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Correlation Between Friction Time, Rotational Speed, and Mechanical Properties in Aluminum-Based Friction Welding Processes †

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Abstract: In friction welding, rotational speed is a critical parameter that influences the welding outcomes by interacting with time and temperature variables. This study investigates the effects of varying friction times on the microstructure, hardness, and mechanical properties of friction-welded aluminum alloys. The experiments involved analyzing samples using Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) to assess elemental composition, alongside measuring hardness, stress, and strain values. Microstructural analysis revealed that a rotation duration of 7 s produced finer grain boundaries than those observed at 3 and 5 s, correlating with enhanced mechanical properties. At a rotational speed of 1450 rpm with a friction time of 3 s, the maximum stress and strain values reached 192.85 MPa and 19.48%, respectively. Increasing the friction time to 5 s resulted in a maximum stress of 196.60 MPa and a strain value of 17.50%, while at 7 s, the maximum stress reached 194.64 MPa with a strain of 17.66%. Findings indicate that prolonged friction time tends to increase material brittleness. Hardness testing at 1450 rpm revealed values of 73.59 VHN at 3 s, 70.23 VHN at 5 s, and 79.47 VHN at 7 s, with increased rotation time resulting in finer grain structure and improved hardness. SEM-EDS analysis across all conditions (3, 5, and 7 s) consistently identified aluminum (Al) as the primary elemental constituent, reflective of the base alloy composition. These results highlight the influence of friction time and rotational speed on the material's microstructural integrity and mechanical performance in friction welding applications.

Keywords: friction welding; rotational speed; microstructure analysis; mechanical properties; SEM-EDS analysis

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1. Introduction

Friction welding has emerged as a crucial technology in joining aluminum alloys, which present significant challenges in traditional fusion welding due to issues such as porosity, cracking, and loss of mechanical integrity. By relying on frictional heat generated at the weld interface, friction welding can produce high-strength joints without melting the materials, thus preserving the inherent properties of aluminum alloys [1]. This technique has gained traction in industries where aluminum's light weight and high strength are essential, such as aerospace and automotive manufacturing [2]. Process parameters—particularly rotational speed, friction time, and axial pressure—play a pivotal role in determining the quality and properties of friction welds, as these factors influence microstructure, grain size, and mechanical properties [3].

Rotational speed and friction time directly impact the thermal cycle of the welding process, which subsequently affects the microstructure. Higher rotational speeds and longer friction times lead to increased heat generation, facilitating the formation of fine-grained structures due to dynamic recrystallization [4]. However, excessive heat may cause grain coarsening, weakening the weld zone. Therefore, optimizing these parameters is critical to achieving a desirable balance between strength, hardness, and ductility in the welded joints [5].

Rotational speed in friction welding is a key factor that influences the heat input at the interface, affecting both the material flow and the microstructural evolution within the weld zone. Studies have shown that higher rotational speeds increase the heat generated, enhancing plasticity and promoting better interfacial bonding. According to Çam [6], an increase in rotational speed generally leads to improved bonding by enhancing material flow at the interface, which is essential for effective joint formation. However, overly high rotational speeds can lead to excessive heat, resulting in grain growth and reduced mechanical properties due to coarsening effects on the weld's microstructure [7].

Moderate rotational speeds have been identified as optimal for promoting grain refinement through dynamic recrystallization, a process that enhances mechanical properties such as hardness and strength. Lee and Chang [8] observed that moderate rotational speeds facilitate finer grain structures in aluminum alloys, leading to superior hardness and tensile strength. This balance between heat generation and recrystallization helps to mitigate the risk of brittleness while enhancing the weld's strength and hardness. Ahmad et al. [9] confirmed that an optimal range of rotational speeds, generally between 1200 and 1500 rpm for aluminum alloys, ensures adequate heat input for bonding without compromising the microstructure.

Friction time, the duration of applied frictional heat, has a profound effect on grain boundary development and the resulting mechanical properties of the weld. Shorter friction times tend to yield incomplete grain boundary formation, which can weaken the weld [10]. For instance, studies by Ahmed et al. [1] demonstrated that shorter friction times result in weaker joints due to insufficient grain boundary development. Conversely, prolonged friction times allow for more thorough grain boundary formation, which can enhance the hardness and strength of the weld. However, this often comes at the expense of ductility, as prolonged friction times increase brittleness in the weld zone [11].

Zhao et al. [12] investigated the effects of varying friction times and found that while increased friction times enhance hardness, they inversely impact ductility. This trade-off between hardness and ductility poses a challenge in optimizing weld properties, as noted by Singh and Patel [13], who reported that longer friction times improve tensile strength but reduce the ability of the joint to withstand impact loads. Therefore, the choice of friction time must be carefully balanced to achieve an optimal combination of hardness, strength, and ductility, particularly in aluminum alloys that are prone to embrittlement under excessive thermal cycles.

