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Hybrid Friction Stir Welding: The Role of Ultrasonic Vibration and Tool Rotation in Enhancing the Joint Properties

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Abstract. Aluminum-lithium (Al-Li) alloys have gained considerable attention in the aerospace sector due to their superior mechanical properties and strength-to-weight ratio. However, joining these alloys through fusion welding presents challenges including solidification cracking. Friction Stir Welding (FSW) has emerged as a viable solution, offering improved mechanical performance and minimized defects. Recently, ultrasonic vibration-assisted FSW (UVaFSW) has been introduced to further enhance weld quality by refining grain structure and improving plastic flow. This study investigates the impact of UVaFSW parameters, specifically tool rotational speed (TRS) and vibration amplitude (Amp), on the microstructural and mechanical properties of AA2060-T8E30 Al-Li alloy widely utilized in the aviation sector. The experimental analysis reveals that TRS of 800 rpm results in enhanced tensile strength, while higher TRS (1600 rpm) induces excessive heat, leading to grain coarsening and reduced mechanical performance. Additionally, increasing vibration amplitude from 7.5 μm to 22.5 μm significantly improves the welded joints quality. The findings emphasize the potential of UVaFSW in enhancing welding of Al-Li alloy, offering a suitable approach for high-performance aerospace applications.

1. Introduction

Nowadays, the industry sectors, including the transportation and aerospace industries, increasingly demand advanced materials that offer high strength while maintaining low weight. Among these materials, aluminum (Al) alloys are widely used for their excellent strength-to-weight ratio [1]. Various modifications have been introduced to further reduce the weight of Al alloys while preserving their mechanical integrity. Lithium (Li), with a low density of 0.54 g/cm³ under standard conditions, exhibits significant solubility in aluminum, reducing its density by approximately 3% and increasing its elastic modulus by 6% for every 1% of lithium added, leading to the development of aluminum-lithium (Al-Li) alloys. Al-Li alloys have undergone several advancements, leading to the development of third-generation Al-Li alloys. These alloys possess exceptional properties, making them highly suitable for aerospace applications where weight reduction and enhanced performance are critical [2, 3].

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However, joining Al-Li alloys in industrial applications presents significant challenges, particularly when using conventional welding techniques. Traditional welding of these alloys is prone to defects including solidification cracking due to residual stresses and shrinkage, as well as the formation of porosity in the nugget zone, all of which significantly degrade the welded joints quality [4]. To overcome these limitations, Friction Stir Welding (FSW) has emerged as an effective welding process, offering superior joint quality and mechanical performance.

FSW is a solid-state welding process, meaning that joining occurs without melting the material. FSW offers superior weld quality and lower residual stresses compared to traditional welding processes [5]. Recently, it has been recognized as a key welding method in the aerospace industry, with major aircraft manufacturers adopting it for structural applications [6]. The concept of the FSW involves plunging the tool while rotating into the joint between the workpieces. Upon contact, the dwelling stage begins, during which the tool rotates, generating frictional heat that softens the material in the welding zone. Before the temperature reaches the melting point, the tool traverses along the welding line, effectively stirring and consolidating the material to form a joint [7].

Several parameters in the FSW process significantly influence weld quality, including tool geometry (shoulder and pin), tool speeds (rotational and traverse), plunge depth, and tilt angle [8, 9]. Among these, tool speeds are considered the most critical factors affecting weld performance [5].

Several studies have examined the influence of FSW parameters on Al-Li alloys' mechanical and microstructural properties. Zhang et al. [10] examined the effect of rotational and traverse speeds on FSWed joint quality of AA2195-T8 Al-Li alloy. Using a concave shoulder tool with a threaded cone-shaped pin, they found that mechanical properties initially improved but declined at higher welding speeds, with all joints exhibiting a strength loss, reaching only 65% of the base metal strength. Similarly, Muthumanickam et al. [11] reported that both tool speeds influenced heat generation, grain size, and mechanical performance, with tensile failure consistently occurring in the thermomechanically affected zone (TMAZ).

