KSÜ Mühendislik Bilimleri Dergisi, 29(3), 2026
Araştırma Makalesi

KSU J Eng Sci, 29(3), 2026
Research Article

Kahramanmaras Sutcu Imam University
Journal of Engineering Sciences

Geliş Tarihi : 09.03.2026
Kabul Tarihi : 11.08.2026

Received Date : 09.03.2026
Accepted Date : 11.08.2026

MICROSTRUCTURAL EVOLUTION AND MECHANICAL PERFORMANCE OF FRICTION STIR WELDED 7XXX ALUMINUM ALLOYS: A REVIEW

SÜRTÜNME KARIŞTIRMA KAYNAĞI İLE BİRLEŞTİRİLEN 7XXX SERİSİ ALÜMİNYUM ALAŞIMLARININ MİKROYAPISAL GELİŞİMİ VE MEKANİK PERFORMANSI: BİR DERLEME

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ABSTRACT

High-strength 7XXX series aluminum alloys are extensively used in aerospace structures due to their superior strength-to-weight ratio, fracture toughness, and fatigue resistance. However, their sensitivity to solidification-related defects limits the effectiveness of conventional fusion welding techniques. Friction Stir Welding (FSW), a solid-state joining process performed below the melting temperature, provides a viable alternative by suppressing solidification defects while introducing complex thermo-mechanical cycles that significantly affect microstructural stability.

This review critically evaluates the microstructural evolution and mechanical performance of friction stir welded 7XXX aluminum alloys, with particular emphasis on the behavior of metastable η′ ($MgZn_2$-based) strengthening precipitates across the characteristic weld regions: Base Material (BM), Heat-Affected Zone (HAZ), Thermo-Mechanically Affected Zone (TMAZ), and Stir Zone (SZ). The influence of welding-induced thermal exposure on precipitate dissolution, coarsening, and overaging is systematically discussed in relation to the development of weld-zone softening and joint efficiency. Furthermore, the role of key process parameters in controlling precipitation stability and mechanical response is examined.

By integrating current findings from the literature, this study highlights the governing metallurgical mechanisms responsible for weld heterogeneity and identifies remaining research challenges associated with precipitation kinetics and process optimization in aerospace-grade 7XXX aluminum alloys.

Keywords: Friction stir welding, 7XXX aluminum alloys, microstructural evolution, precipitation hardening, aerospace structures

ÖZET

Yüksek mukavemetli 7XXX serisi alüminyum alaşımları, üstün mukavemet-ağırlık oranları, kırılma tokluğu ve yorulma dirençleri nedeniyle havacılık yapılarında yaygın olarak kullanılmaktadır. Ancak bu alaşımların katılaşmayla ilgili hatalara olan duyarlılığı, geleneksel ergitme kaynak tekniklerinin etkinliğini sınırlandırmaktadır. Erime sıcaklığının altında gerçekleştirilen katı hal birleştirme yöntemi olan Sürtünme Karıştırma Kaynağı (SKK), katılaşma hatalarını bastırırken mikroyapısal kararlılığı önemli ölçüde etkileyen karmaşık termo-mekanik döngüler ortaya koyarak uygun bir alternatif sunmaktadır.

Bu derleme çalışması, sürtünme karıştırma kaynağı ile birleştirilen 7XXX serisi alüminyum alaşımlarının mikroyapısal evrimini ve mekanik performansını eleştirel bir bakış açısıyla değerlendirmektedir. Çalışmada özellikle metastabil η′ ($MgZn_2$-esaslı) güçlendirici çökeltilerin davranışı; Ana Malzeme (BM), Isıdan Etkilenen Bölge (HAZ), Termo-Mekanik Olarak Etkilenen Bölge (TMAZ) ve Karıştırma Bölgesi (SZ) gibi karakteristik kaynak bölgeleri boyunca ayrıntılı olarak incelenmiştir. Kaynaktan kaynaklanan ısıl etkinin çökelti çözünmesi, irileşmesi ve aşırı

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yaşlanma üzerindeki etkisi; kaynak bölgesi yumuşaması ve bağlantı verimliliğinin gelişimiyle ilişkilendirilerek sistematik biçimde ele alınmaktadır. Ayrıca temel işlem parametrelerinin çökelti kararlılığı ve mekanik davranış üzerindeki rolü de incelenmiştir.