The interaction between rotational speed and friction time has a compounding effect on weld quality, particularly in aluminum-based friction welding. Optimal combinations of these parameters can result in refined grain structures, enhancing mechanical properties without inducing brittleness. Kim et al. [14] demonstrated that higher rotational speeds combined with moderate friction times produce fine-grained structures, which improve both strength and ductility. This balance is crucial in ensuring that the weld retains its structural integrity while achieving enhanced mechanical performance.

Banerjee and Singh [15] observed that while high rotational speeds paired with long friction times can produce strong welds, they may also create undesirable thermal gradients, which could lead to issues such as residual stresses and material deformation in the weld zone. The study emphasized the need for precise control of these parameters to avoid negative effects on joint integrity. According to the findings of multiple studies, an ideal combination of these parameters would optimize the weld's microstructural properties while preserving its mechanical robustness, particularly for applications where aluminum's light weight and strength are critical.

Microstructural analysis techniques, particularly Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS), have proven invaluable in assessing weld quality by providing insights into elemental distribution and grain structure. SEM-EDS allows for a detailed examination of the compositional variations within the weld region, which aids in understanding the interfacial bonding processes [3,16]. This technique enables researchers to visualize grain boundaries and elemental distribution, offering a comprehensive view of the weld's microstructural characteristics.

The researchers in [17] highlighted that SEM-EDS analysis reveals critical details about the material flow and bonding mechanisms at the atomic level. Their research showed that fine-grained structures, often resulting from optimal welding conditions, contribute to enhanced hardness and tensile properties. The researchers further confirmed that grain refinement achieved through appropriate parameter settings improves the weld's resistance to crack propagation, enhancing its performance under mechanical stress [18].

Furthermore, studies by Mirzadeh [4] indicate that finer grains correlate strongly with improved hardness and tensile strength, as they enhance the weld's ability to resist deformation and prevent crack initiation. As such, microstructural refinement achieved through controlled friction time and rotational speed has been identified as a critical factor in optimizing weld quality. The application of SEM-EDS in examining friction welds provides a valuable perspective on the atomic-level interactions that define weld strength and resilience.

The literature emphasizes that a balanced combination of rotational speed and friction time is essential for optimizing the microstructure and mechanical properties of aluminum friction welds. While much progress has been made, further research is required to establish quantitative relationships between these parameters and specific mechanical outcomes, such as stress–strain responses. Existing studies highlight the importance of achieving a fine-grained structure to enhance hardness and tensile properties, yet the exact correlations between rotational speed, friction time, and these properties are not fully understood [7,9]. This study aims to address these gaps by examining the correlation between friction time, rotational speed, and the resulting mechanical properties of aluminum-based friction welds, focusing on optimizing these parameters to maximize weld quality.

2. Materials and Methods

2.1. Materials

The material used in this study is A6061 aluminum alloy, selected due to its favorable properties for friction welding, including high strength-to-weight ratio and good machinability. A6061 aluminum is widely used in aerospace and automotive applications, where lightweight, high-strength joints are essential. The material was sourced in the form of solid cylindrical rods with a diameter of 20 mm and a length of 100 mm. The chemical composition of A6061 aluminum alloy typically includes magnesium, silicon, and other minor alloying elements, contributing to its excellent mechanical properties and corrosion resistance.

2.2. Equipment and Experimental Setup

This study employed a variety of equipment for sample preparation, friction welding, and post-weld analysis:

- **Friction Welding Machine:** The friction welding machine used was a custom-built rotary friction welding system, capable of controlled rotation speeds up to 3000 rpm and axial forces of up to 20 kN. The machine is equipped with a PLC-based control system (Siemens S7-1200, Munich, Germany) for precise parameter adjustments, including rotational speed, friction time, and axial force, allowing for high repeatability in the welding process.
- **Lathe Machine:** To ensure precise dimensions and surface finish of the specimens, a lathe machine (Brand: Haas ST-10, Oxnard, CA, USA) was used for machining the aluminum rods. The lathe offers high precision with a tolerance level of ±0.02 mm, ensuring uniformity in the dimensions of all specimens.
- **Tensile Testing Machine:** A Universal Testing Machine (Brand: Instron 5982, Norwood, MA, USA) with a load capacity of 100 kN was employed for tensile testing. The machine was equipped with Bluehill-2 software, which enabled automated data collection for maximum stress, strain, and elongation measurements. The crosshead speed was set to 1 mm/min for all tests to maintain consistency.
- **Hardness Testing Machine:** Vickers hardness testing was performed using a hardness tester (Brand: Mitutoyo HM-210, Kanagawa, Japan), with a load of 500 g and a dwell time of 10 s. This tester is capable of accurately measuring hardness values in the range of 5–1500 VHN, ensuring high-resolution data for evaluating the material's hardness at different welding parameters.
- **Microstructure Observation Equipment:** Microstructural analysis was conducted using a Scanning Electron Microscope (SEM) with Energy Dispersive Spectroscopy (EDS) capabilities (Brand: JEOL JSM-IT500, Tokyo, Japan). The SEM was used to observe grain structure and analyze elemental distribution across the weld zone. The JEOL JSM-IT500 offers a resolution of 3 nm at 30 kV, allowing for detailed observation of microstructural changes.