Nayan et al. [12] studied the microstructure of FSWed AA2198-T8 joints, showing that average grain size increased with rotational speed beyond 800 rpm, leading to coarser grains and reduced joint performance. This trend aligns with findings from [13] on stationary shoulder FSW of 2A97 Al-Li alloy, where tensile strength and hardness initially increased but later decreased as rotational speed rose from 600 to 1000 rpm, with minimal grain size variation in the stir zone (SZ). Similarly, Yan et al. [14] analyzed the microstructural evolution of 2060 Al-Li alloy joints at rotational speeds of 600, 800, and 1300 rpm with a fixed traverse speed of 100 mm/min. They observed grain coarsening with increasing rotational speed, with the highest ultimate tensile strength (UTS) of 443 MPa (83.58% of 2060 Al-Li alloy) at 600 rpm. Fracture analysis revealed that inadequate material flow and secondary phase coarsening contributed to joint failure.

Although FSW offers superior performance compared to fusion welding, further advancements have been made to enhance the process. These include the development of specialized tools and the hybridization of FSW with other welding techniques, such as laser welding, arc welding, and ultrasonic vibration welding [5].

Among the previously mentioned techniques, UVaFSW stands out as it enhances the welding process through ultrasonic vibrations rather than excessive heat input. The vibration system in UVaFSW consists of a generator, transducer, and horn, which transmits high-frequency vibrations into the weld zone. This vibration softens the material, promotes plastic deformation, and improves weld quality without significantly increasing thermal exposure. Additionally, UVaFSW reduces grain size, lowers axial forces, and enhances the precipitation of strengthening phases [5].

Meng et al. [15] investigated the UVaFSW effect in welding AA6061-T6 and AZ31B Mg alloys dissimilar joints through experimental and numerical study. By applying ultrasonic vibration to the advancing side (Mg workpiece), they observed enhanced material flow, improved weldability, refined Al/Mg mixture in the SZ, and improved tensile properties. Similarly, Muhammad et al. [16] applied

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UVaFSW to weld AZ31B and AA7075-T6 alloys using a 20 kHz frequency and 25 μm amplitude. The ultrasonic effect reduced intermetallic compounds (IMC) thickness, promoted grain recrystallization and enhanced mechanical properties.

While previous studies have examined the UVaFSW joint quality, research on its impact on third-generation Al-Li alloys remains limited. This study aims to investigate the effects of UVaFSW parameters, specifically tool rotational speed (TRS) and vibration amplitude (Amp), on the AA2060-T8E30 joint quality. As a widely used 3rd generation Al-Li alloy in the aviation industry, understanding its behavior under UVaFSW can contribute to developing high-efficiency joining techniques for these advanced materials.

2. Experimental work

2.1. Material

In this study, AA2060-T8E30 Al-Li alloy workpieces with dimensions of 100 × 60 × 4 mm were used. Butt joints were fabricated with a welding line length of 100 mm, ensuring consistent joint formation across all trials. Table 1 shows the AA2060-T8E30's chemical composition and mechanical properties. Four experimental runs were conducted, varying the TRS between 800 rpm and 1600 rpm and the Amp between 7.5 μm and 22.5 μm while keeping the traverse speed at 120 mm/min, tilt angle at 1°, and axial force at 6 kN, based on previous studies and trials [17]. Welded samples are designated using brief notation. For instance, sample 800-7.5 refers to welding conditions with a TRS of 800 rpm and an Amp of 7.5 μm.

Table 1 Base material's chemical and mechanical properties.

Element	Li	Fe	Cu	Mg	Mn	Ag	Ti	Zn	Si	Zr	Al
%	0.8	0.02	3.7	0.8	0.29	0.33	0.03	0.35	0.02	0.11	Remain

UTS (MPa)	Yield stress (MPa)	Elongation %	Hardness (Vickers)
504	432	15.5	175

2.2. Methods

The welding process in this study was carried out using a robotic arm with a 5-axis kinematic system. This system was chosen to enhance flexibility and precision when replicating industrial FSW applications. The custom-designed FSW tool was fabricated from H13 hot-work tool steel. The tool featured a 12 mm shoulder diameter, a tapered pin with a 6 mm root and 4 mm tip diameter, and a tri-flats threaded design. The tool was mounted rigidly in the robotic system, ensuring optimal material flow and weld quality. Figure 1 illustrates the tool and robotic arm setup.