Literatürdeki güncel bulguların bütüncül bir değerlendirmesiyle bu çalışma, kaynak heterojenliğinden sorumlu temel metalurjik mekanizmaları ortaya koymakta ve havacılık sınıfı 7XXX serisi alüminyum alaşımlarında çökelme kinetiği ile süreç optimizasyonuna ilişkin mevcut araştırma boşluklarını ve gelecekteki araştırma gereksinimlerini belirlemektedir.

Anahtar Kelimeler: Sürtünme karıştırma kaynağı, 7XXX alüminyum alaşımları, mikroyapısal gelişim, çökelme sertleşmesi, havacılık yapıları

Abbreviation	Full Form
AS	Advancing Side
BM	Base Material
DRX	Dynamic Recrystallization
FSW	Friction Stir Welding
FSWed	Friction Stir Welded
GP	Guinier–Preston (zones)
HAZ	Heat-Affected Zone
ISRO	Indian Space Research Organization
MIG	Metal Inert Gas (welding)
NASA	National Aeronautics and Space Administration
ND	Normal Direction
NG	Nugget Zone
PFZ	Precipitate-Free Zone
PWHT	Post-Weld Heat Treatment
RS	Retreating Side
SCC	Stress Corrosion Cracking
SKK	Sürtünme Karıştırma Kaynağı
SLS	Space Launch System
SSJ	Solid-State Joining
SSS	Supersaturated Solid Solution
SZ	Stir Zone
TD	Transverse Direction
TIG	Tungsten Inert Gas (welding)
TMAZ	Thermo-Mechanically Affected Zone
TWI	The Welding Institute
UTS	Ultimate Tensile Strength
WD	Welding Direction

INTRODUCTION

The increasing demand for lightweight yet mechanically robust structures in aerospace and advanced transportation systems has intensified the reliance on high-strength aluminum alloys, particularly those offering superior strength-to-weight ratios. Among these materials, precipitation-hardened aluminum alloys play a crucial role due to their excellent specific strength, fracture toughness, and corrosion resistance. However, their successful structural application is not solely dependent on intrinsic material properties but also on the reliability of joining technologies used in fabrication.

High-strength heat-treatable aluminum alloys, especially those belonging to the 7XXX (Al–Zn–Mg–Cu) series, present significant challenges during conventional fusion welding. The melting and solidification cycles inherent to fusion-based techniques frequently result in solidification cracking, porosity, elemental segregation, and severe degradation of strengthening precipitates. In precipitation-hardened systems, such thermal exposure can lead to precipitate dissolution, overaging, and the formation of precipitate-free zones (PFZs), ultimately causing substantial

mechanical softening and reduced joint efficiency. To overcome these limitations, Solid-State Joining (SSJ) techniques have emerged as advanced alternatives. Among them, Friction Stir Welding (FSW) represents one of the most transformative developments in modern materials processing. Operating below the melting temperature, FSW generates joints through intense plastic deformation and frictional heat, thereby avoiding solidification-related defects. The process induces complex thermo-mechanical cycles that significantly alter grain structure, precipitate distribution, and dislocation density across distinct weld regions, including the BM, HAZ, TMAZ, and SZ.

In 7XXX series alloys, where mechanical strength is predominantly governed by fine metastable η′ ($MgZn_2$-based) precipitates, the welding-induced thermal cycle directly influences precipitation stability and hardening mechanisms. The resulting microstructural heterogeneity across the weld cross-section often leads to characteristic softening zones, typically located within the HAZ or TMAZ, which control the overall mechanical performance of the joint. Therefore, understanding the interplay between heat input, plastic deformation, precipitate evolution, and mechanical response is critical for optimizing FSW parameters in high-strength aluminum alloys.

Several review articles have examined friction stir welding of aluminum alloys in recent years; however, these contributions have largely addressed FSW within a broad multi-alloy or multi-process context, without systematically focusing on the precipitation-specific mechanisms that govern mechanical performance in 7XXX series alloys (Ahmed et al., 2023; Mishra & Ma, 2005; Threadgill et al., 2009). Unlike previous reviews that primarily focus on welding defects, tool geometry, or general process parameters, the present review offers a distinct perspective by establishing a mechanistic correlation between microstructural evolution and mechanical performance in 7XXX series aluminum alloys. In particular, this work systematically analyzes the governing precipitation behavior by connecting thermal exposure and η′ ($MgZn_2$-based) precipitate stability, including dissolution, coarsening, and overaging—to localized softening and mechanical response across the characteristic weld zones (BM, HAZ, TMAZ, and SZ). By integrating current findings with mechanistic interpretation, this review aims to clarify existing knowledge gaps and provide a foundation for the optimization of FSW processing strategies tailored for aerospace-grade 7XXX aluminum alloys.