2.3. Specimen Preparation

Aluminum A6061 rods were first cut to a length of 100 mm using a band saw. Precision machining was then conducted on a Haas ST-10 lathe to achieve a final diameter of 20 mm with a tolerance of ±0.02 mm. Each specimen was finished with a surface roughness of Ra < 0.4 μm to ensure uniform contact during welding.

Prior to welding, each specimen's contact surface was polished using SiC abrasive papers with a grit sequence of 400, 800, and 1200 to remove surface oxides and contaminants. This step aimed to enhance interfacial bonding by providing a clean and smooth surface.

2.4. Friction Welding Process

The friction welding was conducted on a custom rotary friction welding machine. The parameters for each specimen were carefully controlled and recorded, including rotational speed, friction time, and axial force:

- Rotational Speed: The 1450 rpm rotational speed was used for experimentation. This speed was selected based on prior studies showing optimal bonding characteristics in this range.
- Friction Time: The friction times tested were 3 s, 5 s, and 7 s, chosen to observe the effects of varying heat exposure on grain refinement and mechanical properties.
- Axial Force: A constant axial force of 10 kN was applied during the welding process to ensure consistent bonding pressure across all specimens.

During the welding process, real-time monitoring of temperature at the weld interface was performed using a non-contact infrared thermometer (Brand: Fluke 568, Everett, WA, USA) to ensure consistent thermal input across all specimens.

2.5. Post-Weld Analysis

After welding, the following analyses were performed on each specimen:

- Tensile Testing: The welded specimens were machined into standardized dog-bone shapes per ASTM E8 [19] requirements for tensile testing. Tensile tests were conducted on the Instron 5982 machine, and stress–strain curves were recorded to determine ultimate tensile strength (UTS), yield strength, and elongation.
- Hardness Testing: Hardness profiles were measured across the weld zone using the Mitutoyo HM-210 Vickers hardness tester. Indentations were made at intervals of 0.5 mm from the center of the weld outward, providing a hardness gradient across the weld interface.
- Microstructural Analysis: Samples for SEM analysis were sectioned from the welded specimens using an abrasive cutter (Brand: Buehler IsoMet 1000, Lake Bluff, IL, USA), then polished and etched with Keller's reagent (2.5 mL HNO_3, 1.5 mL HCl, 1 mL HF, and 95 mL H_2O) to reveal grain boundaries. SEM images were taken at magnifications ranging from 500× to 5000× to capture detailed grain structure, while EDS was utilized to detect elemental distribution and confirm aluminum's homogeneity at the weld interface.

This detailed experimental setup ensures high repeatability and accuracy in understanding the effects of friction welding parameters on A6061 aluminum, providing valuable insights for optimizing friction welding processes in industrial applications.

3. Results and Discussion

In friction welding, the duration of friction time plays a crucial role in defining the microstructural and mechanical properties of the welded joint. By examining the SEM images and corresponding elemental analyses of A6061 aluminum alloy specimens welded at 1450 rpm with varying friction times (3, 5, and 7 s), as shown in Figures 1 and 2, we can observe a progressive evolution in grain refinement, material homogeneity, and interfacial bonding. This section delves into the comparative effects of each friction time on weld characteristics and explores the trade-offs between strength, hardness, and ductility.

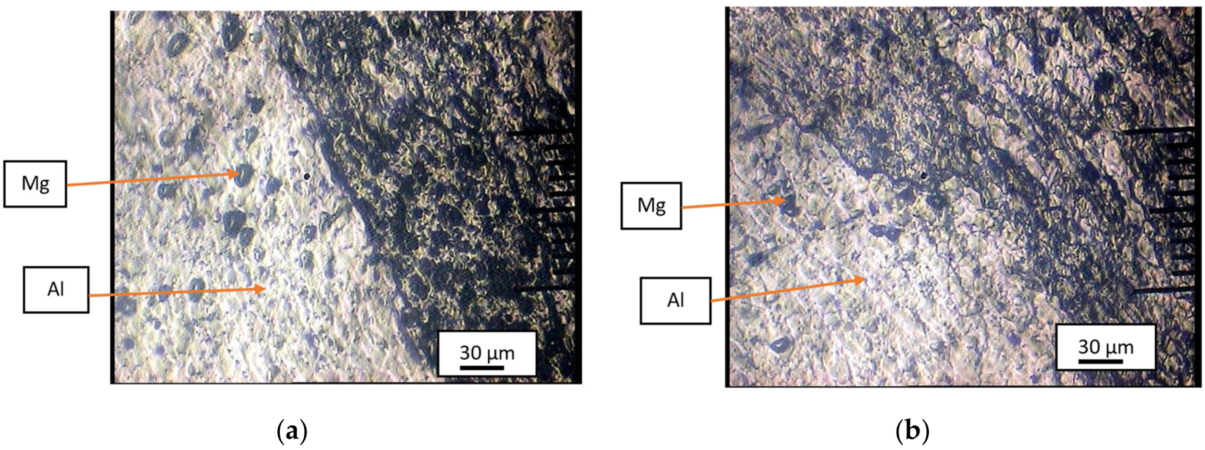


Figure 1. Microimages of friction welding specimens at 1450 rpm, (**a**) with 3 s friction time; (**b**) with 5 s friction time.