Additionally, an ultrasonic vibration (UV) system was incorporated into the FSW system. The UV system consisted of a generator, transducer, horn, and connecting cables, with a power capacity of 2000 W, capable of producing sinusoidal waves at a specified frequency. The setup for the ultrasonic vibration tool is shown in Figure 2.

Following welding, the samples were prepared for mechanical and microstructural characterization. Tensile testing was conducted on three specimens, prepared according to the ASTM B557 standard for substandard tensile test dimensions, with the average value recorded. Microhardness measurements were taken at the cross-section mid-thickness of the SZ. For microstructural analysis, an Optical Microscope (Olympus Corporation, Japan) was utilized to examine the weld regions.

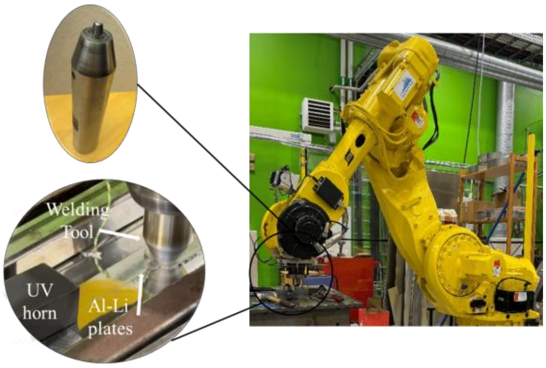

Figure 1. UVaFSW process setup

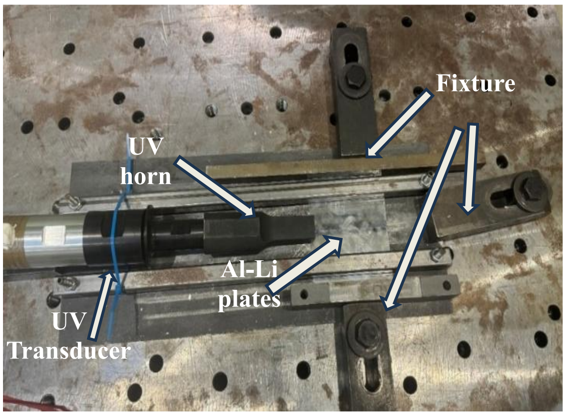

Figure 2. UVaFSW tool setup

3. Results and Discussion

Following the welding process, a visual inspection was conducted to evaluate weld quality. At a TRS of 800 rpm, no visible defects were observed, whereas defects appeared along the weld line at 1600 rpm, as shown in Figure 3. For sample C, increasing the vibration amplitude from 7.5 µm to 22.5 µm at 1600 rpm reduced the presence of surface defects and improved weld appearance. The formation of groove defects was also diminished, demonstrating the beneficial effect of ultrasonic vibration on weld integrity. A detailed characterization of the welded joints is discussed in the following sections.

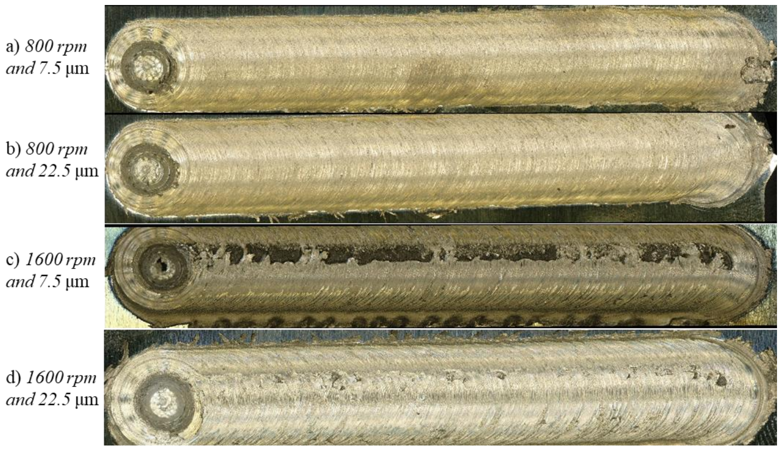

Figure 3. The seam lines of the welded samples.