HIGH-STRENGTH 7XXX SERIES ALUMINUM ALLOYS: COMPOSITION, PROPERTIES AND AEROSPACE APPLICATIONS

The rapid advancements in modern technology have ushered in a significant trend toward the use of lightweight materials across various industries, with aerospace and automotive sectors leading the way (Graf, 2021). This movement has catalyzed extensive global efforts by nations and corporations to explore and develop cutting-edge high-strength aluminum alloys. The central aim is to maximize weight reduction while maintaining mechanical stability and corrosion resistance, enabling the replacement of traditional materials like steel (Dursun & Soutis, 2014; Prabhu, 2015; Schmid-Fetzer & Zhang, 2018; Sharma & Srinivas, 2020).

Aerospace applications require a broad spectrum of material systems, encompassing metallic, ceramic, polymeric, and composite materials (Prasad & Wanhill, 2017). Within the metallic category, core structural materials include aluminum (Threadgill et al., 2009), magnesium (Z. Liu et al., 2023; K. S. Wang et al., 2006; Yang et al., 2008), titanium (Fujii et al., 2010; Meikeerthy et al., 2023; Nirmal & Jagadesh, 2021), and steel alloys, as well as Ni-based superalloys. These materials are typically classified based on their melting temperatures into low (like aluminum and magnesium alloys) and high (such as nickel-based superalloys, titanium alloys, and steel alloys) groups. Aerospace manufacturing demands top-tier welding and joining methods, with Friction Stir Welding (FSW) emerging as a pivotal technology. FSW has consistently demonstrated its efficiency in achieving superior-quality joints for a variety of materials, particularly low-softening-temperature alloys (Mabuwa et al., 2021; Pandian & Kannan, 2020). Furthermore, it has also proven effective for joining high-softening-temperature materials, such as titanium (Campanella et al., 2022; Su et al., 2022; Z. Zhang et al., 2023) and steel alloys (Gain et al., 2023; Han et al., 2022; Ipekoglu et al., 2019; J. Liu et al., 2023; Varghese et al., 2022) due to advancements in durable tool materials that enable long and reliable joints without significant wear (Ahmed, Ataya, et al., 2021; Ahmed, Seleman, et al., 2021; Hirata et al., 2007).

Historically, two key aluminum alloy series have dominated aircraft structures: the high-strength Al 2XXX and the ultra-high-strength Al 7XXX series. Examples include Al 2024, 2224, 2324, 2424, and 2524 from the 2XXX series, alongside Al 7075, 7475, 7050, 7150, 7055, and 7085 from the 7XXX series. However, from the 1980s onward, new materials such as aluminum–lithium alloys, rapid solidification alloys, and aluminum matrix composites have broadened the material landscape (Sabirov et al., 2013). Despite these developments, the traditional 2XXX and

7XXX series alloys remain pivotal due to their exceptional performance characteristics (Bucci et al., 2000; Filatov et al., 2000; J. Liu & Kulak, 2000). Statistics reveal that these high-performance alloys still constitute over 70% of structural materials used in current aircraft. Additionally, aviation aluminum is classified according to its final processing method into categories like casting, extruded, rolled, and forged aluminum alloys (Georgantzia et al., 2021).

Among high-strength aluminum alloys, the Al 7XXX series excels for its outstanding properties, including high specific strength, stiffness, toughness, processability, and suitability for solid-state joining processes like FSW. These characteristics make it indispensable for critical load-bearing components in aircraft manufacturing, such as frames, spars, and stringers. This makes the Al 7XXX series one of the most vital structural material groups within the aerospace industry. (Ahmed et al., 2023; K. Q. Wang et al., 2024; Zhou et al., 2021).

Table 1. Composition and Function of Main Alloying Elements in High-Strength Aluminum Alloys (Ahmed et al., 2023; K. Q. Wang et al., 2024; Zhou et al., 2021) .

