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Recent Progress in Process and Mechanical Properties of Ultrasonic-Assisted Friction Stir Welding of Aluminum Alloys: A Review

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Abstract: Aluminum alloys, as pivotal structural materials for lightweight manufacturing, have been extensively applied in cutting-edge industries such as aerospace, rail transit, and automotive engineering. However, the conventional solid-state joining technology, friction stir welding (FSW), often faces critical bottlenecks when processing ultra-high-strength aluminum alloys or dissimilar materials, including non-uniform heat input, excessive tool wear induced by high axial forces, restricted grain refinement, and a high susceptibility to welding defects like tunneling and kissing bonds. As an advanced solid-state hybrid joining technology that deeply integrates a high-frequency acoustic field with a thermal-mechanical coupled field, ultrasonic-assisted friction stir welding (UAFSW) introduces high-frequency ultrasonic vibrations during the welding process. This hybrid process significantly improves the rheological characteristics of plasticized metals, reduces mechanical loads, and refines the joint microstructure. This paper systematically reviews recent research progress in UAFSW for both similar and dissimilar aluminum alloys. Special emphasis is placed on elucidating the underlying mechanisms of microstructural reconstruction and mechanical performance enhancement driven by the acoustic volume and acoustic surface effects. Furthermore, representative process parameters and experimental data are comprehensively deconstructed, followed by an outline of key future research trends in this field.

Keywords: Ultrasonic-assisted friction stir welding; Aluminum alloys; Microstructure; Mechanical properties.

1. Introduction

1.1. Process Background and Limitations

Aluminum alloys, particularly high-strength Al-Cu, Al-Mg-Si, and ultra-high-strength Al-Zn-Mg-Cu systems, serve as indispensable core materials in modern lightweight transport equipment due to their outstanding specific strength, high toughness, excellent corrosion resistance, and favorable processability. Nevertheless, due to the high thermal conductivity, large linear expansion coefficient, and active chemical reactivity of aluminum, conventional fusion welding methods are highly prone to defects such as porosity, hot cracking, alloying element burnout, and severe softening of the heat-affected zone (HAZ) resulting from the coarsening or excessive dissolution of strengthening precipitates[1-3].

As a revolutionary solid-state joining technology developed at the end of the twentieth century, friction stir welding (FSW) effectively circumvents the metallurgical defects associated with material melting. However, in practical industrial applications involving thick plates or ultra-high-hardness heat-treatable aluminum alloys, the flow stress of the material remains substantial even at elevated temperatures. This leads to massive mechanical and thermal fatigue loads on the welding tool, severe wear of the stir pin and shoulder, and a narrow processing window. Such limitations restrict the widespread adoption of FSW in high-volume, high-productivity automated manufacturing [4-8]. Consequently, the hybrid introduction of high-frequency ultrasonic energy into the inherent system of frictional heating and mechanical stirring has emerged as a crucial and innovative research frontier known as ultrasonic-assisted friction stir welding (UAFSW).

1.2. Hybrid Introduction Mechanisms of Ultrasonics

Depending on the transmission path, propagation direction, and ultimate targeted zone of the acoustic waves, UAFSW configurations in engineering practice are primarily classified into two mainstream categories: tool-side ultrasonic assist and workpiece-side ultrasonic assist. In tool-side configurations, the ultrasonic transducer is integrated inside the rotating welding spindle or the tool assembly. The high-frequency ultrasonic energy is directly transmitted to the surrounding plasticized zone via the high-speed rotating shoulder and pin, forcing the metal adjacent to the pin to undergo severe shear strain rates and high-frequency micro-amplitude oscillations [9, 10]. Conversely, workpiece-side ultrasonic assist involves fixing the transducer and acoustic booster to one end or underneath the backing plate or fixtures. The high-frequency energy is then radiated to the butt interface and adjacent areas of the base plates through acoustic wave propagation within the substrate [5, 11-13].

During the physical joining process, the introduction of ultrasonic waves primarily triggers two highly beneficial acoustic phenomena. The first is the acoustic volume effect, also referred to as the Blaha effect or acoustic softening mechanism. When high-frequency ultrasonic strain waves propagate through a solid-state metal lattice undergoing severe plastic deformation, the induced alternating stress significantly activates internal dislocation sources, promoting dislocation cross-slip and climb. This substantially diminishes the critical resolving shear stress for lattice movement, macroscopically manifesting as an instantaneous and drastic reduction in yield strength, flow stress, and deformation resistance within the weld core of the aluminum alloy [3, 14].

