Microstructure and Mechanical Properties of High-Speed Friction Stir Welded Joints of Aluminum Alloy Thin Sheets (Postprint)

Authors: Liu Fenjun, Fu Li, Chen Haiyan

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Abstract

Butt joining of 0.8 mm thick 6061-T6 aluminum alloy thin sheets was achieved using a high-speed micro friction stir welding process. The influence of high rotational speed on the microstructure and mechanical properties of the joints was investigated using testing techniques such as OM, SEM, TEM, and EBSD. The results show that when welding 6061-T6 thin sheets at high rotational speeds, the weld surface exhibits good formation, and the microstructure in each region of the weld shows a continuous and uniform transition. Compared with conventional friction stir welding, under high-speed process conditions, the number of precipitates including -Mg2Si, S-phase (Al2CuMg), and Al8Fe2Si in the weld zone increases, particularly the quantity of elongated -Mg2Si, resulting in a significant increase in microhardness values in the weld zone. Under conditions of rotational speed 8000 r/min and welding speed 1500 mm/min, the maximum tensile strength of the joint reaches as high as 301.8 MPa, which is 85.8% of the base material tensile strength (351.7 MPa). Rotational speed has a minor influence on the tensile strength of butt joints in high-speed friction stir welding of ultra-thin 6061-T6 aluminum alloy sheets, and the joint fracture mode is a ductile-brittle mixed fracture dominated by brittle fracture.

Full Text

Microstructures and Mechanical Properties of Thin Plate Aluminium Alloy Joint Prepared by High Rotational Speed Friction Stir Welding

LIU Fenjun[1], FU Li[1,2,3], CHEN Haiyan[1,2,3]

[1] School of Materials Science and Engineering, Northwestern Polytechnical University, Xi' an 710072, China

[2] State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi' an 710072, China
[3] Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi' an 710072, China
Correspondent: FU Li, professor, Tel: (029)88460250, E-mail: fuli@nwpu.edu.cn

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Abstract

Aluminium alloys are widely applied in rail transit, shipbuilding, and aerospace industries owing to their unique properties, including low density, high specific strength and stiffness, outstanding corrosion resistance, and excellent low-temperature performance. As structural materials, joining of aluminium alloys is often inevitable. However, these alloys are considered difficult to weld using traditional fusion welding techniques due to associated metallurgical defects, large deformation, and residual stress. Friction stir welding (FSW), an innovative solid-state welding technology invented at The Welding Institute (TWI), has been recognized by designers as an effective method for joining aluminium alloys because of its low heat input, minimal stress-strain, and environmental friendliness.

In this work, 0.8 mm thick 6061-T6 aluminium alloy plates were successfully welded using high rotational speed friction stir welding technology. The microstructure and mechanical properties of the butt joints were analyzed in detail. The results show that welds exhibited excellent surface topography and bonding interface in the nugget zone (NZ). The microhardness of the weld seam was lower than that of the base material, with the lowest values located in the transition region between the thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ). Compared with conventional rotational speeds, the number of -Mg Si, Al CuMg, and Al Fe Si precipitated phases in the NZ increased significantly, leading to substantially improved microhardness in this region. Rod-shaped Mg Si precipitates exhibited the greatest influence on microhardness. Optimal mechanical properties were obtained at a rotational speed of 8000 r/min and welding speed of 1500 mm/min, achieving a maximum tensile strength of 301.8 MPa, which corresponds to 85.8% of the base material strength (351.7 MPa). The fracture mode exhibited quasi-cleavage characteristics, representing a ductile-brittle mixed fracture with predominant brittle fracture.

KEY WORDS thin plate 6061-T6 aluminium alloy, high rotational speed, friction stir welding (FSW), microstructure, tensile property

1. Introduction

Energy efficiency, safety, and environmental protection are primary development directions in modern transportation and aerospace industries, with lightweighting being a crucial approach to achieving these goals. Aluminium alloys, characterized by high plasticity, large specific strength, and good corrosion resistance, are widely used in vehicles, ships, automobiles, rail transit, and aircraft, particularly in general aviation and unmanned aerial vehicles. Under conditions of adequate structural stiffness and strength, thin-walled aluminium alloy components can significantly reduce weight and enhance flight performance. Traditional manufacturing methods primarily employ riveting or fusion welding. However, riveting involves complex manufacturing processes, high costs, and is detrimental to structural weight reduction [1]. Fusion welding often results in defects such as hot cracking, porosity, and significant residual stress and deformation [2,3].

