allowing fracture to occur within the welded region. Additionally, dimensions are sometimes adjusted to reduce edge effects and ensure uniform stress distribution, especially for high-strength or thick aluminum alloys (Mishra & Ma, 2005). The FSW specimens were fabricated on CNC machines and machined in accordance with ASTM E8/E8M, which is shown in Fig. 6 (Gedney, 2013).

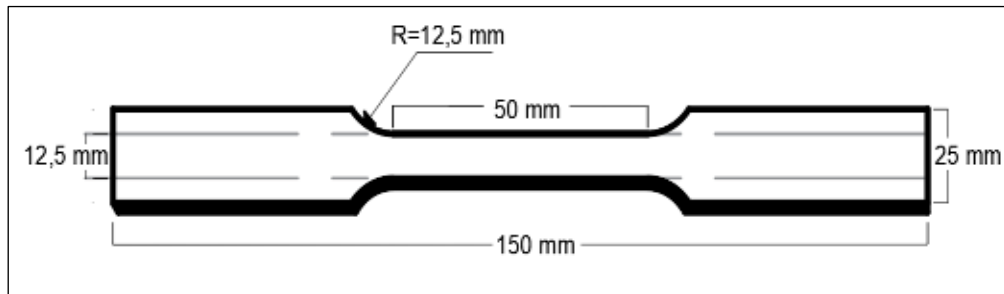


Fig. 6. Schematic of the tensile test specimen (150 mm total length, 50 mm gauge length, fillet radius 12.5 mm, widths 12.5 mm and 15 mm).

After friction stir welding and specimen preparation, only samples taken from the central weld region are tested to ensure inclusion of the nugget and heat-affected zone, while peripheral samples are excluded due to potential defects (Mishra & Ma, 2005), see Fig. 7.



Fig. 7. Tensile testing specimen for FSW joints.

To identify the tool shape that produces the highest joint strength, tensile testing was performed on the fabricated joints to evaluate their mechanical performance. The tool configuration that resulted in the maximum tensile strength was considered to provide the most effective welding conditions.

Hardness test

The hardness distribution in friction stir-welded (FSW) joints is examined using Vickers microhardness testing to assess the hardness of the stirring zone, base metal, and the heat-affected zone (HAZ).

Microhardness measurements were done at room temperature using a LARYEE Vickers microhardness testing machine (Model HVM10/50). (HV-1000, Laryee Technology Co., Ltd., Beijing, China) under a load of 500 g and a dwell time of 15 s. The testing procedure was carried out strictly in accordance with <https://doi.org/10.24191/jmeche.v23i3.11248>

the ASTM E92 standard. The specimens were machined and oriented in their individual carrier mounts by sectioning, grinding, polishing, and setting in epoxy resin to provide a sufficient surface finish before testing and supporting during the indentation stage (Fakhri et al., 2024b; Fakhri et al., 2024c).

Hardness tests were performed in a cross-section of the weld with 1 mm space between subsequent indentations, thus allowing for obtaining a detailed hardness profile across the weld zones. Fig. 8 illustrates the indentation path and measurement locations.



Fig. 8. (a) LARYEE Vickers microhardness testing machine and (b) epoxy resin mold.

FSW improvement processing (cryogenic treatment)

Cryogenic treatment is widely employed in classical metallurgical processing, where wear resistance and dimensional stability (or mechanical performance) increases were demonstrated for steels and some aluminum alloys (Hao & Liu, 2022; Du et al., 2024). Nonetheless, despite these advantages, its characterization as a post-weld treatment for friction stir welding (FSW), particularly for aluminum alloys, for instance, AA2024 and AA7075, has not been widely phenomenologically elucidated in the literature.

This work fills this important research gap by promoting cryogenic treatment as a new welding post-process enhancement route for FSW joints. In this technique, the welded samples were cooled to ultra-low temperatures in liquid nitrogen ($\sim 196^\circ\text{C}$) as cryogenic media. The samples were put in a thermally isolated box and cooled under well-timed conditions to reach thermal equilibrium with homogeneous temperature distribution, avoiding all thermal gradients and preventing thermal shock. To minimize surface damage and microcrack initiation during the rapid cooling process, a thin layer of paraffin wax was applied as a coating before treatment.

In FSW, the redistributions of residual stress, evolution of precipitates, and refinement in microstructure due to this implementation are expected, which results in better joint efficiency and mechanical performance. The specific cryogenic treatment parameters used for AA2024 and AA7075 FSW joints are given in Table 5.

Cryogenic treatment is a well-established post-processing technique that can alter the microstructure and alleviate residual stresses generated during the FSW process. This leads to improvements in phase stability, deposition state, and the strength of weld joints and is primarily associated with enhancing the microstructure and redistributing internal stress at very low temperatures (cryogenic treatment). The cryogenic treatment workflow used in this study is illustrated in Fig. 9 as a schematic diagram, representing the experimental protocol and data processing steps.

Table 5. Cryogenic treatment for AA2024 and AA7075 FSW joints (thickness = 6 mm)

Parameter	AA2024	AA7075	Unit
Material Thickness	6	6	mm
Cryogenic Medium	Liquid Nitrogen	Liquid Nitrogen	-
Cryogenic Temperature	-196	-196	°C
Holding Time	20	20	h
Number of Cycles	1	1	-
Post-Treatment Condition	Air cooling	Air cooling	-
Treated Region	FSW Joint Zone	FSW Joint Zone	-

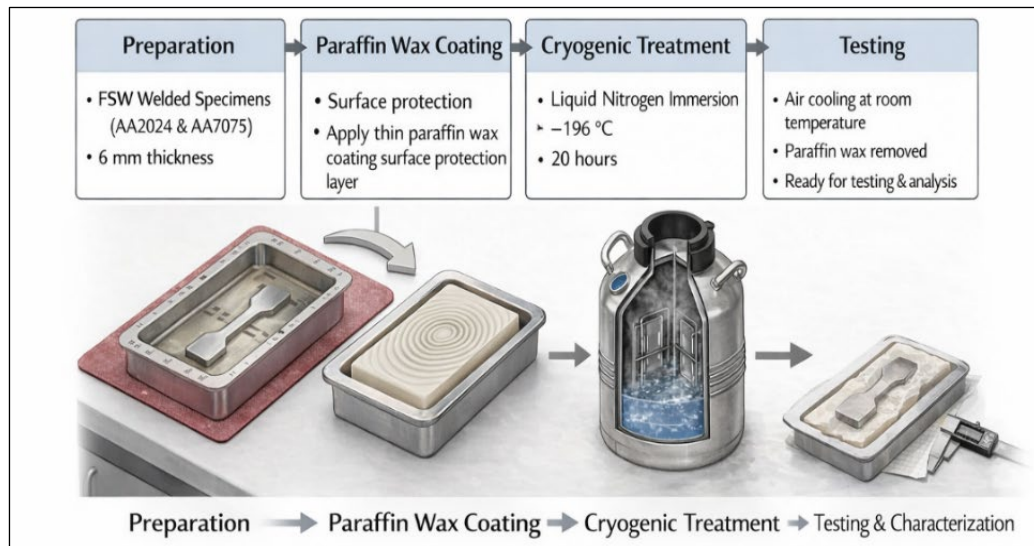


Fig. 9. Schematic diagram illustrating cryogenic treatment after friction stir welding joints.

Joint efficiency

Joint efficiency is a key criterion for evaluating the mechanical behaviour of friction stir-welded (FSW) joints, depending on their comparison with the base material. It indicates the extent to which the welding process, or any subsequent treatment (such as cryogenic treatment), can maintain or enhance the joint strength (Pereira et al., 2021).

$$\text{Joint Efficiency (\%)} = ((UTS \text{ Joint}) / (UTS \text{ Base Metal})) \times 100 \quad (2)$$

Where:

UTS joint : Weld joint ultimate tensile (MPa)
 UTS Base Metal : Base metal ultimate tensile (MPa)

Statistical analysis

Mechanical testing was conducted for three specimens at each condition, and the mean values are documented. Equation 3 was used to calculate the standard deviation to evaluate the repeatability and reliability of the measurements:

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$$SD = \sqrt{\sum (x_i - \bar{x})^2 / (n - 1)} \quad (3)$$

Where:

- x_i : individual measured value
 $\bar{x}$: mean value
 n : number of samples

The calculation of the standard deviation according to Equation 3 was performed in order to assess the repeatability of obtaining results.