Element	Concentration Range (wt%)	Main Function / Effect	Phases / Compounds Formed
Zinc (Zn)	4.0 - 8.0	Main strengthening element.	$MgZn_2$-based precipitates (GP zones, η, η′)
Magnesium (Mg)	1.0 - 3.0	Forms the η phase ($MgZn_2$) with Zn, provides precipitation hardening.	$MgZn_2$ precipitate (η phase)
Copper (Cu)	0.5 - 2.5	Increases strength, contributes to precipitation hardening.	Al_2CuMg (S phase, Al_2Cu (θ phase) and Cu-substituted η′)
Chromium (Cr)	0.1 - 0.3	Grain refiner, forms dispersoids, controls recrystallization.	Al_7Cr dispersoid
Zirconium (Zr)	0.08 - 0.15	Strong grain refiner.	Al_3Zr dispersoids.
Manganese (Mn)	0.1 - 0.3	Dispersoid formation, corrosion resistance.	$Al_{20}Cu_2Mn_3$ and Al_6Mn dispersoids
Iron (Fe) & Silicon (Si)	< 0.5	Impurity elements, should be limited.	Coarse, insoluble constituent particles such as Al_7Cu_2Fe and Mg_2Si.

Table 2. Chemical Composition (wt%) and Key Applications of Main 7XXX Series Aluminum Alloys in Aerospace (Ahmed et al., 2023; K. Q. Wang et al., 2024; Zhou et al., 2021).

Alloy	Zn %	Mg %	Cu %	Application
7075	5.1 - 6.1	2.1 - 2.9	1.2 - 2.0	Fuselage skin, wing lower surface
7050	5.7 - 6.7	1.9 - 2.6	2.0 - 2.6	Thick sections, forged parts
7055	7.6 - 8.4	1.8 - 2.3	2.0 - 2.6	High-strength structures
7085	7.0 - 8.0	1.2 - 1.8	1.3 - 2.0	Heavy-section forgings, wing ribs and spars (optimized for stress corrosion resistance)
7150	5.9 - 6.9	2.0 - 2.7	1.9 - 2.5	Forged components

A notable drawback of Al 7XXX alloys is their susceptibility to stress corrosion cracking (SCC), a serious defect attributed to interactions between environmental factors and operational stresses (Brotzu et al., 2017). SCC has historically been associated with various aircraft failures, underscoring the necessity for materials capable of thriving in harsh operating conditions over extended periods. To meet these rigorous demands, structural materials that exhibit a comprehensive set of properties- high static strength, high fracture toughness, high fatigue strength, excellent high-temperature performance, and robust stress corrosion resistance- summarized in Tables 1 and 2, are needed. To achieve these multifaceted requirements, specific heat treatment processes have been designed for Al 7XXX alloys. Typical treatments encompass homogenization, thermal deformation (like rolling or extrusion), solid solution processes, quenching, and aging treatments aimed at optimizing their performance characteristics (Imran & Khan, 2019; J. L. Zhang et al., 2019).

The development of 7XXX series aluminum alloys is driven by a strategy of precise improvements, focusing on enhancing one set of properties to achieve complementary advancements in others. This evolution in alloy design demonstrates three prominent trends:

- Progressively minimizing impurity elements, notably Fe and Si.
- Increasing the overall content of alloying elements to tap into maximum strength potential.
- Employing trace transition elements such as Cr, Zr, and Mn in a more refined and strategic manner for better microstructural control (Zhou et al., 2021).

Table 3. Comprehensive Summary of 7XXX Aluminum Alloys: Composition, Temper Characteristics, and Key Aerospace Applications (Ahmed et al., 2023; K. Q. Wang et al., 2024; Zhou et al., 2021).

Alloy / Temper	Zn % (Typical)	Mg % (Typical)	Cu % (Typical)	Temper Characteristic	Main Application Areas (Aerospace)
7075-T6	5.1 - 6.1	2.1 - 2.9	1.2 - 2.0	Maximum Strength (Low Corrosion Resistance)	Fuselage Outer Skin Panels, Wing Lower Skin (Tension), Ribs, Control Surfaces.
7075-T73	5.1 - 6.1	2.1 - 2.9	1.2 - 2.0	High Corrosion Resistance (Lower Strength)	Corrosion-critical zones.
7050-T7451	5.7 - 6.7	1.9 - 2.6	2.0 - 2.6	Strength/Toughness Balance (Good Corrosion Resistance)	Frames, Wing Spars, Pressure Bulkhead, Engine Mount Structure.
7050-T7651	5.7 - 6.7	1.9 - 2.6	2.0 - 2.6	Strength-Corrosion Balance	Thick Sections, Forged Parts.
7055-T77	7.6 - 8.4	1.8 - 2.3	2.0 - 2.6	Very High Strength	Wing Upper Skin (Compression), Stringers.
7085-T7	7.0 - 8.0	1.2 - 1.8	1.3 - 2.0	Enhanced Corrosion Resistance (For Thick Sections)	Ultra-Thick Monolithic Forgings, Main Wing Spars, Heavy Frame Ribs
7150-T7751	5.9 - 6.9	2.0 - 2.7	1.9 - 2.5	High Strength	Forged Components.