The second phenomenon is the acoustic surface effect, or the tribological effect. The high-frequency, reciprocating micro-amplitude motion induced by ultrasonics thoroughly alters the tribological status at the interface between the tool contact surface and the plasticized flowing metal. This converts the conventional sticking friction condition partly into rolling or high-frequency micro-sliding friction. Consequently, the sticking friction coefficient at the solid-solid and solid-plasticized interfaces decreases significantly, which effectively reduces the normal force and spindle torque exerted on the tool, suppresses mechanical wear, and broadens the process window [15, 16].

In conventional FSW, the stir zone (SZ) undergoes continuous dynamic recrystallization (CDRK) or discontinuous dynamic recrystallization (DDRK) under severe thermo-mechanical coupling, leading to a noticeable refinement of the initial grains. With the hybrid introduction of high-frequency ultrasonic energy, the crystallographic evolution, grain boundary misorientation reconstruction, and microstructural evolution within the SZ and the thermo-mechanically affected zone (TMAZ) exhibit more intense and unique characteristics.

2. Microstructural Evolution Characteristics during UAFSW

2.1. Grain Refinement and Recrystallization Driving Force

The extra acoustic activation energy introduced by high-frequency mechanical vibration provides an excellent thermodynamic driving force for regions with high lattice distortion and dislocation density. This significantly accelerates subgrain boundary evolution, thereby enhancing the reconstruction and transformation rate of low-angle grain boundaries (LAGBs) into high-angle grain boundaries (HAGBs) [7, 17]. Quantitative metallographic observations and electron backscatter diffraction (EBSD) analyses indicate that under identical heat input conditions, the average grain size within the SZ of UAFSW joints can be further refined by 20% to 40% compared to conventional FSW [18, 19].

In sub-microscopic texture analyses of 6xxx series aluminum alloys, researchers have found that the intense, omnidirectional, isotropic material flow induced by ultrasonic assistance significantly weakens the strong shear textures typically generated by intense shoulder shearing, shifting the grain orientation toward a more uniform and randomized isotropic distribution [18, 20]. Furthermore, in recent investigations on third-generation Al-Cu-Li alloys utilized in advanced aerospace structures, ultrasonic action demonstrated exceptional capabilities for material flow homogenization. It facilitates a more complete and thorough dynamic recrystallization, entirely eliminating unrecrystallized, coarse, elongated residual matrix grains caused by insufficient boundary shear strain in conventional FSW, thereby achieving fully equiaxed grain structures across the stir zone [21, 22].

2.2. Evolution of Second Phases and Strengthening Precipitates

For heat-treatable aluminum alloys, the final mechanical load-bearing capacity and joint stability are fundamentally governed by the type, distribution, average size, and number density of nanoscale strengthening precipitates. In the SZ and TMAZ of conventional FSW joints, due to the high total heat input and prolonged thermal cycles, the original metastable strengthening precipitates of the base metal are highly susceptible to clustering, severe coarsening, or even complete dissolution under prolonged high-temperature exposure. This induces a prominent microhardness "softening valley" within the heat-affected zone (HAZ) [2, 23].

The localized, intense, high-frequency, high-shear hydrodynamic effects and acoustic cavitation impact forces generated by ultrasonic waves exert a powerful mechanical fragmentation effect. This can effectively fragment coarse, needle-like, or irregular blocky iron (Fe)-rich and manganese (Mn)-rich intermetallic compounds (IMCs) or brittle phases formed at dissimilar joint interfaces. Additionally, a core process breakthrough enabled by ultrasonics is that owing to the substantial drop in material flow stress, the welding tool can smoothly and stably produce high-quality welds at extremely low rotational speeds and faster travel speeds (referred to as low-temperature "cold parameters") [24, 25]. On one hand, this significantly shortens the dwell time of the joint within the hazardous high-temperature zone that triggers precipitate coarsening. On the other hand, the alternating shear strain from ultrasonic assistance induces a massive number of non-equilibrium vacancies and high-density intertwined dislocation sources within the matrix. These abundant structural defects drastically lower the critical nucleation energy for nanoscale precipitates, strongly promoting the re-precipitation, dispersion, and nucleation of fine strengthening precipitates with high density and uniformity during subsequent natural or artificial aging, fundamentally mitigating and repairing the thermal softening effect of the joint [5, 26].

3. Mechanical Properties of Welded Joints

Numerous experimental studies have fully confirmed that introducing an acoustic field into the friction stir welding process yields significant benefits for industrial manufacturing.