Results and Discussion

Tensile test of base materials (AA7075 and AA2024)

The mechanical properties of AA2024 and AA7075 aluminum alloys were evaluated using tensile tests. To assess reliability, three specimens were created for each alloy, and the average values are reported. Table 6 shows the mechanical characteristics of the metals used in this work (Aluminium Alloys 2024 and 7075), along with stress and strain curves of the materials, as shown in Fig. 10.

Table 6. Tensile properties of aluminum alloys 2024 and 7075

Alloy	Ultimate Tensile Strength (MPa)	SD (MPa)	Yield Strength (MPa)	SD (MPa)
2024	485	± 10	345	± 8
7075	585	± 12	505	± 10

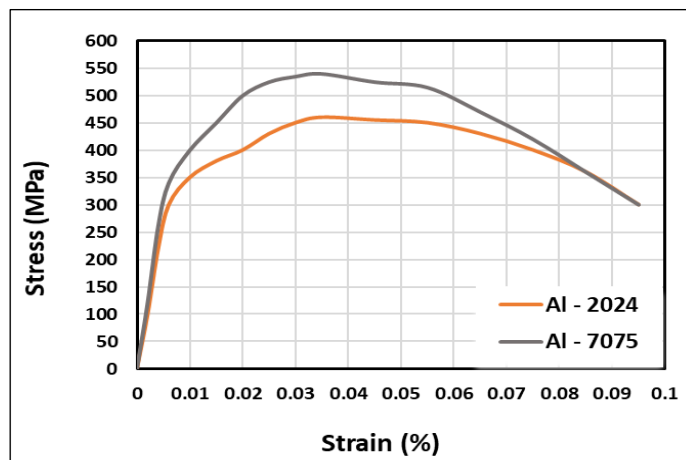


Fig. 10. Stress–strain curves of base materials (AA2024 and AA7075).

The mechanical (tensile) properties of AA7075 aluminum alloy were significantly higher and better than those of AA2024 aluminum alloy, with yield strength and a maximum tensile strength of 505 MPa and 585 MPa, respectively. This superior performance is primarily attributed to the stronger response to precipitation hardening.

This mechanical behavior of the alloy can be mainly explained by the presence of copper-bearing deposits, which provide a higher level of strengthening. In comparison, AA7075 has higher Zn and Mg

content that promotes better heat treatment precipitation strengthening due to the formation of fine MgZn_2 precipitates. This leads to greater resistance to plastic deformation and increased load-carrying capacity. Additionally, AA7075 displays a more sensitive response to thermomechanical processing as it increases both yield strength and ultimate tensile strength. These microstructural strengthening mechanism nuances can explain the more advanced mechanical properties of AA7075 over AA2024.

Effect of pin geometry on mechanical performance

Tool pin shape controls material flow, heat output, and weld performance throughout friction stir welding (FSW). The tapered pin showed a good material flow behavior with respect to the weld zone among the different profiles investigated.

The improved joint performance can be largely attributed to the tapering of the pin diameter, which facilitates easier material movement and enhances the mixing of plasticized material, while also increasing the volume present in the stirred zone. The enhanced performance is due to the generation of a homogeneous and refined microstructure, which contributes to reducing defects such as voids and lack of bonding. On the other hand, cylindrical and hexagonal pins exhibit less optimal material flow behavior, which could potentially result in heterogeneous zones in the weld. As a result, using a tapered pin improves the welding quality and mechanical qualities of the joints (Table 7).

Table 7. Tensile test results of FSW joints with different tool geometries

Tool Shape	Joint	Stress (MPa)	SD (MPa)
Cylindrical	7075–7075	377	± 8
Cylindrical	2024–2024	360	± 7
Tapered	7075–7075	430	± 9
Tapered	2024–2024	390	± 8
Hexagonal	7075–7075	352	± 7
Hexagonal	2024–2024	359	± 7

Thermal behavior and temperature distribution

Thermal images demonstrate a non-uniform heat distribution through the weld surface. Higher temperatures are observed near the tool–workpiece interaction zone. This distribution indicates steep thermal gradients, which are vital governing factors in the transportation of materials and microstructural evolution during the FSW process (Borah et al., 2025). Recorded temperatures can be found in Table 8, and are plotted in Figs. 11 and 12, indicating that the maximum nugget zone temperatures reached approximately 60–80% of the melting temperatures for AA2024 and AA7075. These temperatures remain well below the respective melting points (502 °C and 477 °C), as expected for a solid-state process. This temperature domain aids dynamic recrystallization (usually > 0.5 T_m) and also develops fine grains and improves mechanical properties in the stir zone (Singh et al., 2025).

Table 8. Thermal imaging measurement of temperature distribution in FSW joints

Alloy	HAZ Max. temperature (°C)	Tool (pin) Max. temperature (°C)	Nugget Max. temperature (°C)	Alloy Melting temperature (°C)
2024-2024	283.4	277.2	287.5	502 (Wang et al., 2022)
7075-7075	273.9	229.1	311.1	477 (Rokni et al., 2011)

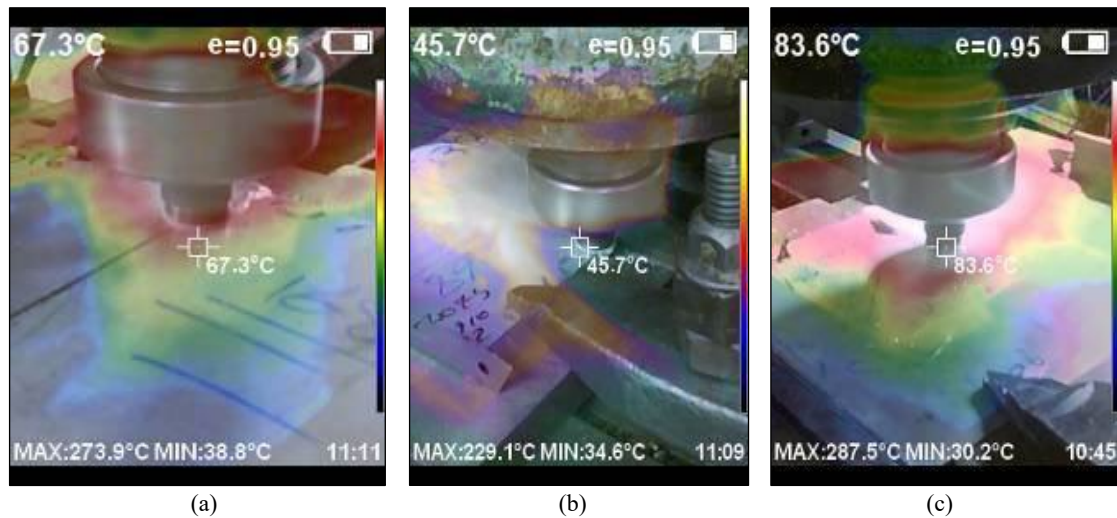


Fig. 11. FSW Joint AA2024–AA2024 distribution of the thermal: (a) HAZ temperature, (b) tool temperature and (c) nugget temperature.