Al-Zn-Mg alloys, forming the basis of the 7XXX series, gain their strength primarily through heat treatment via precipitation hardening. These alloys offer a balanced combination of high strength, excellent solid-state weldability, good hot workability, and a wider range of quenching temperatures. When subjected to optimized heat treatment, this ternary alloy achieves heightened strength, enhanced welding capabilities, and improved corrosion resistance

(Rodríguez et al., 2019; Zhou et al., 2021). The strengthening response in these alloys is governed by a well-established precipitation sequence: upon solution treatment and quenching, the supersaturated solid solution (SSS) decomposes progressively through Guinier–Preston (GP) zones, metastable η′ ($MgZn_2$-based) precipitates, and finally the equilibrium η ($MgZn_2$) phase. Peak strength is achieved at the η′ stage, while overaging — either intentional or thermally induced — promotes the formation of coarser equilibrium η precipitates at the expense of mechanical performance. The incorporation of copper into Al-Zn-Mg alloys creates Al-Zn-Mg-Cu alloys, noted for their even greater strength levels. With ultimate tensile strength surpassing that of 2XXX series alloys, these copper-enriched alloys are classified as ultra-high-strength aluminum alloys. One defining feature is their high yield strength, which closely approaches their tensile strength, culminating in remarkable specific strength. However, this improvement comes with trade-offs, including reduced ductility and low strength at elevated temperatures. As a result, these alloys are best suited for load-bearing structural applications operating at room temperature or below 120°C. Despite the compromises in ductility and thermal stability, they retain favorable attributes such as good workability, fracture toughness, and corrosion resistance (Marlaud et al., 2011; Zhou et al., 2021). Collectively, the Al 7XXX alloy family represents critical materials with high strength and toughness. They are prized for their exceptional specific strength and stiffness alongside excellent toughness and advantageous processing and suitability for solid-state welding properties. Due to their proven reliability and performance, these alloys find widespread use in the manufacture of essential aircraft components, including frames, spars, and stringers, as given in Table 3 (Jeshvaghani et al., 2012; Zhou et al., 2021).

FRICTION STIR WELDING OF 7XXX ALUMINUM ALLOYS: PROCESS FUNDAMENTALS, MICROSTRUCTURAL ZONES AND INDUSTRIAL APPLICATIONS

Friction Stir Welding (FSW) is a significant solid-state joining method, particularly suited for low-melting-point alloys like aluminum, due to the absence of melt pool formation. This process employs a rotating tool consisting of a shoulder and a probe. Heat generated through the frictional contact of the shoulder induces localized softening, faciliating plastic material flow around the tool from the advancing side to the retraining side. Figure 1 provides a schematic representation of the FSW process. The interaction between the shoulder and probe governs mechanical phenomena such as plastic deformation and material flow, which occur alongside accompanying thermal cycles. These intricately linked thermo-mechanical processes result in a distinct weld cross-section comprising four main regions: BM, HAZ, TMAZ,and SZ (K. Q. Wang et al., 2024). For aluminum alloys that can undergo heat treatment, examining precipitation changes within these regions is vital for understanding how precipitate evolution affects the weld's overall mechanical performance.