3.1. Welding Process Load Variations

Through real-time in-situ online monitoring during UAFSW, with multi-dimensional force sensors integrated into the welding spindle and mechanical fixtures, macroscopic mechanical feedback induced by the ultrasonic action can be directly captured. The axial force during welding typically drops sharply by 15% to 30%, accompanied by conspicuous reductions in traverse force and spindle torque [3, 14]. This represents the most direct manifestation of the micro-level instantaneous flow stress reduction caused by the Blaha acoustic volume softening effect at the macroscopic equipment load level. This dual reduction in torque and axial force not only minimizes the power load on the spindle motor, thereby extending the fatigue life of expensive tools such as CNC machines and high-precision welding tools, but also completely shatters the inherent industrial limitations of conventional FSW, which cannot implement high-speed, high-efficiency welding or join ultra-high-strength hard aluminum alloys on lightweight robotic arms due to equipment overload [11, 12].

3.2. Tensile Properties of Similar Aluminum Alloy Joints

Attributed to the narrowing of the HAZ, the formation of finer grains within the SZ, and the high dispersion of nanoscale precipitates within the matrix, the ultimate tensile strength (UTS), yield strength, and elongation of similar aluminum alloy joints fabricated via UAFSW undergo a substantial leap compared to conventional FSW joints.

For 2219-T6 high-strength Al-Cu alloys, which hold a dominant position in the manufacturing of cryogenic liquid propellant tanks for aerospace launch vehicles, tool-side axial ultrasonic hybrid joining was applied. Experimental results indicate that at a spindle speed of 1200 rpm, a travel speed of 150 mm/min, and an ultrasonic power of 1.8 kW, the prominent reduction in axial force vastly optimizes material filling on the advancing side (AS). The UTS of the 2219 alloy joint fabricated by this method increased by over 10.5% compared to conventional FSW joints [23]. Subsequent mechanism studies verified that the mechanical oscillations of the ultrasonic waves enhanced the plastic flow behavior of the material at the bottom layer of the joint, facilitating sufficient overlap of the localized shear layers and fundamentally eliminating hazardous defects such as kissing bonds, micro-voids, or tunneling [1].

For the highly aging-sensitive 7075-T6 ultra-high-strength aluminum alloy widely utilized in aircraft wing primary load-bearing structures, conventional joints are prone to brittle fracture at the boundary between the AS and the retreating side (RS), or within the weakest region of the HAZ. By applying tool-side high-frequency ultrasonic assistance and optimizing the spindle speed, it was found that the introduction of ultrasonics not only increased both the tensile strength and fatigue life of the 7075 alloy joint but also narrowed the width of the minimum microhardness zone (the softest valley bottom in the classic W-shaped hardness curve) [2]. The refinement of precipitates and the reduction of the softened layer width lowered the stress concentration factor under tensile loading, yielding an excellent recovery of elongation.

Similarly, in workpiece-side fixed ultrasonic-assisted welding experiments on advanced third-generation Al-Cu-Li-Mg alloys, researchers introduced ultrasonics within a rotational speed range of 800 to 1200 rpm, successfully refining the average grain size in the stir zone to 4.6 μm. This extreme grain refinement strongly stimulated the uniform, dispersed precipitation of strengthening phases within the grains. Mechanical testing revealed that the joint not only exhibited high UTS at room temperature but also achieved a major breakthrough in impact toughness under cryogenic environments, demonstrating exceptional comprehensive service performance [5].

Furthermore, in process modeling, numerical simulation, and experimental verification of the mass-applied 6061-T6 aluminum alloy series, a three-dimensional thermal-fluid-solid-acoustic coupled simulation clearly calculated and demonstrated that the localized strain rate and temperature fields were optimally planarized and enhanced [14]. The introduction of ultrasonics directly expanded the effective process window for the 6061 alloy, eradicating defect layers and voids that typically appear in conventional FSW due to insufficient heat input, and ensuring high consistency and stability in joint strength and elongation [20, 12].

3.3. Interface Control of Dissimilar Materials

Because aluminum and dissimilar metals possess vast mismatches in physical and chemical properties, including melting points, thermal conductivities, lattice constants, and linear expansion coefficients, severe atomic diffusion spontaneously occurs at the interface during friction stir welding or friction stir lap welding (FSLW). This results in the generation of thick, highly brittle intermetallic compound (IMC) reaction layers. Extensive research has confirmed that once the thickness of these brittle phase layers exceeds 2 μm, severe stress concentrations are generated, inducing trans granular fracture under loading and severely degrading the shear tensile failure load of the joint [13, 27].