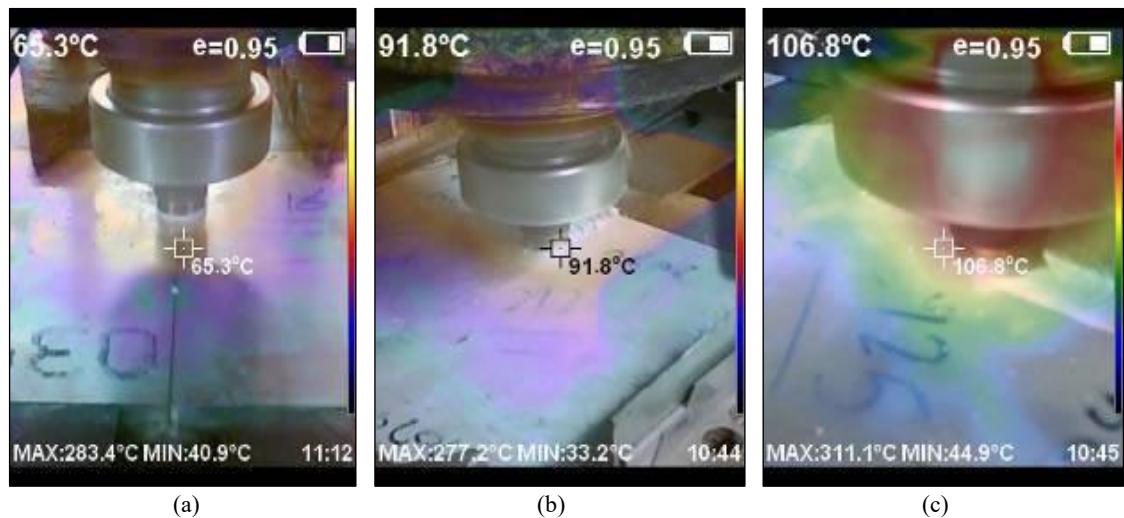


Fig. 12. Thermal distribution of AA7075–AA7075 FSW joint: (a) HAZ temperature, (b) tool temperature, and (c) nugget temperature.

It is observed that nugget temperature in AA7075 joints is higher than that of AA2024. This behavior can be explained by the higher resistance to plastic deformation of AA7075, which causes an increment in frictional heat generation. The variation for alloy types is due to their different thermal conductivity and chemical composition, leading to large differences in temperature distribution.

However, the heating conferred at these temperature levels is sufficient for inducing mechanical behavior such as severe plastic deformation and DRX in the stir zone, allowing controlled thermal exposure to improve grain regrid and microstructural homogeneity. The heat input in FSW is meticulously calibrated to maintain a reasonably small HAZ in such materials, which consequently causes little thermal softening.

Additionally, the generation of heat is limited only to just below the tool path and has a steep thermal gradient into the surrounding base material, allowing tried-and-true material flow down through regions of the tool, resulting in consolidation. This thermal behavior results in relatively defect-free welds, which are directly related to improved mechanical performance, such as joint efficiency and stiffness distribution.

Tensile and hardness properties of the stir-welded joints

Tensile test

The mechanical behaviors of friction-welded (FSW) joints are generally greatly influenced by the alloy composition, as well as the micro-deformations resulting from the welding process. The tensile test results in Table 9, also shown in Fig. 13, indicate that AA7075 alloy joints exhibited the highest tensile strength, reaching a maximum value of 430–450 MPa, with an elongation of 6–7%. This finding is consistent with previous investigations, which indicate that AA7075 alloy friction-welded joints achieve similar levels of strength (approximately 380–500 MPa) and ductility (5–12% elongation). This generally means that the applied thermal and mechanical conditions preserve a large portion of the base material's strength and its recrystallization. Flexibility increases due to dynamic recrystallisation, particularly in the mixing zone. Furthermore, the tensile properties of the AA2024-AA2024 joints were significantly lower, with a maximum tensile strength of 320–365 MPa and an elongation of 4–5%. This substantial decrease is attributed to the melting of the precipitates and thermal softening, especially in the heat-affected zone (Guo & Sun, 2025).

Table 9. The mechanical properties of the friction-stir weld (FSW) joints, in addition to the standard deviation

Joint	UTS (MPa)	SD (MPa)	Yield Strength (MPa)	SD (MPa)
2024–2024	360	± 7	245	± 5
7075–7075	430	± 9	310	± 6

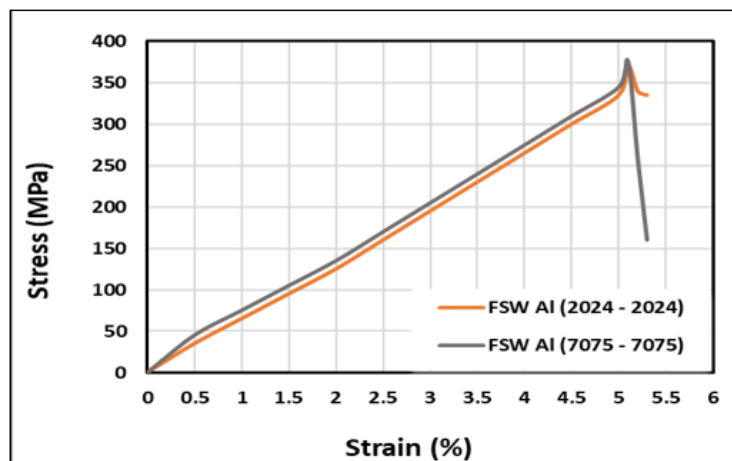


Fig. 13. Stress–strain curves of FSW joints.

The purpose of the fractographic examination is to confirm the results of the tensile test. The fracture surfaces of both AA2024 and AA7075 FSW joints exhibited a mixed ductile–brittle fracture mode. Cleavage-like regions are associated with brittle fracture behavior and are typically linked to the presence of coarse intermetallic particles and local strength mismatches, which promote rapid crack propagation (Thomas & Sreejith, 2025). In contrast, dimpled regions indicate ductile fracture governed by plastic deformation within the refined grain structure of the stir zone. These behaviours are consistent with the

diverse microstructure throughout the welding regions, such as HAZ, TMAZ, and stir zone, where the grain size and precipitate distribution vary in various weld regions, leading to a local reduction in ductility and fracture resistance (Fig. 14).



Fig. 14. Fracture surface morphology of FSW joint.

In Fig. 13, the tested tensile strength of the AA7075–AA7075 joints measured using the as-welded condition (430 MPa) is similar to those published above (up to now) for friction stir-welded aluminum alloys (Rathinasuriyan et al., 2024).

Hardness test result (as-welded conditions)

The Vickers hardness test was conducted on various zones of the FSW joints to assess the variation in mechanical properties. Table 10 summarizes the mean hardness value of BM, HAZ, and SZ, whereas these individual results are graphically represented in Fig. 15.

Table 10. Vickers' hardness of FSW joint zones (as-welded conditions)

Joint	BM (HV)	SD	HAZ (HV)	SD	Stir Zone (HV)	SD
2024–2024	127	±3	99	± 2	130	± 3
7075–7075	166	±4	128	± 3	190	± 5

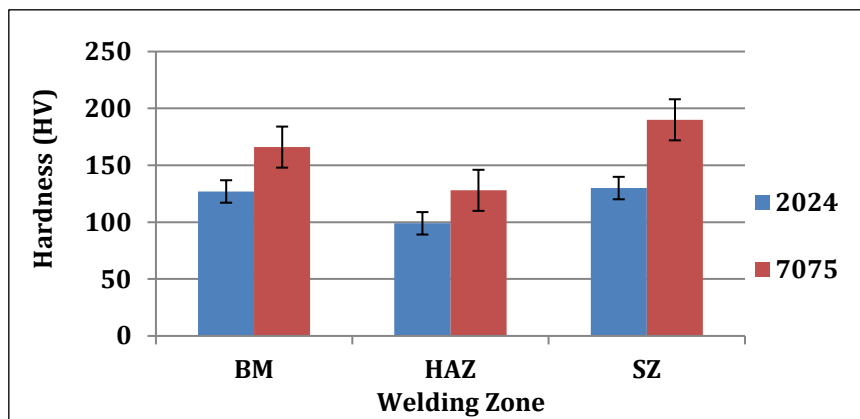


Fig. 15. As-welded hardness profile in FSW joint zones.