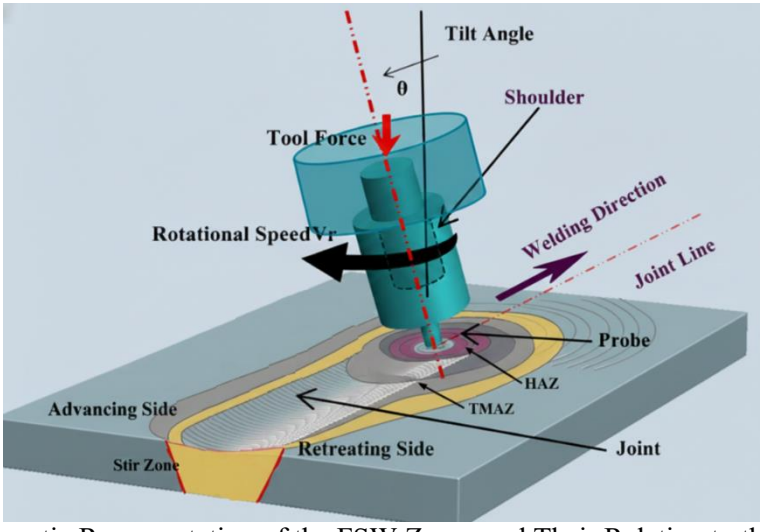

Figure 1. Schematic Representation of the FSW Zones and Their Relation to the Original BM

Material joining is achieved below the melting point, effectively preventing the formation of undesirable microstructures commonly observed in fusion welding. This process results in superior mechanical properties within the weld zone, which is particularly advantageous for heat-treatable lightweight alloys. Friction stir welding (FSW) produces joints with improved mechanical performance, including reduced residual stresses, the elimination of microdefects, and excellent dimensional stability (De Backer et al., 2014; G. Liu et al., 1997; Mishra & Ma, 2005; K. Q. Wang et al., 2024). Under optimized conditions, FSW has been reported to improve tensile strength, ductility, and fracture toughness relative to conventional fusion welding in some 7XXX series aluminum alloys (Ahmed et al.,

2023; Habba et al., 2023; K. Q. Wang et al., 2024). However, the magnitude of these improvements strongly depends on alloy composition, temper condition, and processing parameters. By addressing the challenges associated with welding lightweight materials, FSW significantly expands the possibilities for material selection in structural design. The microstructure of a weld is intrinsically influenced by the intricate interaction between thermal factors, particularly the rates of heating and cooling, and mechanical factors, such as plastic deformation and material flow. The thermal cycle experienced during welding often drives significant microstructural transformations, including the coarsening or dissolution of strengthening precipitates within the material, as noted in multiple studies (Ren et al., 2008; Sivaraj et al., 2021; Upadhyay & Reynolds, 2010; K. Q. Wang et al., 2024). These changes can result in a marked reduction in joint strength and the localized formation of softened regions. Consequently, a detailed examination of the precipitation behavior of strengthening phases within the weldment is essential.

Friction stir welds, in contrast to fusion welds, exhibit a distinctly unique microstructural profile. Their structure comprises four main zones, which are clearly distinguishable in the transverse cross-section (see Figure 2).

- **Base Material (BM)**: The base material refers to the unaffected parent metal that lies far from the weld center. This region is not exposed to significant heat or plastic deformation, allowing it to maintain its original microstructure and mechanical properties.
- **Heat-Affected Zone (HAZ)**: Positioned adjacent to the BM, the HAZ experiences the thermal effects of welding without any plastic deformation. However, the heating process can induce changes in the microstructure, such as modifications in the distribution of precipitates in age-hardenable alloys. These alterations can impact mechanical properties like hardness and strength, with their severity depending on factors such as peak temperature, thermal history, and the particular alloy involved.
- **Thermo-Mechanically Affected Zone (TMAZ)**: This zone undergoes both heat exposure and plastic deformation as a result of tool movement during the welding process. The grains in this region become deformed and elongated, though full recrystallization is not typically achieved. In heat-treatable aluminum alloys, the TMAZ is often identified as the weakest region due to the combined effects of precipitate coarsening caused by heat and the incomplete restoration of microstructure. As a result, tensile failures in friction stir welding (FSW) joints frequently originate from this zone.
- **Stir Zone (SZ) / Nugget Zone (NG)**: Situated at the core of the weld, this zone is characterized by intense plastic deformation, material mixing, and frictional heat. The extreme thermo-mechanical conditions lead to the formation of a fine-grained, recrystallized structure. The boundary between the stir zone and the TMAZ can vary in sharpness depending on its location within the weld, often appearing more defined on the Advancing Side (AS) compared to the Retreating Side (RS).