Friction stir welding (FSW), invented by The Welding Institute (TWI) in 1991, is a novel and promising solid-state welding method. Compared with traditional aluminium alloy joining technologies, FSW only heats the material to a plastic state, effectively avoiding metallurgical defects and large stress-strain associated with fusion welding. Additionally, the process requires no filler material, substantially reducing structural weight [4,5]. Current research on microstructure and properties of aluminium alloy FSW joints has primarily focused on conventional rotational speeds for plates 2 mm and thicker [6–10]. Studies on 1 mm thick 6016-T4 [11], 5182-H111 [12], and 5182-H111/6016-T4 [13] homogeneous or heterogeneous aluminium alloy FSW have revealed the influence of tool shoulder geometry and process parameters on plastic metal flow, microstructure, and mechanical properties.

Scialpi et al. [14–16] investigated 1.5 mm thick 6082-T6 and 0.8 mm thick 2024-T3/6082-T6 aluminium alloys, exploring the effects of tool geometry and process parameters on joint microstructure and mechanical properties. Murr et al. [17] studied precipitate distribution and microstructure in 0.6 mm thick 6061 aluminium alloy FSW joints at 400 r/min using transmission electron microscopy (TEM). Zhao et al. [18] reported microstructural characteristics and temperature field distribution in high rotational speed (25000 r/min) FSW lap joints of LF3 aluminium alloy thin plates. However, detailed investigations on the influence of high rotational speeds on microstructure and mechanical properties of thin aluminium alloy FSW butt joints remain limited.

This work focuses on high rotational speed FSW of 6061-T6 aluminium alloy thin plates, aiming to elucidate the effects and underlying mechanisms of high rotational speed on joint microstructure and mechanical properties, thereby providing theoretical and practical guidance for engineering applications of high rotational speed FSW technology.

2. Experimental

2.1 Materials and Welding Parameters

The experimental material consisted of 0.8 mm thick 6061-T6 aluminium alloy plates. Welding was performed along the rolling direction using an FSW-TS-F08-DZ micro bench-top high rotational speed friction stir welding machine. The tool, machined from H13 die steel, featured a three-spiral groove shoulder and a conical pin with a length of 0.65 mm. The tool was oriented perpendicular to the joint line and rotated clockwise without tilt angle. The welding setup and tensile specimen sampling are schematically illustrated in [Figure 1: see original paper].

Welding parameters were as follows: for high rotational speed welding, the welding speed was fixed at 1500 mm/min with rotational speeds of 7000, 8000, 9000, 10000, and 11000 r/min; for conventional rotational speed welding, the parameters were 300 mm/min welding speed and 2000 r/min rotational speed.

2.2 Characterization Methods

Cross-sectional specimens for microstructural observation were cut perpendicular to the welding direction. Metallographic samples were etched with 5% hydrofluoric acid solution (5 mL HF + 95 mL H O) for 2 minutes. An MG3 optical microscope (OM) was used to examine the bonding interface morphology and microstructural characteristics. A VEGA3LMU scanning electron microscope (SEM) equipped with electron backscatter diffraction (EBSD) and a Tecnai G2 F30 transmission electron microscope (TEM) were employed to characterize fracture morphologies, recrystallization, and precipitate distribution. EBSD samples were mechanically ground and polished, followed by electropolishing in a perchloric acid-ethanol solution (50 mL HClO + 950 mL C H OH) at 55 V for 15 seconds. TEM foils were prepared by mechanical thinning and subsequent twin-jet electropolishing (25 mL HClO + 475 mL C H OH). Microhardness profiles across the joint cross-section were measured along the centerline using an HMV-2 microhardness tester with a load of 1.96 N and dwell time of 15 seconds. Tensile testing was conducted on an INSTRON 3382 universal testing machine at a crosshead speed of 1 mm/min.

3. Results and Discussion

3.1 Macroscopic Weld Formation

[Figure 2: see original paper] shows the surface macro-morphology of 6061-T6 aluminium alloy thin plate FSW joints at different rotational speeds. The weld surfaces exhibited good formation with minimal flash and no defects such as grooves or cracks. Compared with conventional rotational speeds, both tool rotational speed and welding speed increased in high rotational speed FSW, with rotational speed having a greater influence on heat generation [19,20]. At high rotational speeds, the thermoplastic material adjacent to the tool shoulder experienced higher degrees of softening, which tended to adhere to the surface during high-speed rotation and advance, resulting in a surface appearance characterized by less distinct arc patterns and more burrs compared to conventional FSW.