Hardness tests showed a clear difference in the welding zones. Both joints AA2024 – AA2024 and AA7075 – AA7075 had their lowest hardness values in the heat-affected zone (HAZ). Secondly, this reduction is mainly ascribed to thermal softening, and for two reasons: the heating cycle during welding that its hardening deposits to be melted or swelled by heat, and vice versa, is attributable to expansion of the other extreme - peak number (Zoning), which changes all criteria across a wide area.

By contrast with the reduction in the heat-affected zones, the hardness values of weld spot areas increased significantly. This increase is the result of dynamic recrystallisation (DRX), which improves the structure of grains and leads to better consistency within microstructures. Second, in the AA7075 – AA7075 joints, the hardness in the weld area greatly exceeded that of the base material, which has a significant and direct contribution to overall hardness. In general, distribution was high. There was uniform softening in the part of the material that was heated and strengthening to some degree in the part that was being fused. This pattern is fundamentally due to the formation of microstructure in the welding process.

Mechanical properties after cryogenic treatment

Cryogenic treatment, an effective post-weld process, results in improved microstructural homogeneity, reduced residual stresses, and better mechanical properties of the friction stir-welded (FSW) joints. At sub-zero exposure in welded joints, microstructural homogeneity is enhanced, residual stresses are reduced, and hardness and tensile strength are improved. Hence, mechanical characterization of cryo-treated FSW joints is essential to assess their suitability for structural applications.

Tensile test result

Tensile tests were conducted to evaluate the effect of cryogenic treatment on the mechanical behavior (ultimate tensile strength and yield strength) of FSW joints. The results obtained are illustrated in Table 11 and represented in Fig. 16.

Table 11. Tensile properties of FSW joints after cryogenic treatment

Joint	UTS (MPa)	SD	Yield Strength (MPa)	SD
2024–2024	405	± 8	275	± 6
7075–7075	485	± 10	345	± 8

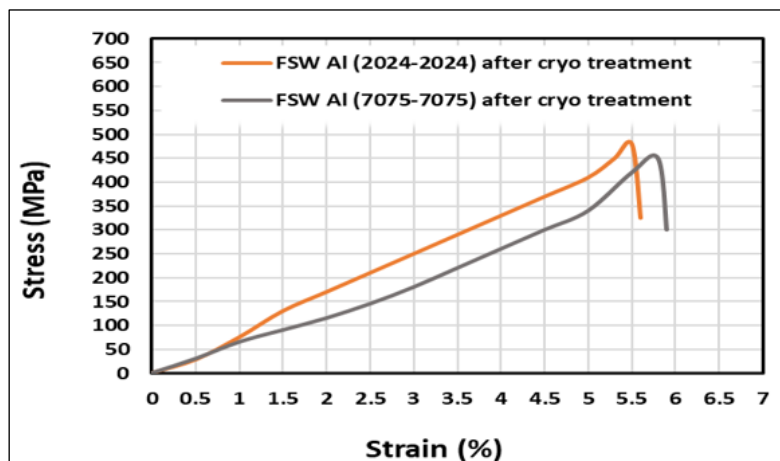


Fig. 16. Stress–strain curves of FSW joints after cryogenic treatment.

The results shown above indicate a significant improvement in the tensile properties of friction-driven welded joints after cryotherapy. This strength improvement is attributed to the enhancement of microstructure and homogeneity at very low temperatures. Furthermore, the removal of residual stress resulting from friction-driven welding improved load-bearing capacity.

The substantial enhancement in tensile strength can be attributed to improved welding conditions and weld zone stability, which decreases plastic deformations. The results demonstrated an increase in strength with minimal loss of ductility, indicating a balance between strength and deformation. Therefore, the results of this study demonstrate that applying cryotherapy as a post-weld process effectively improves the tensile and structural strength properties of welded joints.

Cryotherapy significantly enhances the mechanical behavior of aluminum alloys, particularly through improved grain size, enhanced phase homogeneity during annealing, and increased dislocation density (Noh et al., 2025).

As shown in Table 12, the present work highly aligns with recent literature, confirming that post-weld cryogenic treatment consistently enhances the tensile properties of FSW aluminum joints (Cai et al., 2025; Sun et al., 2024; Han et al., 2022).

Table 12. Comparison of ultimate tensile strength (UTS) before and after cryogenic treatment between the present study and previous reference studies

Study / Reference	UTS Before (CT) (MPa)	UTS After (CT) (MPa)	Strength Increase (MPa)	Strength Increase (%)
Present Study (AA7075)	430	485	+55	12.8%
Present Study (AA2024)	360	405	+45	12.5%
(Cai et al., 2025) AA2195	~390	~425	+35	9.0%
(Sun et al., 2024) AA2198	335	371	+36	10.7%
(Han et al., 2022) AA6061-T6	210	232	+22	10.5%

Fig. 17 illustrates the effect of cryogenic treatment on the strength of aluminum alloy and compares it with the results of the present study.

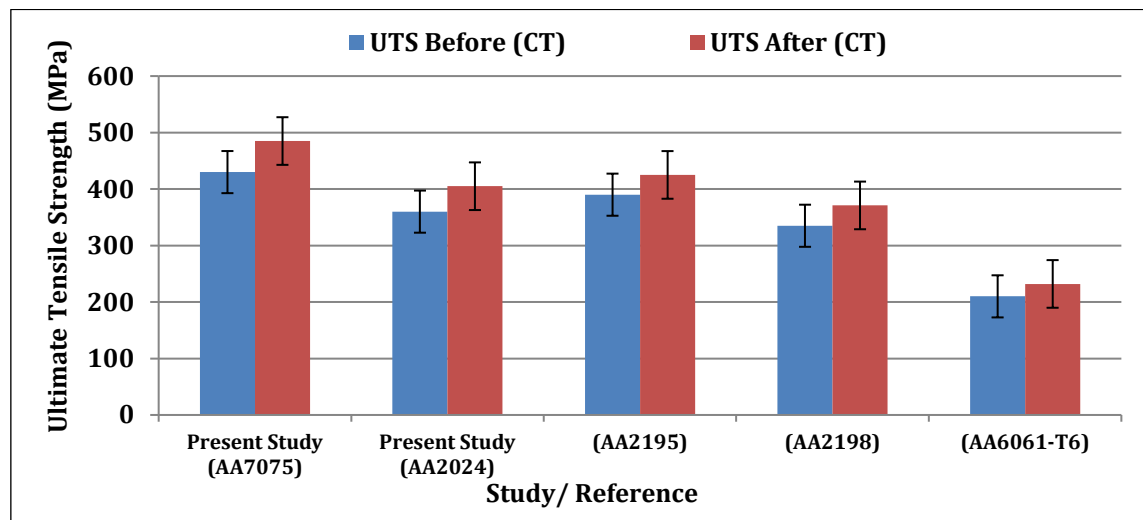


Fig. 17. Comparison of tensile strength before and after the cryogenic treatment with previous research.

Hardness distribution after cryogenic treatment

The hardness test is broadly defined as a measure of localised plastic deformation resistance, as well as overall mechanical behaviour, under various processing conditions. Table 13 and Fig. 18 illustrate the average hardness values in different weld zones of cryogenically treated joints.

