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Enhancing mechanical properties of dissimilar pure Cu/Mg AZ31B friction stir welds via ultrasonic assistance

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Abstract-Joining dissimilar pure copper (Cu) and magnesium (Mg) alloy AZ31B through friction stir welding (FSW) presents considerable metallurgical challenges due to contrasting thermo physical properties and brittle intermetallic compound formation at the weld interface. This study examines FSW of Cu/Mg AZ31B butt joints using a tool rotational speed of 1070 rpm, welding speed of 31.5 mm/min, tilt angle of 2°, and a 1.5 mm pin offset toward the Mg AZ31B side to optimize heat generation and material flow. Conventional FSW produced an ultimate tensile strength (UTS) of 110 Map, limited by inadequate inter-material mixing and interfacial defects. To overcome these constraints, ultrasonic-assisted friction stir welding (UAFSW) was implemented, superimposing high-frequency acoustic energy to enhance material plasticization, reduce flow stress, and promote dynamic recrystallization in the weld nugget. The UAFSW joints achieved UTS of 125 Map, representing a ~13.6% improvement over conventional FSW. This enhancement is attributed to acoustic softening and cavitations-driven grain refinement, improved inters material mixing, and reduced interfacial defect density. These findings establish ultrasonic assistance as a viable strategy for welding dissimilar material systems, with significant implications for electrical, automotive, and lightweight structural applications requiring reliable Cu–Mg joints.

Keywords: Friction stir welding, dissimilar materials, copper, magnesium AZ31B; ultrasonic assistance, tensile strength, intermetallic compounds

1. Introduction:

In today's manufacturing industry, dissimilar metal joining is one of the most important research fields, considering the need for joining components that are optimized for their performance and reduced in weight. Current progress hasn't quite solved the inherent friction that comes with bonding mismatched materials. Because creating flawless, multi-material systems is still a major hurdle, the field must prioritize fresh, creative approaches and continued experimentation to

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bridge the remaining gaps[1]. Friction Stir Welding (FSW) is an effective solid-state joining process for dissimilar metals with advantages over conventional fusion welding techniques. Dissimilar FSW has been successfully applied to material combinations such as Al-Cu, Al-Mg, Al-steel and Mg-Ti where conventional welding often suffers from metallurgical difficulties. Nevertheless, the material flow behaviour and the formation of brittle intermetallic compounds have a significant impact on the microstructure and mechanical properties of the joints [2]. Ultrasonic assistedFSW (UAFSW) reduces the intermetallic compound (IMC) thickness of Al/Mg dissimilar alloys by decreasing the dislocation density, which suppresses atomic diffusion [3]. A Taguchi-based optimization study on UAFSW of AA6082 alloy identified 20 µm vibration amplitude, 80 mm/min traverse speed, and 800 rpm rotational speed as the optimum parameters, resulting in a tensile strength of 297 Map. The results indicated that rotational speed was the dominant factor affecting weld strength and overall joint quality [4]. Recent studies have demonstrated that UAFSW significantly enhances material flow and dynamic recrystallization, resulting in refined microstructures and improved joint integrity. The application of ultrasonic vibration has also been shown to suppress weld defects and reduce the formation of brittle intermetallic compounds through acoustic softening and enhanced plastic deformation. Consequently, UAFSW has emerged as an effective approach for improving the mechanical performance of both similar and dissimilar alloy joints, including Al–Li, Al–Mg, Mg–Al, and Al–Ti systems [5-8]. El-Zachary et al. concluded that the application of ultrasonic vibration during friction stir welding of AA2060-T8 Al–Li alloy improved material flow and micro structural refinement. Under optimized conditions, the ultimate tensile strength increased from 201 Map for conventional FSW to 265 Map, while elongation improved from 2.1% to 6.0%, demonstrating the effectiveness of UAFSW in enhancing joint [9]. The application of ultrasonic vibration during friction stir welding was found to refine the grain structure and improve the uniformity of second-phase particle distribution. These micro structural changes enhanced the corrosion resistance of the joints, as evidenced by a decrease in pitting density from 123 to 86 mm^{-2} and a reduction in intergranular corrosion depth from 39.28 am to 19.20 am[10]. Improvements in performance include tensile strengths exceeding 370 Map, an increase in joint strength of up to 31.8%, a 27.9% improvement in tensile load for dissimilar joints, a reduction in tensile residual stress of approximately 45%, and significant decreases in intermetallic compound thickness and corrosion susceptibility. These findings highlight the effectiveness of ultrasonic assistance in producing stronger, defect-free joints with improved structural integrity and service performance [11-15]. UAFSW increased joint failure load by up to 21.4% while reducing the intermetallic layer thickness from 5.01 am to 0.71 am, leading to superior mechanical performance of Al/steel lap joints [16]. UAFSW reduced interfacial stress and welding load by approximately 5%, while enhancing material flow and heat distribution within the weld zone. These improvements contributed to superior weld formation and overall joint quality [17]. Ultrasonic assistance improved interfacial bonding and micro structural refinement in 6061-T6 Al/Ti6Al4V joints, resulting in a maximum tensile strength of 236 Map, equivalent to 85% of the base alloy strength [18]. Ultrasonic vibration was found to reduce frictional heat generation and lower the peak welding temperature during friction stir welding of 6061 aluminium alloy. The study also showed that vibration amplitude had a greater influence on the temperature field than ultrasonic frequency [19]. The optimized ultrasonic-assisted welding condition was achieved at 1200 rpm rotational speed, 6 mm plunge depth, and 6 s dwell time, which significantly enhanced the mechanical performance of the joint by maximizing both lap shear force and hardness [20].