3.2 Microstructure

Macroscopic morphologies of joints at different rotational speeds are presented in [Figure 3: see original paper]. Both conventional (FIG. 3a) and high rotational speed (FIG. 3b) conditions exhibited slight thinning in the weld zone, with the high rotational speed condition showing overall compressive deformation relative to the base material. A distinct Zigzag bonding interface was observed in all welds, which originated at the initial plate center, bent upward from the bottom to the top, and deviated toward the retreating side, disappearing in the region immediately beneath the weld surface. The deviation distance of the bonding interface toward the retreating side was significantly greater at high rotational speeds than at conventional speeds.

The welded joint consisted of base material (BM) and weld zone, with the latter comprising heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and nugget zone (NZ). The HAZ contained coarsened equiaxed grains ([Figure 4: see original paper]a and d), the TMAZ consisted of elongated deformed grains and partial equiaxed grains (FIG. 4b and e), and the NZ exhibited fine equiaxed grains (FIG. 4c and f). At high rotational speeds, no distinct boundary existed between HAZ and TMAZ ([Figure 3: see original paper]b), and the quantity of precipitated phases—including rod-like or needle-like -Mg Si, circular S-phase (Al CuMg), and rectangular Al Fe Si—was significantly greater than at conventional speeds, as shown in [Figure 5: see original paper].

During FSW, the weld zone metal softens under the combined action of frictional heat and plastic deformation heat, with thermoplastic metal undergoing rotational flow under the shear stress from the rotating tool. The initial contact interface is fragmented by the tool’ s stirring action and the shear forces from adjacent plastic metal flow, subsequently depositing behind the tool after flowing around from the advancing side to the retreating side, thereby forming the Zigzag bonding interface on the retreating side.

The heat input during FSW can be expressed by the following equation [19]:

$$Q = \frac{2\pi\omega}{3}\left[\delta\tau + (1-\delta)\mu p\right]\left[R_s^3(1+\tan\alpha) + 3R_p^2 H_p - R_p^3\right]$$

where Q is heat input, is the contact state variable, is material yield stress at welding temperature, is friction coefficient, p is contact interface pressure, is angular velocity, R is shoulder radius, R is pin radius, is shoulder concave angle, and H is pin length.

As indicated by Equation (1), heat input increases with rotational speed when other parameters remain constant. At high rotational speeds, significantly increased heat input widens the softened material region and expands the flow zone of thermoplastic metal around the tool. During the backfilling and consolidation process from the advancing side to the retreating side, a larger-radius compressive deformation layer forms on the retreating side, causing more pronounced deviation of the bonding interface from the weld center. Additionally, increased heat input reduces the temperature gradient across the joint, promoting small-gradient continuous microstructural transition between HAZ and TMAZ [21] and resulting in an indistinct interface, as shown in [Figure 4: see original paper]e. This occurs because significant dynamic recrystallization occurs at high rotational speeds ([Figure 6: see original paper]), with recrystallized structures in different weld zones tending toward continuous transition under extensive thermal cycling. The fraction of recrystallized grains gradually increased from HAZ to NZ, while deformed grains decreased, and subgrains were slightly larger in NZ and TMAZ than in HAZ ([Figure 7: see original paper]).

During FSW, the NZ experiences the strongest thermo-mechanical stirring, followed by TMAZ. Intense thermal deformation in the NZ generates numerous low-angle grain boundaries, which migrate to form subgrain boundaries. Under sufficient thermal conditions, these subgrain boundaries grow and merge to form recrystallized grains [21], resulting in a grain structure dominated by recrystallized grains with subgrains and minimal deformed grains in the NZ ([Figure 7: see original paper]). In TMAZ, where thermo-mechanical action is less severe, some deformed grains transform into recrystallized grains through dynamic recrystallization, while others form subgrains via low-angle grain boundary formation and migration, yielding a balanced distribution of recrystallized grains, subgrains, and deformed grains. In HAZ, which experiences only thermal cycling, recrystallization does not occur, and the region consists primarily of deformed grains from the base material. The continuous gradient transition of recrystallized grains, subgrains, and deformed grains across weld zones contributes to the uniform microstructure and indistinct interfaces observed in high rotational speed FSW.