Table 13. Vickers hardness of FSW joints after cryogenic treatment

Joint	BM (HV)	SD	HAZ (HV)	SD	Stir Zone (HV)	SD
2024–2024	146	± 3	115	± 3	150	± 4
7075–7075	193	± 5	147	± 4	220	± 6

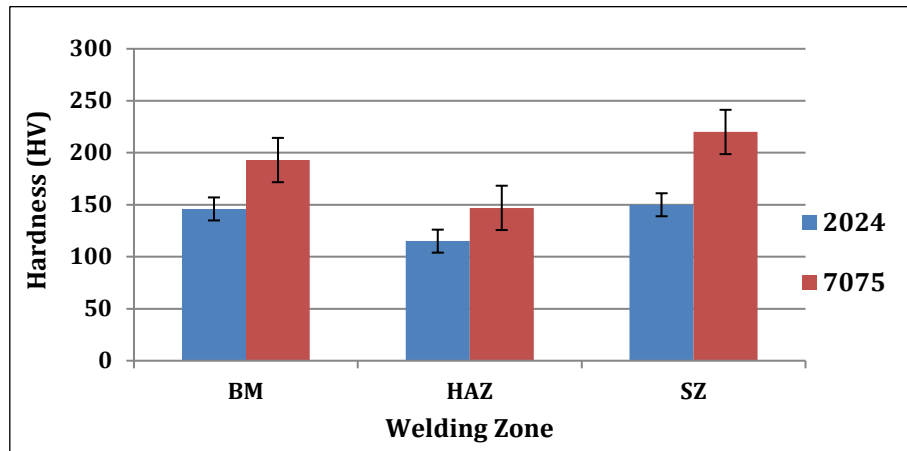


Fig. 18. Hardness distribution of welded joints after cryogenic treatment.

The results of cryogenic treatment show an overall increase in stiffness, with an average improvement of approximately 15% in the welded joint zones. The highest stiffness value was observed in the weld zone (weld spot area), which is significantly affected by the intense plastic deformation occurring during the welded joint process.

The increase in stiffness during extreme cryotherapy can be attributed to improvements in microstructure, enhanced deposition behavior, and stress relief. The reduced stiffness dispersion across the weld zones is due to improved mechanical homogeneity. Consequently, increased stiffness enhances resistance to localized plastic deformation, thus improving the overall mechanical properties of the welded joints. This increase in stiffness following extreme quenching treatment is consistent with the marked increase in ultimate tensile strength and joint efficiency, as both microstructure improvement and residual stress relief worked together to improve resistance to localized deformation.

To further validate the effectiveness of deep cryogenic treatment (DCT) as a post-weld enhancement technique, the mechanical performance obtained in this study was systematically compared with recent literature. Recent investigations on standard as-welded high-strength aluminium alloys typically report joint efficiencies ranging between 70% and 75% due to the inevitable thermal softening in the HAZ and microstructural heterogeneities in the stir zone.

A recent foundational study demonstrated that deep cryogenic treatment on AA7075-T6 aluminum alloys significantly refines grains, increases dislocation density, and promotes the uniform distribution of secondary phase particles (Han et al., 2022). Furthermore, many studies highlighted DCT as a highly

promising technique for achieving profound microstructural enhancements and phase transformations in various metal alloys (see Table 14) (Kumar et al., 2023).

Table 14. Comparative Vickers hardness of FSW joints (before & after treatment) across all zones

Study / Reference	Alloy	State	BM (HV)	HAZ (HV)	SZ (HV)
Current Study	AA2024	Before (CT)	127	99	130
		After (CT)	146	115	150
Current Study	AA7075	Before (CT)	166	128	190
		After (CT)	193	147	220
(Kumar et al., 2023)	AA7075	Before (CT)	155	115	180
		After (CT)	175	132	205

In alignment with these mechanistic findings and other recent FSW studies, the integration of optimized FSW geometric designs with deep cryogenic treatment (-196 °C for 20 h) in the present study successfully elevated the joint efficiency to 83.52% for AA2024 and 82.96% for AA7075. Furthermore, the ultimate tensile strength (485 MPa for AA7075) and peak hardness (220 HV) achieved herein are highly competitive. This superior mechanical response strongly confirms that deep sub-zero conditioning provides an efficient and structurally reliable alternative for mitigating residual stress and homogenizing the precipitation behavior across the aluminum weld zones.

Joint efficiency

Table 15 presents the effect of cryogenic treatment on the joint efficiency of AA2024-AA2024 and AA7075-AA7075 FSW joints, both before and after cryogenic treatment.

Table 15. Evaluation of joint efficiency before and after cryogenic treatment

Joint	As Welded (%)	SD	After CT (%)	SD
2024–2024	74.26	± 1.2	83.52	± 1.5
7075–7075	73.58	± 1.3	82.96	± 1.6

The joint efficiency of both alloys improved significantly with cryogenic treatment. The strength efficiency of AA2024–AA2024 joints was improved from 74.26% to 83.52%, and for AA7075–AA7075 joints, it was enhanced from 73.58% to 82.96%, which corresponded to increments of approximately 12.5% and 12.7%, respectively. The findings highlight a significant improvement in the mechanical properties of the FSW joints post-cryogenic treatment.

Cryogenic treatment plays a crucial role in relieving residual stress and refining the microstructure, thereby enhancing joint efficiency. The lowering of residual stress enables a better load transfer across the joint, the reduced undesirable phase formation phenomena, and the delayed initiation of the crack are consequences of the fine microstructure and enhanced phase stability. Furthermore, the more uniform hardness distribution obtained along the weld zones also favors strengthening without losing ductility. Thus, the results collectively indicate that cryogenic treatment is a highly efficient post-weld process for increasing the structural strength and mechanical performance of FSW joints (Salih et al., 2023; Zhang et al., 2023).

Integrated analysis of thermal, microstructural, and mechanical behavior

The results obtained have shown a significant relationship between thermal behavior, microstructural development, and mechanical response of friction stir welding (FSW) joints. It can be noted from Fig. 11 and Fig. 12 that the results of thermal analysis in Table 8 have confirmed that the peak temperatures in the

weld zones are significantly lower than the melting points of AA2024 and AA7075 alloys. This ensures that the process takes place entirely in the solid-state domain. This level of thermal input is adequate to trigger dynamic recrystallization (DRX), resulting in microstructural refinement in the stir zone as shown in Fig. 19.

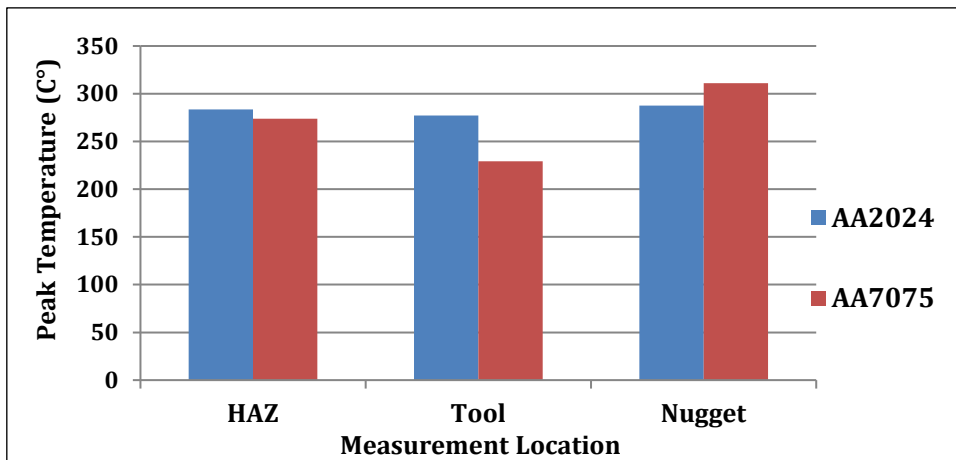


Fig. 19. Peak temperatures at HAZ, tool-contact region, and nugget zone for AA2024–AA2024 and AA7075–AA7075 FSW joints.

The refined microstructure also influences the hardness profile in the welding zone. The hardness level in the stir zone is much higher than that in the base metal (BM) and heat-affected zone (HAZ), as shown in Fig. 19 and Fig. 20. As can be seen from Tables 10 and 13, this has been confirmed. This is because the process of friction stir welding can reduce grain size and produce significant deformation. Furthermore, cryogenic treatment leads to an additional 15% rise in the degree of hardness.