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The best performance achieved at 70% ultrasonic power, 1200 rpm rotational speed, and 40 mm/min processing speed. Under these conditions, higher strength, ductility, and processing efficiency were obtained[21]. Residual stress in 7075 aluminium alloy friction stir welds was found to be primarily governed by welding speed, whereas rotational speed, tool tilt angle, and plunge depth had a relatively minor influence [22]. The proposed constitutive model reduced peak temperature prediction errors from over 50 °C to less than 8 °C and revealed that a 17.1% reduction in total heat generation is responsible for the lower welding temperatures observed in Al/Mg dissimilar friction stir welding [23]. Pure Cu/AZ31B Mg dissimilar joints offer significant potential for lightweight structural and electrical applications, however, the formation of brittle Cu–Mg intermetallic compounds and poor interfacial bonding remain major challenges during friction stir welding. While ultrasonic-assisted friction stir welding has been successfully applied to several alloy systems, its effect on the interfacial microstructure, material flow behaviour, and mechanical performance of Cu/Mg joints is still not well understood. Therefore, further investigation is required to establish the feasibility of UAFSW for producing high-quality Cu/AZ31B Mg dissimilar joints.

2. Materials and Methods:

Welding experiments were conducted using pure Cu and AZ31B Mg plates with dimensions of 100 mm in length, 50 mm in width, and 3 mm in thickness. The chemical compositions of both base materials are provided in Table 1.To prevent shifting and minimize unwanted movement during the process, all specimens were securely locked down using stainless steel fixtures. The welding itself was carried out with an H13 tool steel setup, featuring a 20 mm flat shoulder and a cylindrical pin 5 mm in diameter and 3 mm long illustrated in Figure 1. The exact welding configurations and operational settings for the FSW machine experiments are presented in Table 2. For optimal material flow and sound joint quality, the AZ31B Mg alloy occupied the retreating side (RS) while pure Cu was placed on the advancing side (AS), a configuration mapped out in Figure 2 Shifting the tool slightly toward the Mg side allowed us to better exploit the softer material's plastic deformation for superior interfacial mixing. We intentionally avoided biasing the tool toward the copper side, as its elevated resistance would restrict effective stirring and hurt the final joint consolidation. The accompanying schematic highlights the auxiliary ultrasonic equipment used to achieve this. The setup integrates an ultrasonic generator operating at 750 W and 20 kHz, which feeds into a transducer and ultrasonic horn assembly. This setup continuously transmits localized vibrations to the weld zone as the UAFSW tool travels along the seam under a constant axial force.

Table 1. Chemical composition of the base materials in weight percent (wt. %).

Material	Al	Zn	Man	Cu	Mg	Others
Pure Cu	–	–	–	≥99.9	–	≤0.1
AZ31B Mg	2.5–3.5	0.6–1.4	~0.2	≤0.05	Balance	≤0.3

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Table 2 Processing parameter range of the dedicated FSW system.

FSW Parameters	Range
Tool Rotational Speed	35–1500 (rpm)
Welding Speed	20–800 (mm/min)
Motor Power	3.0 HP
Tool Tilt Angle	0° - 50° (in both welding direction)

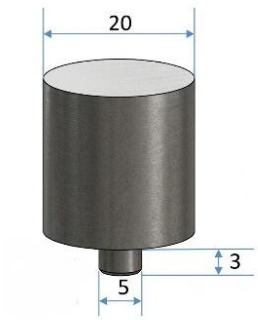

Figure 1: H13 tool steel.