For heat-treatable 6xxx series aluminium alloys, precipitate dissolution and coarsening are primarily governed by the welding thermal cycle. Research indicates that precipitate dissolution occurs when rotational speed exceeds 900 r/min [22]. During high rotational speed FSW of 6061-T6 thin plates, the large heat input and relatively extended high-temperature dwell time promote sufficient dissolution of -Mg Si, Al CuMg, and Al Fe Si precipitates during heating. During subsequent cooling, extensive reprecipitation occurs, resulting in significantly higher precipitate density compared to conventional rotational speeds

([Figure 5: see original paper]).

3.3 Microhardness

Microhardness distributions across the weld cross-section at different rotational speeds are shown in [Figure 8: see original paper]. All joints exhibited a “W” -shaped hardness profile, consistent with other heat-treatable aluminium alloy FSW joints [23]. Weld zone microhardness was lower than base material, with minimum values occurring in the transition region between TMAZ and HAZ. High rotational speeds significantly increased microhardness values and improved uniformity across the transverse section.

For 6061-T6 heat-treatable aluminium alloy, microhardness is closely related to grain size and precipitate geometry, size, and distribution, particularly influenced by rod-like or needle-like -Mg Si precipitates [24,25]. As shown in [Figure 5: see original paper], high rotational speed joints contained substantially more rod-like -Mg Si, circular S-phase (Al CuMg), and rectangular Al Fe Si precipitates in both HAZ and NZ compared to conventional speed joints, especially -Mg Si and S-phase (FIG. 5c and d), resulting in significantly higher microhardness. Although HAZ contained more precipitates than NZ, its microhardness was slightly lower because dynamic recrystallization in the NZ produced fine grains and high-density low-angle grain boundaries ([Figure 9: see original paper]), causing hardness recovery. This demonstrates that high rotational speed FSW substantially reduces softening in 6061-T6 thin plate welds.

3.4 Tensile Properties

Tensile properties of 6061-T6 base material and FSW joints at different rotational speeds are summarized in . High rotational speed joints exhibited superior tensile properties compared to conventional speed, achieving 80% or more of base material strength. At a welding speed of 1500 mm/min and rotational speed of 8000 r/min, optimal tensile performance was obtained with ultimate tensile strength, yield strength, and elongation reaching 85.8%, 73.0%, and 25.1% of base material values, respectively. Tensile properties decreased slightly at 11000 r/min. All tensile specimens fractured in the transition region between TMAZ and HAZ on the advancing side ([Figure 10: see original paper]a). Fractography revealed relatively flat fracture surfaces at high rotational speeds ([Figure 10: see original paper]b) with large shear lips containing dimples of varying depths, indicating quasi-cleavage fracture characteristics.

During conventional rotational speed FSW of aluminium alloy thin plates, insufficient heat input due to rapid heat dissipation can lead to weak bonding defects [26]. While reducing welding speed increases heat input and eliminates defects, it also causes severe softening ([Figure 8: see original paper]). High rotational speed FSW addresses this through high rotational speed coupled with fast welding speed: the high speed ensures adequate heat input for precipitate dissolution, while the fast welding speed accelerates cooling and suppresses precipitate growth and coarsening during cooling, thereby reducing softening compared to conventional speeds ([Figure 8: see original paper]). Consequently, the tensile strength of high rotational speed FSW joints reached 1.26 times that of conventional speed joints, demonstrating superior mechanical properties.

4. Conclusions

(1) Successful high rotational speed FSW of 0.8 mm thick 6061-T6 aluminium alloy butt joints was achieved with excellent surface appearance and bonding interface. Optimal mechanical properties were obtained at 8000 r/min and 1500 mm/min, achieving an ultimate tensile strength of 301.8 MPa—126.3% of conventional speed joints and 85.8% of base material.

(2) The NZ of high rotational speed FSW joints consisted primarily of equiaxed recrystallized grains and subgrains, TMAZ contained recrystallized grains, subgrains, and elongated deformed grains, while HAZ was dominated by deformed grains with minor recrystallized grains and subgrains. A continuous small-gradient transition in grain structure existed across all weld zones.

(3) High rotational speed FSW joints exhibited significantly higher densities of rod-like -Mg Si, circular S-phase (Al CuMg), and rectangular Al Fe Si precipitates compared to conventional speed joints, resulting in reduced softening, higher microhardness values, and more uniform hardness distribution across the transverse section.

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