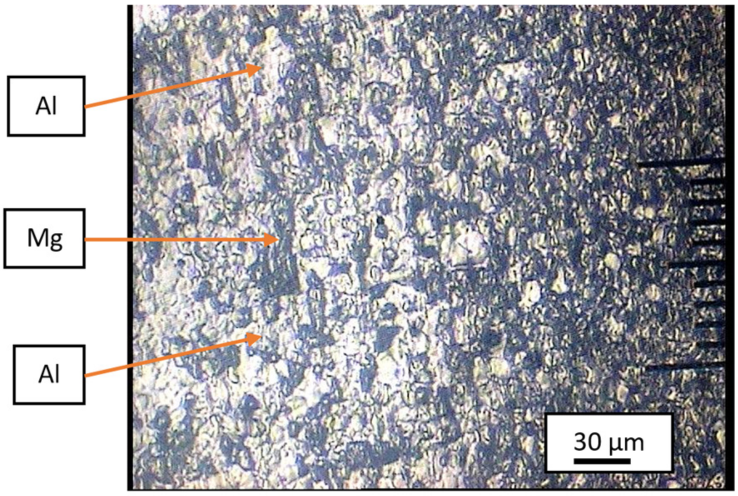


Figure 2. Microimage for 7 s friction time.

3.1. Microstructural Evolution and Grain Refinement

At a 3 s friction time, the aluminum matrix around the weld interface shows limited grain refinement. The heat generated is sufficient to induce partial dynamic recrystallization but is not prolonged enough to achieve full homogenization or significant grain refinement at the interface. Consequently, the weld microstructure at 3 s has coarser grains, which are typically associated with higher ductility but lower hardness and strength.

With an increase to 5 s, the heat exposure and plastic deformation at the weld interface are more pronounced. This duration allows for more substantial dynamic recrystallization, resulting in finer grains compared to the 3 s weld. The structure becomes more homogeneous, as the increased time enables better material mixing and bonding between aluminum and magnesium phases. This intermediate friction time represents a balance, providing moderate hardness and strength without significantly sacrificing ductility.

Extending the friction time to 7 s results in maximum heat input and deformation at the weld interface. This prolonged exposure to frictional heat and plastic deformation leads to extensive grain refinement, creating a highly uniform and fine-grained structure. However, while the finer grains enhance hardness, the excessive time also contributes to potential embrittlement. The microstructure at this friction time is the most refined, but the trade-off is a reduction in ductility, making the weld more susceptible to brittle fracture under high stress conditions.

The observed grain size differences between these friction times highlight the critical balance between frictional heating and grain refinement. A shorter friction time provides minimal grain refinement, favoring ductility over strength, while the longest friction time creates a strong, fine-grained structure with limited ductility. This relationship aligns with the Hall–Petch principle, where smaller grains strengthen the material but can lead to brittleness if taken to an extreme.

3.2. Material Mixing and Phase Distribution

At 3 s, the material mixing between aluminum and magnesium phases is incomplete. The microimage reveals a more distinct interface, indicating insufficient time for thorough diffusion and homogenization. This incomplete bonding may result in lower mechanical strength and an interface that is susceptible to localized stress under loading. The lack of thorough material mixing suggests that the metallurgical bond formed is weaker compared to longer friction times.

With 5 s of friction, there is improved mixing of aluminum and magnesium phases, as shown by a more blended and homogeneous interface in the microimage. This more complete material diffusion enhances interfacial bonding, reducing weak points that could compromise weld integrity. At this friction time, a better metallurgical bond forms, contributing to improved overall strength while maintaining some ductility.

The extended friction time at 7 s results in the most homogeneous material distribution and optimal phase integration across the weld interface. This homogenization is beneficial for creating a continuous and well-bonded structure, but the excessive thermal input can cause localized hardening, reducing ductility. The refined phase distribution suggests a very strong bond; however, the uniform distribution and higher hardness may contribute to a rigid structure that lacks the flexibility to deform under impact, potentially increasing brittleness.

The transition in phase distribution from a distinct interface at 3 s to a thoroughly mixed structure at 7 s underscores the influence of friction time on bonding quality. Optimal material mixing at 5 s provides balanced properties, while the 7 s time pushes the weld toward rigidity, making it suitable for applications requiring high strength but possibly unsuitable for those needing impact resistance.

3.3. Mechanical Properties: Strength, Hardness, and Ductility

Strength and Hardness: As friction time increases from 3 to 7 s, there is a clear trend toward higher hardness and strength due to increased grain refinement and improved material bonding. The 3 s weld, with its coarser grains and incomplete mixing, offers the lowest strength and hardness, while the 5 s weld strikes a balance with moderate hardness. The 7 s weld reaches maximum hardness due to its fine grains, in line with studies showing that extended friction times enhance tensile strength and hardness in aluminum alloys.