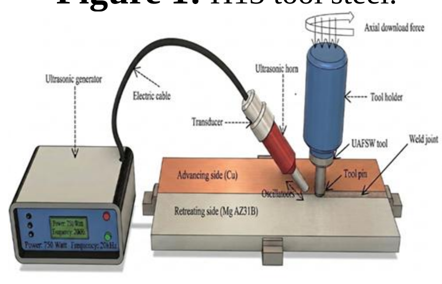

Figure 2: Schematic layout of the UAFSW configuration for pure Cu and AZ31B Mg and integrated 750 W / 20 kHz ultrasonic vibration system.

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Figure 3: Actual experimental setup

Table 3: Experimental Welding Parameters and System Specifications

Parameter / Specification	Conventional FSW	Ultrasonic-Assisted FSW
Tool Rotational Speed	1070 rpm	1070 rpm
Welding speed	31.5 mm/min	31.5 mm/min
Tool Tilt Angle	2°	2°
Ultrasonic Power Output	-----	750 W
Ultrasonic Frequency	-----	20 kHz
Amplitude	-----	90%

The experimental configuration placed the sonotrode at a 45° tilt from the horizontal plane, positioned with a 20 mm offset from the tool pin's center to the sonotrode's contact point on the base metal. To ensure continuous energy transfer, the sonotrode pressed firmly against the work piece, staying activated from start to finish[24]. The actual experimental arrangement used for the fabrication process is presented in Figure 3, showing the modified vertical milling machine integrated with the external ultrasonic generator and control unit positioned alongside the workspace. To properly isolate the impact of acoustic assistance, the core mechanical parameters identical for both the conventional FSW and UAFSW run. Each experiment was conducted using a tool rotational speed of 1070 rpm, a forward travel speed of 31.5 mm/min, and a fixed 2° tilt angle. The defining upgrade for the UAFSW trials was the continuous injection of supplemental energy, supplied via a 750 W ultrasonic system oscillating at a stable frequency of 20 kHz and configured to 90% vibration amplitude as shown in Table 3. Comprehensive joint characterization was performed via tensile testing, fractography, SEM, and EDS. The tensile geometries featuring a 25 mm gauge length were sectioned via a CONCORD 7732 VC wire EDM in strict accordance with ASTM E8 criteria as illustrated in Figure 4. For micro-scale evaluation, the fractured or polished joint regions were ultrasonically cleaned in acetone and subsequently characterized using an FEI Quanta 200 F SEM operating at 30 kV.

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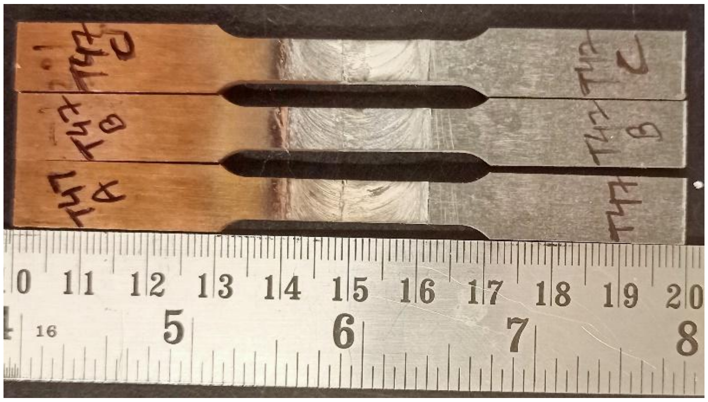

Figure 4: Tensile evaluation specimen prepared from the welded interface

3. Results and Discussion:

3.1 Surface morphology and visual inspection

Visual inspection of the weld crowns reveals a distinct topographic transition between the two processing conditions, proving that the superimposition of a high-frequency acoustic field fundamentally alters interface mechanics Figure 5. Under conventional FSW, the joint displays an irregular, rugged surface characterized by severe flash expulsion along the retreating side and coarse onion rings, which stems from stick-slip friction variations and plastic flow resistance between the dissimilar metals. Conversely, the application of a 750 W ultrasonic field (UAFSW) drastically smoothes out the surface profile, yielding uniform, finely spaced ripple marks and completely eliminating macro-scale flash. This significant morphological refinement is directly attributed to acoustic softening (acoustoplasticity), which lowers dynamic yield strength and enhances material plasticity, allowing the plasticized metal to enter a highly fluidic state and consolidate seamlessly behind the tool shoulder.