3.1. Tensile Properties

The welded samples' mechanical properties are presented in Figure 4. As expected, the welded joints have lower mechanical properties than the BM due to the joint softening phenomenon. The TRS significantly influenced the heat generation during welding, directly impacting the mechanical properties of the joints. At 800 rpm, adequate heat was generated to facilitate proper material flow and grain refinement, resulting in higher tensile strength compared to 1600 rpm. Conversely, at 1600 rpm, excessive heat input led to grain coarsening, thermal softening, and the potential formation of defects, which collectively contributed to a reduction in tensile strength. Similar observations have been reported in previous study [14].

Furthermore, the Amp played a crucial role in determining the tensile properties of the welded joints. As shown in Figure 4, increasing the vibration amplitude from 7.5 µm to 22.5 µm led to improvement in tensile strength for all samples, which is attributed to the effect of UV in enhancing material plasticity and reducing residual stress.

The ultrasonic energy acts at the microstructural level, effectively softening the material by facilitating dislocation movement and refining the grain structure. Unlike conventional thermal energy, ultrasonic energy is absorbed at dislocation sites within the grains which promotes dynamic recrystallization and improved grain uniformity, which ultimately enhances the joint's mechanical properties.

Moreover, the combined effect of TRS and ultrasonic vibration suggests that optimized process parameters are essential for achieving high-quality welds. While lower TRS prevents excessive heat accumulation, the application of ultrasonic vibration compensates for any potential reduction in material plasticity by improving material flow and reducing welding defects. This synergy between TRS and ultrasonic vibration highlights the importance of process optimization in UVaFSW to maximize joint performance.

Overall, the results indicate that excessive heat input at high TRS negatively impacts tensile strength, while the introduction of ultrasonic vibration helps mitigate these effects by enhancing plastic deformation and refining the microstructure. The following sections provide a detailed discussion of microstructural analysis to further explain the observed mechanical property trends.

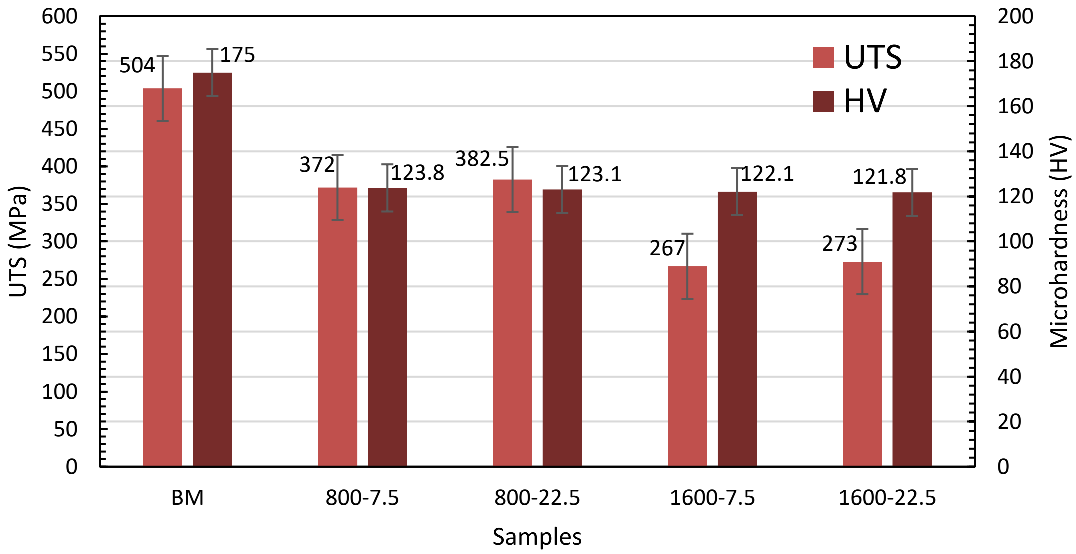

Figure 4. Mechanical properties results.