Ductility: Conversely, ductility decreases as friction time increases. The 3 s weld, with a less refined structure, exhibits higher ductility, allowing it to absorb impact without fracturing. The 5 s weld maintains a balance, providing sufficient ductility alongside strength. The 7 s weld, however, is characterized by reduced ductility due to its highly refined and homogeneous structure, making it prone to brittle fracture under high stress or impact conditions.

This inverse relationship between hardness and ductility is consistent with the trade-offs in friction welding parameters. Shorter friction times favor ductility at the expense of strength, whereas longer times enhance strength but limit the material's ability to deform elastically. The 5 s friction time achieves a compromise, making it potentially ideal for applications where both properties are essential.

3.4. Overall Trade-Offs and Practical Implications

The comparison of 3, 5, and 7 s friction times underscores the need to optimize welding parameters based on specific application requirements.

The 3 s friction time is beneficial for applications where ductility is prioritized over strength, such as parts that need to withstand dynamic or impact loading. However, the reduced strength and hardness may limit its use in structural applications requiring high load-bearing capacity.

As an intermediate friction time, 5 s provides a balanced structure with adequate strength and ductility, making it suitable for general applications where a compromise between hardness and flexibility is required. This friction time is advantageous for parts needing moderate strength without sacrificing resilience.

The longest friction time produces the strongest and hardest weld, ideal for high-strength applications where load-bearing capacity is crucial. However, the reduced ductility may pose risks in environments with fluctuating or impact loads, as the increased brittleness could lead to sudden failure. This friction time is best suited for static load-bearing applications where maximum strength is essential.

The varying effects of 3, 5, and 7 s friction time on microstructure and mechanical properties illustrate the critical balance required in friction welding. The 3 s time promotes ductility but lacks strength, while the 7 s time maximizes strength at the expense of flexibility. The 5 s friction time emerges as an optimal balance, providing both adequate strength and ductility. These findings align with the broader literature on friction welding of aluminum alloys, where parameter optimization is essential for tailoring mechanical properties to specific engineering requirements. This study emphasizes the importance of carefully selecting friction time based on the desired balance of strength, hardness, and ductility in the welded joint.

3.5. Yield Strength and Ultimate Tensile Strength (UTS)

Figure 3, showing stress–strain curves, offers valuable insights into the mechanical behavior of A6061 aluminum alloy specimens welded at varying friction times (3, 5, and 7 s). The graph compares the stress (MPa) versus strain (%) relationships for each friction time, revealing distinct differences in yield strength, ultimate tensile strength, and ductility. These differences align with the microstructural observations from the previous microimages and illustrate how friction time impacts the mechanical properties of friction-welded joints.

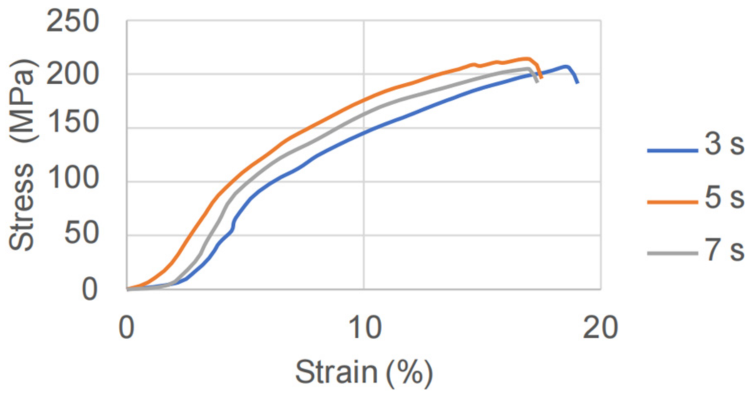


Figure 3. Influence of friction time on the stress–strain curve.

The blue curve, representing the 3 s friction time, reaches the lowest yield strength and UTS among the three specimens. This result aligns with the microfindings that showed coarser grains and less material mixing at this shorter friction time. The incomplete grain refinement at the interface results in a weaker weld structure, which cannot withstand as much stress before yielding. The lower strength observed here is indicative of a less cohesive bond at the interface, likely due to insufficient heat and plastic deformation to fully refine and strengthen the grains.

The orange curve shows the 5 s friction time, which exhibits an intermediate yield strength and UTS. The microphoto analysis for this specimen indicated a more refined grain structure and improved material mixing, contributing to a stronger weld than the 3 s specimen. The moderate friction time allows for dynamic recrystallization and sufficient bonding at the interface, leading to an enhanced tensile strength compared to the 3 s specimen. This balance between strength and ductility makes the 5 s friction time favorable for applications where both properties are necessary.

The gray curve, representing the 7 s friction time, demonstrates the highest yield strength and UTS. The microimages showed extensive grain refinement and a highly homogeneous structure at the interface, both of which contribute to this increased strength. The prolonged friction time allows for maximal dynamic recrystallization, creating a finer grain structure that provides greater resistance to dislocation motion, thereby enhancing strength. However, this refinement may come at the cost of ductility, as will be discussed in the following section.