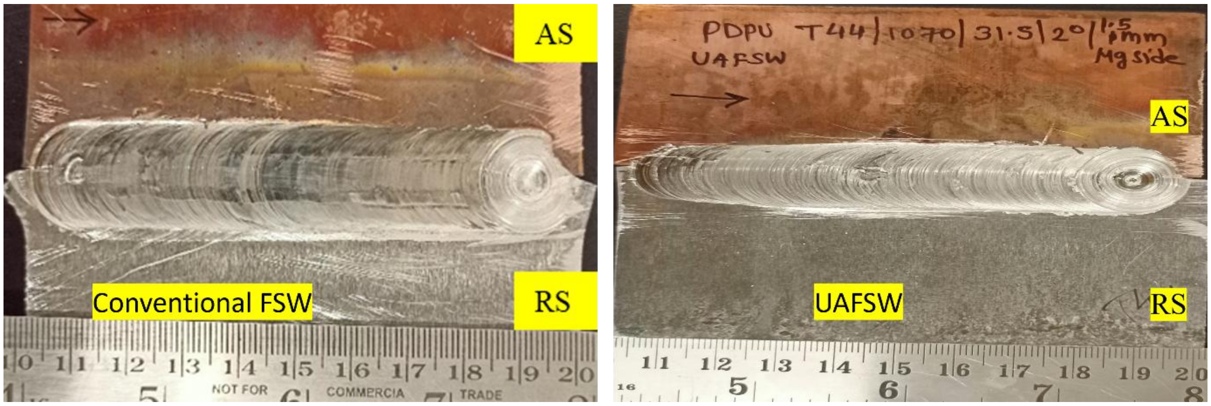

Figure 5: Surface morphology (a) conventional FSW (b) UAFSW.

3.2 Tensile strength evaluation:

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Uniaxial tensile testing was used for quantitative assessment of mechanical integrity of dissimilar Cu/Mg butt joints. The comparison of the ultimate tensile strength (UTS) of the joints produced using the conventional FSW and UAFSW 1.5 mm pin offset towards the Mg AZ31B side is shown in figure 6. The specimen obtained from the conventional FSW had a tensile strength of 110 Map. This low strength is strongly correlated with the formation of poor-quality material interfaces and macro structural defects that frequently occur between unassisted dissimilar Cu/Mg interfaces. The temperature difference and high plastic flow resistance of the materials often results in the formation of a brittle, non-uniform layer of intermetallic compounds (IMCs) or micro-voids, which are likely to cause early failure when the product is put under tensile load. However, superimposing the high frequency acoustic field in UAFSW process increased tensile strength to 125 Map, which showed a significant improvement in joint efficiency. The 750 W ultrasonic assistance is directly correlated to this enhanced performance and is called acoustoplastic effects. The acoustic field has a beneficial effect on the dynamic shear strength of the base metals, thus ensuring good material consolidation and smooth material flow around the tool pin. The improved flow behavior causes reduction of the macroscopic voids and better refinement of the distribution of inter-metallic interfacial layers in the joint giving it improved resistance and soundness in its structure to withstand higher tensile load before fracture.

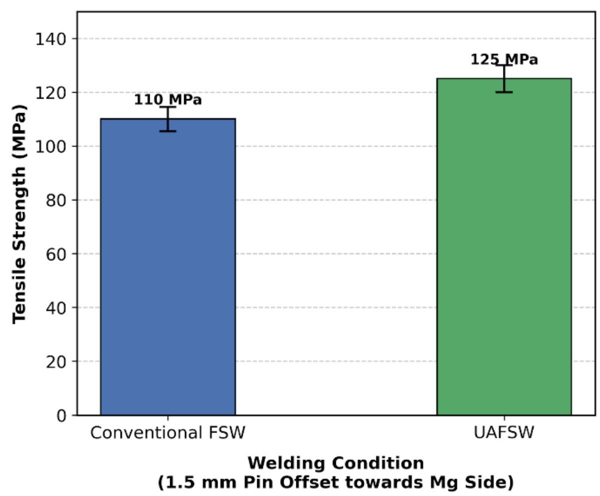

Figure 6 UTS comparison of Pure Cu– AZ31B Mg joints produced by FSW and UAFSW at a 1.5 mm pin offset toward the Mg side

3.3 Fractographic Analysis:

It is clearly observed that the fracture surfaces of the conventional FSW and UAFSW joints differ from each other as shown in Figure 7. The conventional FSW specimen showed partial interfacial separation and traces of weak bonding, suggesting that the main failure mode was interfacial (Cu/Mg interface). The bonded region on the UAFSW specimen was larger, and the fracture surface was relatively uniform with less variation in bonded region, indicating better metallurgical bonding and mixing of materials. These observations are in good agreement with the results of tensile testing, which indicated that the UAFSW joint had stronger strength because

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of improved integrity of the interface and the diminished defect formation from the ultrasonic-assisted material flow.