3.2. Microhardness

Microhardness was measured perpendicularly to the weld line along the SZ mid-thickness, with 41 readings taken at 0.5 mm intervals. The microhardness profile of the welded samples is shown in

Figure 5, displaying a characteristic W-shape, a common feature in Al-Li alloys. The thermal cycles in FSW influence microhardness by inducing recrystallization and grain growth. Additionally, the material's grain structure and precipitates dissolution in the welded zones significantly affects hardness [18].

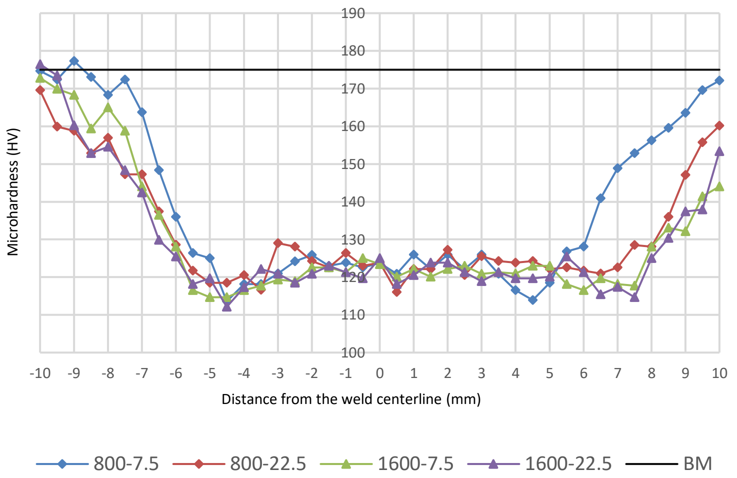

Figure 5. Microhardness distribution of welded samples.

Figure 5 illustrates that the BM exhibits higher microhardness than the welded samples, with a reduction of approximately 30% due to the thermal cycle. The welded samples demonstrate an average hardness ranging from 121.8 to 123.8 HV. The lowest hardness values were observed at the interface between the TMAZ and the HAZ, where the combined effects of thermal exposure and plastic deformation weaken the material structure. The current observations are consistent with earlier findings [19].

The tool rotational speed significantly influenced microhardness. At 800 rpm, the hardness values are higher compared to 1600 rpm, where excessive heat input leads to grain coarsening and precipitate dissolution, reducing hardness. Additionally, a slight variation is observed with different vibration amplitude values, indicating that UV has a minor effect on hardness compared to the dominant influence of heat input and grain structure evolution. However, the overall trend suggests that, UVaFSW contributes to a more uniform hardness distribution across the weld region, potentially reducing hardness discrepancies and improving joint performance.

3.3. Microstructure analysis

The macrostructure of the welded samples (Figure 6) reveals the distinct welding zones: BM, HAZ, TMAZ, and SZ. Variations in grain size across samples are attributed to differences in heat input and material flow, influenced by both TRS and Amp.

Figure 6 highlights a notable asymmetry in the TMAZ, where the retreating side (RS) extends further into the SZ compared to the advancing side (AS). This effect is more pronounced at 1600 rpm than at 800 rpm, which is attributed to the tool shoulder's stirring action [17]. The increased heat under the shoulder surface reduces flow stress, promoting more deformation, particularly at higher TRS due to excessive thermal input.

Grain structure and precipitate formation play a crucial role in determining the mechanical behavior of welded Al-Li alloys, with recrystallized grain size being governed by strain rate, and temperature evolution during FSW. It is observed that the BM grains are elongated due to the rolling process and remained unchanged due to minimal heat input. In contrast, grain coarsening is observed in the HAZ due to the welding cycle.