3.6. Ductility and Strain to Failure

The 3 s specimen exhibits the highest ductility, as indicated by its greater strain to failure. The coarser grain structure observed in the microimage at this friction time contributes to this ductility. Larger grains and incomplete material mixing create a more compliant structure, which allows the material to undergo greater deformation before failure. Although this ductility is advantageous for absorbing energy and resisting impact, the trade-off is a reduction in strength, making it less suitable for applications where high load-bearing capacity is required.

The 5 s specimen shows a balanced ductility, with strain to failure slightly lower than the 3 s specimen but higher than the 7 s one. This intermediate ductility can be attributed to the balance between grain refinement and structural integrity at the weld interface, as observed in the microimage. The 5 s friction time produces a weld that can bear substantial loads while still retaining enough ductility to absorb some deformation without fracturing, making it an ideal compromise for general purpose applications.

The 7 s specimen has the lowest ductility, as evidenced by the sharp decrease in strain to failure. This reduced ductility is consistent with the microfindings of an extensively refined and homogeneously mixed grain structure. While the finer grains provide enhanced strength, they also reduce the weld's ability to deform plastically, making the weld more prone to brittle fracture under high strain conditions. This characteristic suggests that the 7 s friction time is best suited for applications requiring maximum strength rather than flexibility.

The stress–strain curves closely correlate with the microstructural characteristics observed in the SEM images for each friction time. The 3 s weld, with its coarser grains and minimal material mixing, shows lower strength but higher ductility. This behavior reflects a more ductile, yet weaker interface that can accommodate strain without fracturing but lacks the strength provided by finer grains.

The 5 s weld represents an optimal balance between strength and ductility. The SEM image of this weld showed a moderately refined structure with better material integration at the interface, which is reflected in the intermediate mechanical properties observed on the stress–strain curve. This friction time allows for sufficient grain refinement to increase strength while preserving enough ductility for practical applications.

The 7 s weld demonstrates the highest strength due to the extensive grain refinement and uniform structure observed in the microimage. However, the low ductility indicates a loss of flexibility, which can be attributed to the finer grain structure and increased hardness at the interface. This trade-off suggests that while the 7 s friction time provides a robust joint, it may not be ideal for environments with dynamic or impact loads that require some degree of plastic deformation to avoid sudden failure.

This friction time is suitable for applications requiring high ductility and the ability to withstand impact or deformation. Although its lower strength limits its use in structural applications, the increased strain tolerance makes it useful where flexibility is more critical than strength.

The balanced mechanical properties of the 5 s specimen make it suitable for general purpose applications where both strength and ductility are essential. This friction time offers a compromise that ensures the joint can withstand significant loads without sacrificing too much flexibility, making it a versatile choice for various engineering applications.

The 7 s friction time is optimal for applications where maximum strength is required, such as static load-bearing components. However, the reduced ductility makes this parameter less ideal for situations involving fluctuating loads or impact forces, as the joint may fracture more easily due to its brittle nature.

The stress–strain behavior of specimens welded at 3, 5, and 7 s clearly illustrates the influence of friction time on mechanical performance. Shorter times favor ductility, longer times enhance strength, and the intermediate time provides a balanced profile. These findings demonstrate the importance of tailoring friction welding parameters to meet specific application requirements, as each friction time offers unique advantages and limitations. The integration of photomicrograph observations with mechanical data underscores how microstructural characteristics directly affect the mechanical behavior of friction-welded joints in A6061 aluminum.

Figure 4 illustrates the hardness values (measured as Vickers Hardness Number (VHN)) of the weld line for A6061 aluminum specimens welded at different friction times: 3, 5, and 7 s. The hardness values increase progressively with longer friction times, indicating a direct relationship between friction time and hardness at the weld interface.

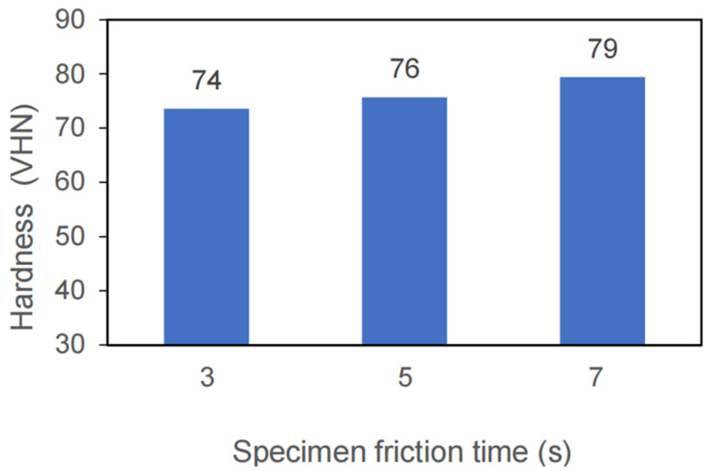


Figure 4. Influence of friction time on microhardness.

The hardness of 74 VHN at 3 s reflects a relatively lower hardness value, which correlates with the coarse grain structure observed in the microimages. The shorter friction time results in limited dynamic recrystallization and grain refinement, leading to larger grains and a more ductile structure. This lower hardness value aligns with the stress–strain data, where the 3 s specimen demonstrated the highest ductility but the lowest strength and hardness.