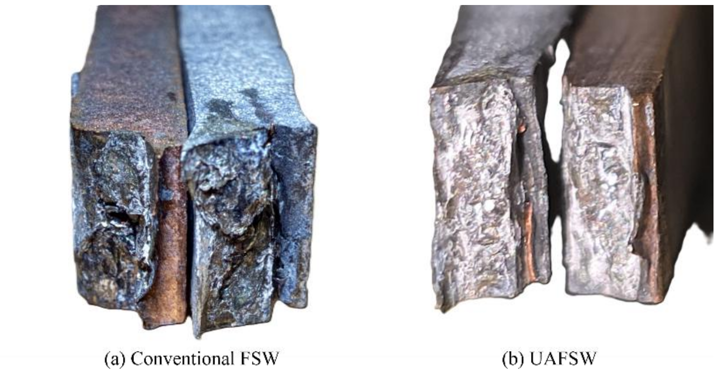

Figure 6: Fractographic images a) Conventional FSW b) UAFSW

3.4 SEM and EDS Analysis:

The SEM fracture morphologies and EDS spectra of the Cu–AZ31B Mg joints fabricated with the conventional FSW and UAFSW processes are shown in Figure 7. The fracture surface of a typical conventional FSW joint (Figure 7a) shows a relatively rough and heterogeneous feature with many cavities, micro-voids, and features similar to cracks, suggesting the presence of local stress concentrations and cracks occurring early in the tensile loading. The corresponding EDS spectrum shows a presence of the Cu and Mg elements at the fracture interface, indicating that there is no complete mixing of the materials, and thus, there are weak bonding conditions at the interface. The UAFSW joint (Figure 7b), however, shows a relatively compact and uniform fracture surface with less voids/discontinuities. The fracture morphology suggests that the plastic deformation is enhanced and the metallurgical bonding between Cu and Mg is strengthened. The Cu and Mg elements are more evenly distributed in the EDS spectrum, indicating improved intermixing of the materials, which was facilitated by ultrasonic vibration. The lower number of interfacial defects and elemental distribution was responsible for increased load transfer across the interface, which is in good agreement with the higher tensile strength of the UAFSW joints than the conventional FSW joints.

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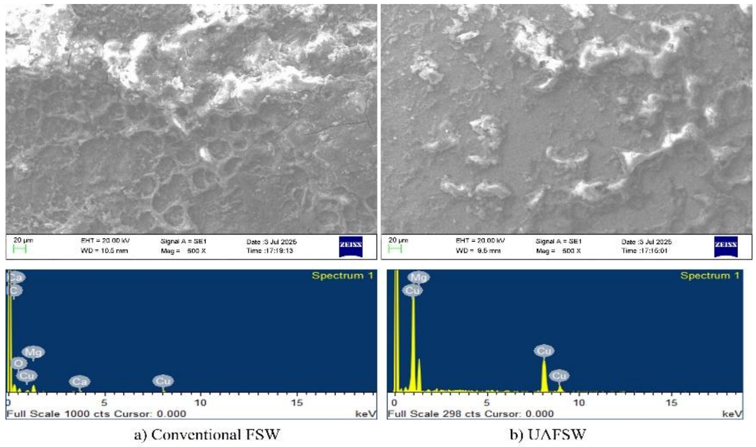

Figure 7: SEM fractography and corresponding EDS spectra of the fractured Cu–AZ31B Mg dissimilar joints fabricated by (a) conventional FSW and (b) UAFSW after tensile testing.

4. Conclusions:

In the present study, the feasibility of ultrasonic-assisted friction stir welding (UAFSW) has been studied to join dissimilar pure Cu and AZ31B Mg alloys. The use of ultrasonic vibration had a significant effect on the flow property of the materials, the bonding between the two materials, and the integrity of the joint, resulting in improved weld quality and mechanical properties compared with traditional friction stir welding. From the experimental observations and characterization results the following can be concluded:

1. With the UAFSW process, smoother defect-free pure Cu/AZ31B Mg welds were obtained with better material flow than conventional FSW process.
2. The maximum tensile strength of the UAFSW joint was 125 Map, which is a 13.6% higher than the conventional FSW joint 110 Map.
3. Fractographic analysis showed an increase in bonding between the two pieces in the UAFSW joint and a larger bonded area, which led to a higher resistance to tensile failure.
4. The SEM–EDS analysis verified that the enhancement of intermixing between pure Cu and AZ31B Mg and reduction of the interfacial defects under the assistance of ultrasonic, has resulted in better mechanical performance.

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