For ultrasonic-assisted FSLW experiments joining 6061-T6 aluminum alloy to 301L stainless steel (processed at 1800 rpm and 200 mm/min), it was confirmed that the powerful mechanical oscillations induced by ultrasonics physically disrupted the dense passive film on the stainless steel surface and accelerated the shear flow velocity of the plasticized aluminum. While significantly enhancing the geometric interlocking of the Al/steel interface via mechanical interlocking and hook structures, this effect leveraged shorter high-temperature diffusion cycles to strictly restrict the thickness of the brittle Al-Fe IMC layer to below 1.5 μm, thereby boosting the shear failure load of the lap joint by 27.9% [28].

In dissimilar lap joints between AA2024 aluminum and AZ31 magnesium alloys, which are highly susceptible to severe low-melting-point eutectic reactions, researchers investigated workpiece-side ultrasonic hybrid welding under low-temperature "cold parameters" at a very low speed of 400 rpm. The results showed that ultrasonics vastly improved the plastic flow filling under ultra-low-temperature conditions, refining the grains in the shear core to an astonishing 0.4 μm. Meanwhile, the acoustic surface effect minimized frictional heat at the tool interface, successfully avoiding the Al-Mg eutectic reaction temperature and entirely eliminating voids and unbonded defects common in conventional welding, which significantly improved the lap shear failure load [24].

For the interface ultrasonic-assisted lap welding process of 2024 aluminum to 304 stainless steel, by synergistically optimizing the tool travel trajectory, the high-frequency acoustic impact waves forcefully shattered coarse oxide scales and discontinuous debris at the interface. This suppressed the initiation of lap voids and stabilized the final shear failure load at a high level of 7.06 kN [6]. Moreover, in the highly challenging titanium/aluminum (Ti/Al) dissimilar welding system, researchers adopted a 20 kHz tool-side ultrasonic enhancement mechanism. Utilizing the acoustic softening mechanism, the macroscopic flow stress discrepancy between the hard titanium alloy and the plasticized aluminum alloy was vastly reduced. The regulation of atomic diffusion by ultrasonics successfully facilitated metallurgical bonding at the atomic scale under lower temperature environments, completely delaying and inhibiting the malignant growth of the interfacial brittle layer, thereby leading to a stepwise increase in interface shear bonding strength [29, 30].

4. Conclusions and Future Outlook

In summary, ultrasonic-assisted friction stir welding (UAFSW), as an advanced solid-state hybrid joining technology integrating acoustic, thermal, and mechanical multi-field dynamic coupling, presents unmatched advantages over conventional techniques in high-quality welding of both similar and dissimilar aluminum alloys. By exploiting the acoustic volume effect (acoustic softening) and acoustic surface effect (tribological effect) induced by ultrasonics, the process effectively and significantly lowers the axial force and spindle torque during welding. This greatly delays the mechanical and thermal fatigue degradation of expensive tools under severe high-strength welding environments. Simultaneously, its unique acoustic regulation and oscillatory homogenization mechanisms refine the grains in the stir zone to micrometer or even sub-micrometer scales, thoroughly restructuring the disordered clustering and coarsening behavior of strengthening precipitates. Furthermore, when dealing with highly challenging dissimilar metal combinations, it efficiently suppresses the rapid growth and diffusion of brittle intermetallic compound (IMC) layers, achieving dual optimization of mechanical interlocking and metallurgical bonding.

To enable this promising advanced hybrid manufacturing process to move toward global industrial mass production and broad engineering applications across multiple sectors, future academic research and engineering breakthroughs should focus on the following two core areas:

(1) Deepening Multi-Physical Field Dynamic Coupling Theory and Constructing Numerical Simulation Frameworks: Currently, the three-dimensional acoustic field distribution, high-frequency energy dynamic attenuation, and absorption mechanisms of high-frequency ultrasonic waves within continuum materials undergoing extremely severe plastic deformation, high-speed flow, and non-uniform flow fields remain obscured by physical ambiguities. It is urgent to develop high-fidelity, quantitative interpretations of the entire welding process by combining more precise three-dimensional, non-linear, fully coupled thermal-fluid-solid-acoustic numerical simulation models.

(2) Extending the Service Life of Highly Efficient Acoustic Energy Transmission Components and Advancing Industrial Standardization: In tool-side ultrasonic configurations, which are ideal for flexible manufacturing, the energy slip rings or non-contact electromagnetic induction transformers between the high-speed rotating spindle and the high-power ultrasonic transducer still face severe reliability challenges regarding fatigue life, overheating protection, and continuous stable operation under high-power, long-duration steady-state conditions. Future engineering efforts must focus on the wear resistance and thermal dissipation design of these core acoustic components, driving the standardization and localization of core UAFSW equipment.

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