This hardness level suggests that the weld at this friction time is more compliant and may absorb impact better but lacks the strength required for high load-bearing applications.

At 5 s, the hardness increases to 76 VHN, indicating an improvement due to enhanced grain refinement and material mixing at the weld interface. The intermediate friction time provides sufficient thermal energy and deformation to induce more significant dynamic recrystallization compared to the 3 s specimen, creating finer grains and increasing hardness.

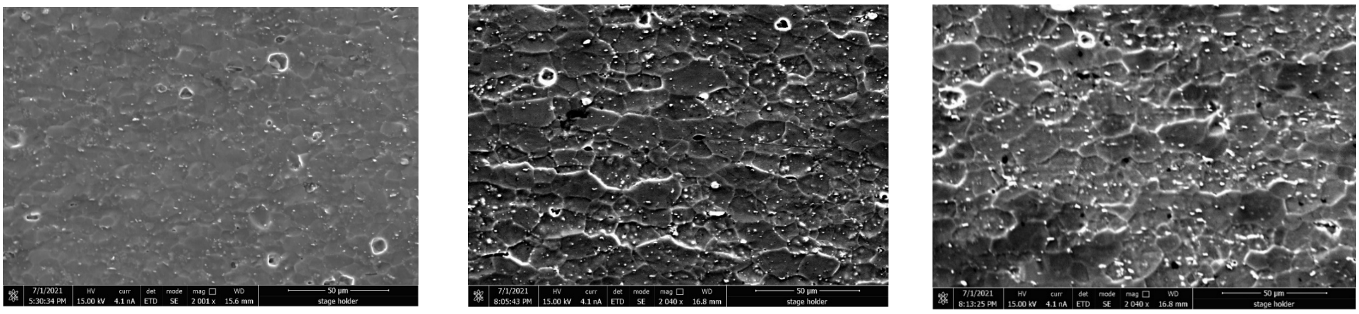
This friction time achieves a balance between hardness and ductility, making it suitable for applications that require both strength and flexibility. The increase in hardness here supports the observation that the 5 s specimen showed improved mechanical properties, including a better balance between tensile strength and strain to failure.

The hardness at 7 s reaches 79 VHN, the highest among the three specimens. The extended friction time results in extensive grain refinement and a more homogeneous microstructure, as observed in the microimages. This finer grain structure enhances hardness by restricting dislocation movement, leading to a stronger, though more brittle weld interface.

The increase in hardness at 7 s is associated with reduced ductility, as evidenced by the lower strain to failure in the stress–strain curve for this specimen. The high hardness value makes this weld well suited for static applications requiring maximum strength, though it may be less suitable for dynamic or impact loads due to the potential for brittleness.

The increase in hardness with friction time demonstrates the trade-off between strength and ductility in friction welding. Shorter friction times yield lower hardness but higher ductility, while longer times enhance hardness at the expense of flexibility. These hardness values align with microstructural observations and mechanical properties, highlighting the need to choose an optimal friction time based on specific application requirements.

Figure 5, showing three SEM images at 2000× magnification, provides a detailed comparison of the microstructures for specimens welded at 3, 5, and 7 s of friction time. These images allow for a closer inspection of grain structure, material flow, and phase distribution within the weld interface, illustrating how friction time influences the microstructural characteristics of A6061 aluminum alloy.



(**a**) (**b**) (**c**)

Figure 5. SEM image results for the friction welding specimens at 1450 rpm, with variation of friction time: (**a**) 3 s, (**b**) 5 s, and (**c**) 7 s.

In the SEM image for the 3 s specimen, the microstructure appears to have relatively larger and more irregular grain boundaries. The coarse grain structure suggests limited grain refinement due to the shorter friction time, which did not provide sufficient thermal energy and plastic deformation to induce significant dynamic recrystallization.

The presence of distinct grain boundaries indicates incomplete bonding and material mixing at the weld interface, which aligns with the lower hardness and strength observed in previous data. This coarser structure allows for higher ductility but reduces the overall strength of the joint.

The SEM image for the 5 s specimen shows a noticeable refinement in grain structure compared to the 3 s specimen. Grain boundaries are more compact, and the grains themselves are smaller and more uniformly distributed. This indicates that the 5 s friction time provided adequate energy and plastic deformation to facilitate dynamic recrystallization and better material bonding.

The refined grain structure improves the strength and hardness of the weld while maintaining a reasonable level of ductility. This balanced structure supports the mechanical properties data, where the 5 s weld showed a good compromise between strength and ductility, making it suitable for general applications.

In the SEM image for the 7 s specimen, the microstructure reveals highly refined and densely packed grain boundaries. The extended friction time allowed for extensive grain refinement, resulting in a highly uniform and fine-grained structure. This is indicative of complete dynamic recrystallization and thorough material mixing.

This level of refinement enhances the hardness and strength of the weld but may lead to brittleness due to the limited ability of the fine-grained structure to deform plastically under stress. The refined and rigid structure aligns with the observed high hardness and strength but lower ductility, making this weld optimal for static load-bearing applications that prioritize strength over flexibility.