Grain refinement is more evident at lower TRS, with samples welded at 800 rpm exhibiting finer grains compared to those welded at 1600 rpm. Additionally, increasing the vibration amplitude from 7.5 µm to 22.5 µm further promotes grain refinement, which correlates with the observed improvements in mechanical properties. Figure 7 presents the microstructure of SZ for the different welded samples. The measured average grain sizes are 8.94 µm and 7.46 µm for samples welded at 800 rpm with vibration amplitudes of 7.5 µm and 22.5 µm, respectively, and 10.54 µm and 10.18 µm for those welded at 1600 rpm under the same amplitudes.

Within the SZ, dynamic recrystallization occurred due to the combined effects of the generated heat, vibration, and forging force, which facilitates grain nucleation and growth, where initially elongated grains formed under plastic deformation fragment into equiaxed fine grains. Additionally, the rotating tool pin stirs the weld material, inducing severe plastic deformation, leading to fine equiaxed grains formation. In the TMAZ, the grains experience tilting and elongation due to the intense shear forces exerted by the tool shoulder and relatively lower heat input, resulting in an elliptical grain structure. In contrast, the HAZ shows evidence of grain coarsening without recrystallization, consistent with typical thermal exposure in this region [20].

Overall, the refined grain structure in samples welded at 800 rpm and with a 22.5 µm vibration amplitude contributes to enhanced mechanical properties, reinforcing the role of UVaFSW parameters in optimizing microstructural characteristics.

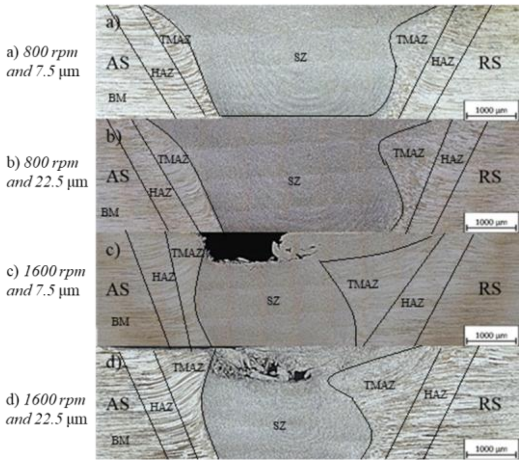

Figure 6. *Macrostructures in cross-sections of joints*

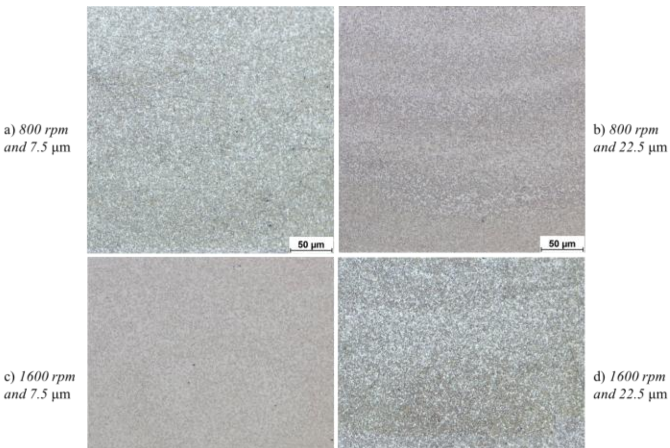

Figure 7. *Microstructure of the SZ of the welded joints.*

4. Conclusion

This study explores the impact of UVaFSW on the mechanical and microstructural properties of AA2060-T8E30. The results indicate that TRS and Amp play crucial roles in determining weld quality. Lower TRS (800 rpm) provides sufficient heat input for proper material flow and grain refinement, leading to superior mechanical properties. In contrast, higher TRS (1600 rpm) results in excessive heat accumulation, grain coarsening, and reduced joint strength. Applying ultrasonic vibration improves the weld integrity by enhancing material plasticity and promoting grain refinement.

Overall, the combination between TRS and ultrasonic vibration highlights the importance of process optimization in UVaFSW to achieve high-quality welds. These findings contribute valuable insights into the development of advanced welding techniques for Al-Li alloys, paving the way for their expanded application in aerospace and other high-performance industries.

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