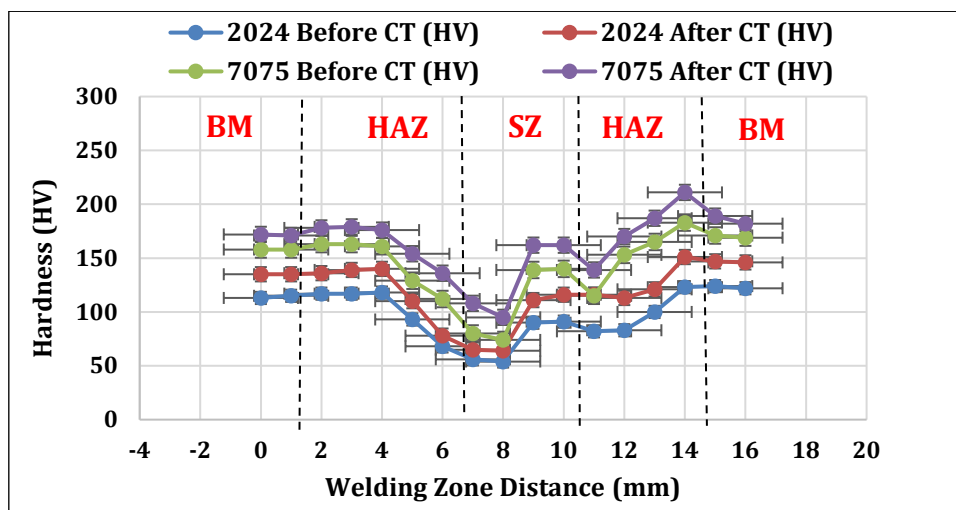


Fig. 20. Comparison of hardness distribution in weld zones (BM, HAZ, and SZ) before and after cryogenic treatment.

This enhancement in microstructure is directly correlated with the observed mechanical properties. As indicated in Fig. 16 and supported by data in Tables 9 and 11, both AA2024-AA2024 and AA7075-AA7075 joints show substantial enhancement in ultimate tensile strengths after cryogenic treatment. These enhancements in mechanical properties can be attributed primarily to homogenized microstructure and reduced stresses, which improve resistance to dislocation motion and facilitate load transfer in the welds.

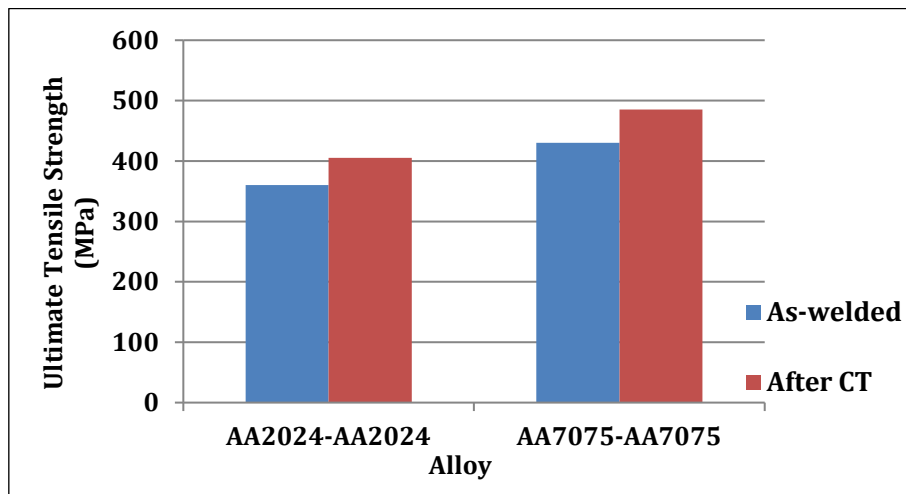


Fig. 21. Comparison of tensile properties of FSW joints before and after cryogenic treatment.

Additionally, it is found that joint efficiency is substantially enhanced after cryogenic treatment. As indicated in Table 15, joint efficiency is found to have increased by 12.5% for AA2024-AA2024 and 12.7% for AA7075-AA7075 joints after cryogenic treatment. This further proves that the combined effect of friction stir welding and cryogenic treatment is effective in improving the integrity of the welds. Thus, it is evident from the results that thermal conditions during friction stir welding (Fig. 11 and Fig. 12) govern the evolution of microstructure, which in turn affects hardness (Fig. 18) and tensile properties (Fig. 16), thereby improving joint efficiency. The application of extreme cryotherapy is attributed to this phenomenon, which leads to superior mechanical and structural properties as shown in Fig. 21.

Mechanistic correlation between cryogenic treatment and regional improvements

To logically interpret the observed mechanical enhancements and improve the quality of analysis, it is essential to correlate the deep cryogenic treatment (DCT) effects with the specific microstructural evolution in each distinct weld region and control samples.

- i. **Base Metal (Control Sample):** The CT process increased the hardness of the base metal by promoting the accelerated precipitation of secondary phase intermetallic particles (such as $MgZn_2$). The ultra-low temperature restricts phase recovery and significantly increases dislocation density, making it more difficult for the movement between slip planes.
- ii. **Heat-Affected Zone (HAZ):** The HAZ typically suffers from severe thermal softening due to the dissolution of strengthening precipitates during the FSW thermal cycle. Cryogenic conditioning facilitates the reprecipitation and uniform distribution of fine secondary phases along the grain boundaries in this region. This reprecipitation partially recovers the hardness and mitigates the steep mechanical gradient between the HAZ and the base metal.
- iii. **Stir Zone (SZ):** The SZ experiences the most significant improvement. The extreme plastic deformation during FSW produces a dynamically recrystallized (DRX) fine-grained structure.

When subjected to CT, this pre-refined region undergoes further microstructural refinement and a massive multiplication in dislocation density. The combination of severe grain boundary strengthening (Hall-Petch effect) and the formation of intergranular precipitates creates robust barriers to localized plastic deformation, culminating in the highest peak hardness and superior ultimate tensile strength.

Conclusion

From the experiment results above, the conclusion can be drawn:

- i. The defect-free welds obtained for AA2024 and AA7075 alloys in the frictional welding process with and without optimization process indicate the feasibility of frictional welding for high-strength aluminum alloys.
- ii. Thermal analysis illustrated that the local maxima temperatures were below the melting points for both alloys; the weld was therefore created in a solid state, and under dynamic recrystallisation of the material, leading to the weld.
- iii. The mechanical properties of the weld joints were significantly improved after the extreme cryotherapy. The hardness increased in the weld material by up to 15%, especially in the frictional zone.
- iv. The tensile properties of the material for welding are enhanced, which is a sign of improved robustness of the welding material when subjected to tensile load after cryogenic treatment.
- v. With the dual weld joint treated cryogenically, joint efficiency was increased by 12.5% for AA2024-AA2024, and 12.7% for AA7075-AA7075 weld joints, thus demonstrating cryogenic treatment as a viable post-weld strengthening treatment.
- vi. Friction welding with deep cooling significantly enhances the weld material, demonstrating its effectiveness in improving friction welding.
- vii. In sustainable engineering applications, friction welding combined with deep cooling improves the service life and performance of lightweight structures, particularly those made of aluminum alloys.

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Conflict of Interest Statement

The authors declare that the study was carried out in the absence of any financial or commercial relationships that could be analyzed as a potential conflict of interest.

Authors' Contributions

The authors confirm their contributions to the paper as follows: study conception and design: Marwah Sabah Fakhri and Tareq Rahman Mahmood; data collection: Marwah Sabah Fakhri; analysis and interpretation of results: Marwah Sabah Fakhri and Tareq Rahman Mahmood; draft manuscript preparation: Marwah Sabah Fakhri and Tareq Rahman Mahmood. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Generative AI in the Writing Process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) to improve language clarity and manuscript formatting and the generation of images, as shown in Fig. 9. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of the University of Technology - Iraq.