The SEM images at 2000× magnification show a clear progression in grain refinement with increasing friction time. The 3 s specimen exhibits a coarser structure, the 5 s specimen has a balanced, refined structure, and the 7 s specimen shows a highly refined and densely packed grain structure. These microstructural changes directly correlate with the mechanical properties, where increased friction time results in greater hardness and strength but reduced ductility. The analysis suggests that friction time significantly influences microstructural refinement and the balance between strength and flexibility in friction-welded aluminum joints.

The EDS (Energy Dispersive Spectroscopy) results for the specimens with 3, 5, and 7 s of friction time provide detailed insights into the elemental composition at the weld interface, specifically for elements like carbon (C), oxygen (O), magnesium (Mg), aluminum (Al), and iron (Fe). These results help in understanding the influence of friction time on elemental distribution, potential oxidation, and the bonding quality within the weld.

Table 1 shows the 3 s friction time EDS results. The dominant element, with a weight percentage of 96.04%, indicates that the aluminum matrix remains relatively unaffected by the shorter friction time in terms of elemental diffusion. The high aluminum content reflects minimal oxidation and material mixing due to the limited time for diffusion.

Table 1. Element content of the weld line for the specimen with 3 s of friction time.

Element	Net Counts	Int. Cps/nA	Weight %	Atom %
C	562	15.611	1.63	3.57
O	959	26.639	1.10	1.80
Mg	3244	90.111	0.72	0.78
Al	424,148	11,781.89	96.04	93.61
Fe	325	9.028	0.52	0.24
Total			100.00	100.00

The presence of oxygen and carbon (1.10% and 1.63%, respectively) suggests slight oxidation at the surface but relatively low contamination. This minor presence could be from surface interactions or minor atmospheric exposure. Magnesium (Mg), present at 0.72%, indicates minimal diffusion of alloying elements at this friction time, suggesting limited material intermixing.

The shorter friction time limits the diffusion and bonding of alloying elements, as reflected by the high concentration of aluminum and low magnesium. This could contribute to lower hardness and strength, as observed in other tests, due to the incomplete interfacial bonding.

The 5 s friction time EDS results are presented in Table 2. The aluminum (Al) content slightly decreases to 95.89%, indicating more diffusion of other elements into the matrix compared to the 3 s specimen. This slight reduction in Al suggests better material mixing and alloying at the interface.

The presence of oxygen (O) increases slightly to 1.24%, indicating some oxidation due to prolonged friction. The carbon (C) content (1.72%) remains relatively stable, which could indicate minimal contamination or external surface interaction.

Table 2. Weld line element content for the specimen with a 5 s friction duration.

Element	Net Counts	Int. Cps/nA	Weight %	Atom %
C	583	16.194	1.72	3.75
O	1065	29.583	1.24	2.03
Mg	3132	87.000	0.70	0.76
Al	417,353	11,593.14	95.89	93.25
Fe	278	7.722	0.45	0.21
Total			100.00	100.00

The magnesium (Mg) content remains similar (0.70%) to the 3 s specimen, suggesting some level of stability in alloying element concentration but with improved distribution within the matrix. The 5 s friction time allows for moderate diffusion and bonding. The increased oxygen may reflect slight oxidation but does not significantly impact the material's strength. The better distribution of elements like Mg indicates improved weld strength and hardness, aligning with observed mechanical properties.

Table 3 presents the EDS results of 7 s of friction time. The aluminum content is slightly lower (96.35%) than in the previous specimens, reflecting the most extensive diffusion among the three. This minor reduction indicates thorough mixing and more uniform elemental distribution due to prolonged friction time.

Table 3. Components of the weld line for the specimen with a friction time of 7 s.

Element	Net Counts	Int. Cps/nA	Weight %	Atom %
C	475	13.194	1.44	3.16
O	799	22.194	0.95	1.57
Mg	2945	81.806	0.68	0.73
Al	409,146	11,365.17	96.35	94.26
Fe	354	9.833	0.58	0.28
Total			100.00	100.00

Oxygen content decreases to 0.95%, potentially indicating reduced surface oxidation or better sealing of the interface with improved material flow. Carbon content also drops to 1.44%, which may reflect better bonding and less exposure to atmospheric contamination.

The magnesium content remains at 0.68%, indicating stable alloying content but likely more uniform distribution across the interface. The 7 s friction time results in the most extensive elemental mixing, creating a more uniform distribution of alloying elements and minimizing oxidation at the interface. This condition corresponds with the highest hardness and strength, as observed in previous tests, though it may also contribute to brittleness due to the rigid structure formed by prolonged friction time.

The EDS analysis shows that increasing friction time improves elemental diffusion and uniformity, reducing oxidation and surface contamination. Shorter friction time (3 s) limits diffusion, resulting in higher aluminum content and less mixing, which contributes to lower strength and hardness. Moderate (5 s) and extended (7 s) friction times enhance material mixing and bonding quality, resulting in higher strength, hardness, and a more homogenous composition at the interface. The trade-off is the potential for brittleness at longer friction times due to reduced ductility.

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