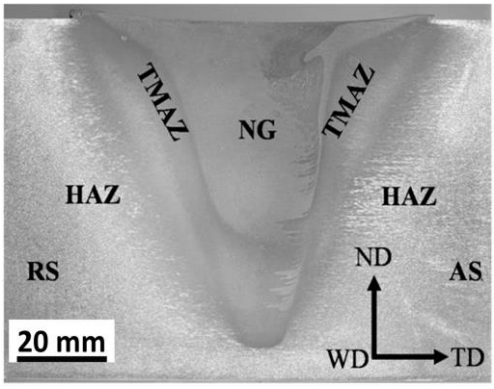

Figure 2. Transverse Cross-Section Optical Macrograph of Friction-Stir-Welded 75 mm-Thick AA6082, Clearly Illustrating the Four Distinct Microstructural Zones: BM, HAZ, TMAZ and SZ. The Figure is Oriented Relative to the Transverse Direction (TD), Welding Direction (WD), and Normal Direction (ND) (Ahmed et al., 2023).

In heat-treatable aluminum alloys, the thermal activity during friction stir welding (FSW) induces substantial metallurgical transformations throughout the joint. These include precipitate dissolution, growth, or changes—such as transitioning from peak-aged to overaged states—which are the main factors contributing to the characteristic softening observed in FSW joints. In the case of Al-Zn-Mg (7xxx series) alloys, the mechanical performance is largely dictated by fine metastable η′ ($MgZn_2$-based) precipitates. As a result, the hardness distribution across a

friction stir weld directly reflects the impact of the welding thermal cycle on these precipitates, including their type, size, arrangement, and volume fraction within each weld zone (K. Q. Wang et al., 2024).

FSW was initially developed to address the challenges of joining high-strength aluminum alloys from the 2XXX and 7XXX series, which were previously considered "non-weldable" using conventional fusion welding techniques (Charit & Mishra, 2005). Since its inception, FSW has gained wide acceptance across various industries such as aerospace, automotive, railway, and marine sectors (Ahmed et al., 2023; Boldsaikhan et al., 2019; Gomez & Smith, 2019; Meisnar et al., 2019; Threadgill et al., 2009; G. Q. Wang et al., 2018; G. Q. Wang et al., 2020). Its success in replacing traditional manufacturing methods has been particularly evident in aerospace applications:

- **Aerospace Structures**: FSW has been employed to construct large-scale fuel tanks, with its first significant application seen in the Delta II and Delta IV rockets, where it replaced traditional fusion welding techniques. Leading aircraft manufacturers are continuing efforts to replace rivets in primary structural components with FSW (Ahmed et al., 2023; Christner et al., 2003; Shepherd, 2003).
- **Aircraft Production**: The Eclipse 500 business jet became a trailblazer in this regard, utilizing FSW for joining components such as upper and lower wing skins, fuselage panels, and engine beams. This innovation achieved joining speeds up to 60 times faster than manual riveting while delivering significant cost reductions and improved quality (Ahmed et al., 2023; Christner et al., 2003).
- **Space Launch Systems:** NASA's Space Launch System (SLS) core stage includes the thickest aluminum structures ever assembled using FSW. Among these is a 39-meter-long liquid hydrogen tank, constructed in a dedicated 52-meter-high facility (Ahmed et al., 2023; Kallee, 2010; Meng et al., 2021; Mishra & Ma, 2005). Similarly, ISRO has integrated FSW into its production of rocket propellant tanks, leading to enhanced efficiency and greater payload capacities (Rajan & Prasad, 2023).
- **Applications Beyond Aluminum**: While tool material limitations persist for high-melting-point alloys, advancements have been made in applying FSW to materials like Ti-6Al-4V for spacecraft components, resulting in reduced lead times and costs (Meisnar et al., 2019). Additionally, FSW demonstrates benefits over other solid-state joining methods, such as accumulative roll bonding (Rahmatabadi et al., 2020; Rahmatabadi et al., 2021). It offers versatility in producing various joint types, including butt, lap, T-shaped, and corner joints (Ahmed, Habba, et al., 2021; Ahmed, Jouini, et al., 2021; Ahmed et al., 2023; Ahmed, Seleman, et al., 2021; Lohwasser & Chen, 2010). Furthermore, the core principles of FSW are being adapted for solid-state additive manufacturing under different configurations (Yu et al., 2018).