References

- Abbass, M. K., Hussein, S. K., & Khudhair, A. A. (2016). Optimization of mechanical properties of friction stir spot-welded joints for dissimilar aluminum alloys (AA2024-T3 and AA 5754-H114). *Arabian Journal for Science and Engineering*, 41(11), 4563–4572. <https://doi.org/10.1007/s13369-016-2172-9>
- Akbari, M., Asadi, P., & Sadowski, T. (2023). A review on friction stir welding/processing: numerical modeling. *Materials*, 16(17), 5890. <https://doi.org/10.3390/ma16175890>
- Alasdi, S. N., & Al-Sabur, R. (2025). In-depth thermal analysis of different pin configurations in friction stir spot welding of similar and dissimilar alloys. *Journal of Manufacturing and Materials Processing*, 9(6), 184. <https://doi.org/10.3390/jmmp9060184>

<https://doi.org/10.24191/jmeche.v23i3.11248>

- Al-Mukhtar, A. M., Rahman, T., & Doos, Q. M. (2019). Spot welding joint's fracture behavior and fundamental. *Proceedings of the 7th International Conference on Fracture Fatigue and Wear* (pp. 18-27). Springer. https://doi.org/10.1007/978-981-13-0411-8_2
- American Society for Testing and Materials. (2013). *Standard Test Methods for Tension Testing of Metallic Materials* (ASTM E8/E8M-13a). ASTM International.
- Arumugam, A., Basak, A. K., Pramanik, A., & Littlefair, G. (2025). Tool geometries and design of friction stir spot welding (FSSW) tools and effect on weld properties - a comprehensive review. *Materials*, 18(14), 3248. <https://doi.org/10.3390/ma18143248>
- Beghdadi, L., Aissani, M., Boukraa, M., & Zitouni, A. H. (2025). A review of recent advances in friction stir welding technologies. *The International Journal of Advanced Manufacturing Technology*, 1–33. <https://doi.org/10.1007/s00170-025-16857-1>
- Behrens, B. A., Duran, D., Matthias, T., & Ross, I. (2021). Enhancement of the interface of friction welded steel-aluminium joints. *Production Engineering*, 15(2), 169–176. <https://doi.org/10.1007/s11740-020-00994-5>
- Borah, M. J., Sarma, K., Nirsanametla, Y., Haldar, B., Mondal, A. K., Louhichi, B., & Joardar, H. (2025). A critical review on friction stir spot welding of aluminium alloys: tool, mechanical, and microstructural characteristics. *Crystals*, 15(9), 755. <https://doi.org/10.3390/cryst15090755>
- Cai, Q., Chang, Z., Zhang, W., Cao, G., Li, H., Jiang, B., Zhang, Z., & Zhang, H. (2025). Investigation on the mechanical properties and microstructural evolution of friction stir welded 2195 aluminum alloy at cryogenic temperature. *Materials Characterization*, 225, 115152. <https://doi.org/10.1016/j.matchar.2025.115152>
- Çam, G., Javaheri, V., & Heidarzadeh, A. (2023). Advances in FSW and FSSW of dissimilar Al-alloy plates. *Journal of Adhesion Science and Technology*, 37(2), 162–194. <https://doi.org/10.1080/01694243.2022.2028073>
- Du, J., Qiao, M., Wang, J., Zhang, L., Bian, W., Wang, H., Sun, R., Zhang, Y., & Su, S. (2024). Effect on microstructure and mechanical properties of friction stir welded 5A06 aluminum alloy joints by deep cryogenic treatment. *Materials Research Express*, 11(4), 46514. <https://doi.org/10.1088/2053-1591/ad3d34>
- El-Morsy, A. W., Ghanem, M., & Bahaitham, H. (2018). Effect of friction stir welding parameters on the microstructure and mechanical properties of AA2024-T4 aluminum alloy. *Engineering, Technology & Applied Science Research*, 8(1), 2493–2498. <https://doi.org/10.48084/etasr.1704>
- Fakhri, M. S., Al-Mukhtar, A. M., & Mahmood, I. A. (2022). Comparative study of the mechanical properties of spot welded joints. *Materials Science Forum*, 1079, 21–28. <https://doi.org/10.4028/p-488xsr>
- Fakhri, M. S., Al-Mukhtar, A., & Mahmood, I. A. (2024a). Effect of mechanical deformation on the electrical conductivity of resistance spot welding joints. *Journal of Applied Science and Engineering*, 27(9), 3165–3173. [https://doi.org/10.6180/jase.202409_27\(9\).0007](https://doi.org/10.6180/jase.202409_27(9).0007)
- Fakhri, M. S., Al-Mukhtar, A., & Mahmood, I. A. (2024b). Mechanical behaviour and failure mechanism of resistance spot welded aluminium and copper joint used in the lightweight structures. *Diagnostyka*, 25(2), 1–11. <https://doi.org/10.29354/diag/186366>
- Fakhri, M., Mahmood, I., & Al-Mukhtar, A. (2024c). The electrical and mechanical aspects of aluminum and copper resistance spot weld joints. *Engineering and Technology Journal*, 42(1), 195–205. <https://doi.org/10.24191/jmeche.v23i3.11248>

<https://doi.org/10.30684/etj.2023.143734.1606>

Gaikwad, V. S., & Chinchani, S. S. (2022). Adaptive neuro fuzzy inference system to predict the mechanical properties of friction stir welded AA7075-T6 joints. *Jordan Journal of Mechanical & Industrial Engineering*, 16(3), 381-393.

Gara, N., Jayaganthan, R., & Velmurugan, R. (2023). Failure analysis through fragmentation behaviour of Al 2024 alloy subjected to high strain rates-experimental and numerical studies. *Engineering Failure Analysis*, 149, 107258. <https://doi.org/10.1016/j.engfailanal.2023.107258>

Gedney, R. (2013). Tensile testing for determining the formability of sheet metals. Absorption, Distribution, Metabolism, Excretion, and Toxicity (ADMET) Inc.

Guo, Y., & Sun, W. (2025). Study on mechanical properties and microstructure of 2024 aluminum alloy cross-welded joint by friction stir welding. *Materials*, 18(10), 2223. <https://doi.org/10.3390/ma18102223>

Han, G., Lee, J. R., Noh, Y., & Jun, T. S. (2022). The role of cryogenic quenching on the mechanical properties of FSWed 6061-T6 aluminum alloy. *Materials Science and Engineering: A*, 840, 142896. <https://doi.org/10.1016/j.msea.2022.142896>

Hao, Y. G., & Liu, W. (2022). Analysis on exceptional cryogenic mechanical properties of AA2219 alloy FSW joints in multi-scale. *Materials Science and Engineering: A*, 850, 143489. <https://doi.org/10.1016/j.msea.2022.143489>

Hirata, Y., Fujii, H., Sato, C., & Serizawa, H. (2023). Welding and joining. *Innovative Structural Materials: Reducing Weight of Transportation Equipment* (pp. 127–222). Springer. https://doi.org/10.1007/978-981-99-3522-2_4

Hussien, R. M., & Al-Shammari, M. A. (2021). Optimization of dissimilar friction stir welded aluminum plates (2024 T3 and 7075T6) by using different methods. *Journal of Mechanics of Continua and Mathematical Sciences*, 16(6), 87-96. <https://doi.org/10.26782/jmcms.2021.06.00007>

Iqbal, M. A., Shafiq, A., & Iqbal, H. (2025). Metallurgical joining in the modern era: techniques, principles, and applications in welding. *Mechanical Theory and Systems*, 1(1), 45–60. <https://doi.org/10.64229/4m2rpk09>

Khedr, M., Hamada, A., Järvenpää, A., Elkatatny, S., & Abd-Elaziem, W. (2023). Review on the solid-state welding of steels: diffusion bonding and friction stir welding processes. *Metals*, 13(1), 54. <https://doi.org/10.3390/met13010054>

Kothandam, N., Kasirajan, L., Yogaraj, P., & Senthamaraikannan, B. (2025). Fatigue studies on cryogenic treated dissimilar FSW AA6066-T6 and AA1060-T6 aluminium alloys. *Materials Science*, 31(3), 331–338. <https://doi.org/10.5755/j02.ms.39775>

Kumar, S. D., Magarajan, U., Kumar, S. S., & Rodríguez-Millán, M. (2023). Effect of deep cryogenic treatment on the microstructural, mechanical and ballistic properties of AA7075-T6 aluminum alloy. *Defence Technology*, 30, 101–110. <https://doi.org/10.1016/j.dt.2023.04.001>

Kumar, P. S. S. R., Mashinini, P. M., & Vignesh, R. V. (2022). Overview of lightweight metallic materials. *Advances in Processing of Lightweight Metal Alloys and Composites: Microstructural Characterization and Property Correlation* (pp. 75–87). Springer. https://doi.org/10.1007/978-981-19-7146-4_4

Lin, X., Chen, Z., Shao, J., Xiong, J., Hu, Z., & Liu, C. (2023). Deformation mechanism, orientation <https://doi.org/10.24191/jmeche.v23i3.11248>

- evolution and mechanical properties of annealed cross-rolled Mg-Zn-Zr-Y-Gd sheet during tension. *Journal of Magnesium and Alloys*, 11(7), 2340–2350. <https://doi.org/10.1016/j.jma.2021.08.006>
- Meng, X., Xie, Y., Sun, S., Ma, X., Wan, L., Cao, J., & Huang, Y. (2023). Lightweight design: friction-based welding between metal and polymer. *Acta Metallurgica Sinica*, 36(6), 881–898. <https://doi.org/10.1007/s40195-023-01552-5>
- 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>
- Muhayat, N., Larasati, R. D., Putri, E. D. W. S., Budiana, E. P., & Triyono. (2025). Effect of tool diameter on the joint properties of AA6061 hollow panels using a novel one-step double-acting friction stir weld method. *Journal of Advanced Joining Processes*, 11, 100277. <https://doi.org/10.1016/j.jajp.2024.100277>
- Noh, Y., Kannan, A. R., Lee, J. R., Kang, H. H., & Jun, T. S. (2025). Effect of welding speed on the cryogenic mechanical properties of friction stir welded AA6061-T6 alloy. *Materials Science and Engineering: A*, 943, 148839. <https://doi.org/10.1016/j.msea.2025.148839>
- Nopriantoko, R. (2025). Advancements in welding technology: a review of techniques, materials, and applications. *Journal PEP Bandung*, 2(1), 62–110. <https://doi.org/10.1234/jm6e4w53>
- Ojetoye, A. A., Akangbe, S. A., & Olorunda, O. M. (2024). Friction welding processes: a review. *FUOYE Journal of Engineering and Technology*, 9(1), 103–110. <https://doi.org/10.4314/fuoyejet.v9i1.16>
- Pereira, M. A. R., Amaro, A. M., Reis, P. N. B., & Loureiro, A. (2021). Effect of friction stir welding techniques and parameters on polymers joint efficiency - a critical review. *Polymers*, 13(13), 2056. <https://doi.org/10.3390/polym13132056>
- Qiao, R., Qin, J., Long, W., Zhong, S., Song, X., Li, P., Fan, X., & Liu, D. (2025). Friction stir welding of 6061 aluminum alloy: process design strategies for joint microstructure and mechanical performance enhancement. *Critical Reviews in Solid State and Materials Sciences*, 395–430. <https://doi.org/10.1080/10408436.2025.2540125>
- Rathinasuriyan, C., Puviyarasan, M., Sankar, R., & Selvakumar, V. (2024). Effect of process parameters on weld geometry and mechanical properties in friction stir welding of AA2024 and AA7075 alloys. *Journal of Alloys and Metallurgical Systems*, 7, 100091. <https://doi.org/10.1016/j.jalmes.2024.100091>
- Rokni, M. R., Zarei-Hanzaki, A., Roostaei, A. A., & Abedi, H. R. (2011). An investigation into the hot deformation characteristics of 7075 aluminum alloy. *Materials & Design*, 32(4), 2339–2344. <https://doi.org/10.1016/j.matdes.2010.12.047>
- Sabbar, H. M., Leman, Z., Shamsudin, S. B., Tahir, S. M., Aiza Jaafar, C. N., Hanim, M. A. A., Ismsrrubie, Z. N., & Al-Alimi, S. (2021). AA7075-ZrO₂ nanocomposites produced by the consecutive solid-state process: a review of characterisation and potential applications. *Metals*, 11(5), 805. <https://doi.org/10.3390/met11050805>
- Salih, O. S., Ou, H., & Sun, W. (2023). Heat generation, plastic deformation and residual stresses in friction stir welding of aluminium alloy. *International Journal of Mechanical Sciences*, 238, 107827. <https://doi.org/10.1016/j.ijmecsci.2022.107827>
- Shonhai, N. (2024). Investigation of corrosion behaviour of aluminium alloy 7075 processed by laser shock peening without coating [Master's dissertation, University of the Witwatersrand]. Retrieved from <https://hdl.handle.net/10539/45389>

- Singh, A., Sharma, S. K., & Batish, A. (2025). Dynamic recrystallization during solid state friction stir welding/processing/additive manufacturing: mechanisms, microstructure evolution, characterization, modeling techniques and challenges. *Critical Reviews in Solid State and Materials Sciences*, 50(1), 77–135. <https://doi.org/10.1080/10408436.2024.2391333>
- Sun, J. Q., Ma, Y., Gao, C., & Luo, H. Y. (2024). Comprehensive tensile properties improved by deep cryogenic treatment prior to aging in friction-stir-welded 2198 Al–Li alloy. *Rare Metals*, 43(10), 5403–5409. <https://doi.org/10.1007/s12598-019-01214-5>
- Sun, Y., Gong, W., Feng, J., Lu, G., Zhu, R., & Li, Y. (2022). A review of the friction stir welding of dissimilar materials between aluminum alloys and copper. *Metals*, 12(4), 675. <https://doi.org/10.3390/met12040675>
- Sunnapu, C., & Kolli, M. (2021). Tool shoulder and pin geometry's effect on friction stir welding: a study of literature. *Materials Today: Proceedings*, 39(4), 1565–1569. <https://doi.org/10.1016/j.matpr.2020.05.601>
- The Aluminium Association. (2007). International designations and chemical composition limits for unalloyed aluminum (The Gold Sheets). The Aluminium Association.
- Thavasilingam, K., Senthil Kumar, A., Sakthimurugan, D., & Giridharan, K. (2025). Aluminum alloys for aircraft structures. *Aerospace Materials* (pp. 385–404). Elsevier. <https://doi.org/10.1016/B978-0-443-22118-7.00016-6>
- Thomas, B., & Sreejith, P. S. (2025). Microstructural analysis and process parameter optimization of friction stir-welded AA8090 alloys for enhanced tensile strength. *Materials Research Express*, 12(10), 106509. <https://doi.org/10.1088/2053-1591/ae0ffb>
- Wang, R., Zuo, Y., Zhu, Q., Liu, X., & Wang, J. (2022). Effect of temperature field on the porosity and mechanical properties of 2024 aluminum alloy prepared by direct chill casting with melt shearing. *Journal of Materials Processing Technology*, 307, 117687. <https://doi.org/10.1016/j.jmatprotec.2022.117687>
- Wu, C., Liu, H., Xie, R., Sun, Y., Lin, J., Zhao, Y., & Chen, S. (2026). Review on interface bonding mechanisms and cross-scale regulation of aluminum-steel dissimilar metals during solid-state friction-based welding/additive manufacturing. *International Journal of Minerals, Metallurgy and Materials*, 1-54. <https://dx.doi.org/10.1007/s12613-026-3415-8>
- Yadav, R., Dwivedi, V. K., & Dwivedi, S. P. (2025). Analysis of mechanical properties and manufacturing process of aluminum series. *Journal of The Institution of Engineers (India): Series D*, 106(3), 1529-1541. <https://doi.org/10.1007/s40033-024-00750-4>
- Zhang, X., Ma, Y., Li, W., Huang, W., Zhang, W., & Wang, Z. (2023). A review of residual stress effects on fatigue properties of friction stir welds. *Critical Reviews in Solid State and Materials Sciences*, 48(6), 775–813. <https://doi.org/10.1080/10408436.2022.2138828>



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