Aluminum alloys are extensively employed in aerospace applications due to their unique blend of low density, high strength, excellent workability, and resistance to corrosion, all complemented by their wide availability (Hatch, 1984; Mouritz, 2012; IJ Polmear, 1995). Their primary advantage lies in their lightweight nature, weighing roughly one-third as much as steel, which significantly boosts aircraft fuel efficiency and payload capacity, relegating steel to roles where extremely high strength is a necessity, such as components in high-speed aircraft. As a result, modern aircraft heavily utilize aluminum in critical structures including wing skins, the fuselage, and rudders. Additionally, all current spacecraft incorporate Al alloys extensively, accounting for 50% to 90% of their material composition. This reliance is evidenced by their historical application in notable programs like Apollo spacecraft, Space Shuttles, Skylab, and the International Space Station (Mouritz, 2012).

In recent decades, the expanding demands of the aerospace sector have driven the need for materials with stringent specifications, particularly low density, enhanced durability, and exceptional fatigue resistance. As a response, Aluminum (Al) alloys have emerged as the leading candidates to meet these requirements. Although numerous aluminum alloy compositions exist (Campbell, 2008; Hatch, 1984; IJ Polmear, 1995; Ian Polmear, 2005), only specific types are suitable for aerospace applications. Table 2 summarizes the chemical compositions and primary aerospace applications of the most widely used 7XXX series alloys, while Table 3 provides a more comprehensive overview incorporating temper characteristics and specific structural uses.

Al 7XXX series alloys are particularly esteemed for their excellent strength-to-weight ratio and natural aging capability, making them widely applicable in various aircraft structures. Extensive research has examined their friction stir welding (FSW) behavior. Kimura et al. (Kimura et al., 2005) observed that the FSW mechanisms of AA7075 share similarities with those of low-carbon steel, attributed to the comparable strength properties between the materials. Process optimization studies have yielded valuable insights; Fu et al. (Fu et al., 2011) demonstrated

that hot water cooling produces optimal mechanical properties during FSW of AA7050 butt joints, achieving joint efficiency values of 92% for ultimate tensile strength (UTS) and 150% elongation relative to the base material. Furthermore, microstructural analysis by Venugopal et al. (Venugopal et al., 2004) on friction stir welded AA7075-T6 revealed that the refined grain structure within the weld metal (stir zone) greatly improved its resistance to pitting corrosion when compared to the TMAZ and the BM.

CONCLUSIONS AND FUTURE PERSPECTIVES

Friction Stir Welding (FSW) has emerged as a highly effective solid-state joining technique for high-strength 7XXX series aluminum alloys, overcoming many of the metallurgical limitations associated with conventional fusion welding. By operating below the melting temperature, FSW suppresses solidification-related defects; however, the process introduces complex thermo-mechanical cycles that significantly influence microstructural stability and precipitation behavior.

The mechanical performance of FSWed 7XXX alloys is primarily governed by the evolution of metastable η′ ($MgZn_2$-based) precipitates, which constitute the principal strengthening phase in these precipitation-hardened systems. The welding-induced thermal exposure leads to partial or complete precipitate dissolution in the SZ, while overaging and precipitate coarsening frequently occur in the HAZ. As a result, a characteristic softening profile develops across the weld cross-section, with the HAZ or TMAZ often representing the weakest region controlling joint efficiency.

The extent of softening is strongly dependent on process parameters such as rotational speed, traverse speed, heat input, and cooling conditions. Optimized parameter combinations can promote dynamic recrystallization in the SZ while minimizing excessive precipitate coarsening in thermally affected regions. In this context, controlling thermal exposure time and cooling rate (e.g., via forced air or liquid cooling strategies) is critical to limiting precipitate degradation and preserving mechanical strength.

Although substantial progress has been achieved in understanding FSW of 7XXX alloys, several research gaps remain. A more quantitative correlation between thermal cycles, precipitation kinetics, and local mechanical response is still needed. Advanced in-situ characterization techniques (such as high-energy-synchroton X-ray diffraction and small-angle neutron scattering) and integrated thermo-metallurgical modeling approaches could further clarify the mechanisms governing weld zone heterogeneity and long-term structural reliability.

Overall, the successful application of FSW to aerospace-grade 7XXX aluminum alloys depends on a precise balance between heat generation, plastic deformation, and precipitation stability. A mechanistic understanding of these interrelated phenomena is essential for improving joint efficiency, minimizing softening effects, and ensuring reliable structural performance in demanding engineering applications.

Artificial Intelligence Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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