Postprint: Interfacial Structure and Mechanical Properties of Dissimilar 2099-T83/2060-T8 Aluminum-Lithium Alloy Friction Stir Welded Lap Joints

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Abstract

Friction stir welding (FSW) was employed to join 2 mm thick 2099-T83 and 2060-T8 Al-Li alloys in a lap configuration. The effects of tool rotation speed and pin length on the interface structure and mechanical properties of the lap joints were investigated using analytical techniques such as OM and SEM. The results show that a distinct bonding interface could be observed in the weld zone of the 2099-T83/2060-T8 lap joints, the microhardness of the weld zone was lower than that of the base material, and the lowest hardness values occurred in the transition region between the thermo-mechanically affected zone (TMAZ) and the nugget zone. When the tool rotation speed was increased from 600 r/min to 800 r/min and the pin length was decreased from 3 mm to 2.5 mm, the interface morphology transformed from a smooth interface to a "sawtooth" -shaped interlocking interface, with the bonding interface morphology in the weld zone being primarily influenced by the pin length. The lap joints with a "sawtooth" interlocking interface exhibited an average failure load of 654 N, representing a 110% improvement in load-bearing capacity compared to those with a smooth bonding interface morphology. All lap joints fractured in the transition region between the thermo-mechanically affected zone and the nugget zone on the 2060-T8 base material side at the bottom, with fracture characteristics of a ductile-brittle mixed mode. After artificial aging treatment at 150°C for 20 h, the lap joints with a "sawtooth" interlocking interface showed increased microhardness in the weld zone, but the joint load-bearing capacity decreased by 20% compared to the as-welded condition, and the fracture surface exhibited a brittle fracture mode.

Full Text

Preamble

INTERFACE STRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDING JOINT OF 2099-T83/2060-T8 DISSIMILAR Al-Li ALLOYS

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ABSTRACT: Friction stir welding (FSW) was employed to join 2 mm thick 2099-T83 and 2060-T8 Al-Li alloys in a lap configuration. The effects of tool rotation speed and pin length on the interface structure and mechanical properties of the lap joints were investigated using optical microscopy (OM) and scanning electron microscopy (SEM). The results revealed a distinct bonding interface in the weld zone of the 2099-T83/2060-T8 lap joints, with the weld zone exhibiting lower microhardness than the base material. The lowest hardness values were observed in the transition region between the thermo-mechanically affected zone (TMAZ) and the weld nugget zone. When the tool rotation speed was increased from 600 r/min to 800 r/min and the pin length was decreased from 3 mm to 2.5 mm, the interface morphology transformed from a smooth interface to a "serrated" interlocking interface. The interface morphology was primarily influenced by the pin length. The lap joints with serrated interlocking interfaces achieved an average failure load of 654 N, representing a 110% improvement in load-bearing capacity compared to those with smooth bonding interfaces. All lap joints fractured in the transition region between the TMAZ and weld nugget zone on the 2060-T8 side of the bottom sheet, exhibiting a mixed ductile-brittle fracture characteristic. After artificial aging treatment at 150°C for 20 h, the microhardness of the weld zone increased, while the load-bearing capacity of the lap joints with serrated interfaces decreased by 20% compared to the as-welded condition, with the fracture mode becoming brittle.

KEYWORDS: 2099-T83 Al-Li alloy, 2060-T8 Al-Li alloy, friction stir welding, artificial aging treatment, interface morphology, joint strength

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Introduction

2099-T83 and 2060-T8 are new Al-Li alloys with high specific strength and stiffness, excellent low-temperature performance, and broad potential applications in aircraft manufacturing, particularly for fuselage skin and stringer structures. Lap joints are in considerable demand for practical applications of these alloys.

However, conventional fusion welding of Al-Li alloys often results in defects such as porosity, hot cracking, and significant residual stress and distortion [1-3]. Riveting technology, while an alternative, involves complex manufacturing processes, high costs, and is detrimental to structural weight reduction [4].

Friction stir welding (FSW), as an innovative solid-state joining method, can effectively avoid fusion welding defects while reducing manufacturing costs and structural weight when applied to aluminum alloys. Cederqvist and Reynolds [5] and Dubourg et al. [6] investigated the effects of different welding parameters on the bonding interface morphology, bonding width, effective sheet thickness, and hook defects in FSW lap joints of 2024-T3 and 7075-T6 aluminum alloys, with shear test results indicating that microstructure significantly affects shear properties. Research on the influence of tool geometry and welding parameters on the lap interface and tensile/shear performance of similar aluminum alloys has focused on alloys such as 2014-T4 [7], 2198-T4 [8], 6082-T6 [9], 5083-O [10], 2024-T3 [11], 6181-T4 [12], and LY12 [13]. Wang et al. [14] studied FSW of Al-Cu-Li alloys, showing that weld nugget zone grain size increased with tool rotation speed, and tensile test results demonstrated that joint strength gradually increased with rotation speed under lower welding speeds. These studies primarily evaluated the relationship between microstructure and properties of similar or dissimilar aluminum alloy lap joints under various tool geometries and welding conditions based on tensile or shear test results. However, comprehensive investigations on the combined effects of tool rotation speed and pin length on joint microstructure and properties are scarce. Moreover, while lap joint structures experience not only shear loads parallel to the bonding interface but also peel loads perpendicular to it, conventional tensile and shear tests cannot effectively evaluate the mechanical performance under peel loading conditions. Therefore, exploring the influence of tool rotation speed and pin length on joint microstructure and properties, and assessing mechanical performance through peel testing, is of significant importance for the practical application of these Al-Li alloys.

This work primarily investigates the interface morphology and mechanical properties of dissimilar 2xxx series Al-Li alloy 2099-T83/2060-T8 lap joints produced under different tool rotation speeds and pin lengths, revealing the influence 规律 of these parameters on the microstructure and mechanical properties. The effects of artificial aging treatment on the performance of 2099-T83/2060-T8 FSW lap joints are also examined, providing theoretical guidance for the engineering application of these alloys.

Experimental Procedures

The base materials used in this study were 2 mm thick rolled 2060-T8 sheets and 2099-T83 stringers. Welding was performed along the rolling direction using an FSW2-4CX-006 friction stir welding machine. The welding tool featured a 10 mm diameter double-ring shoulder and a 3 mm diameter conical pin with lengths of 2.5 mm and 3 mm. The tool rotated clockwise at speeds of 600 r/min and 800 r/min, with a constant welding speed of 400 mm/min. Selected lap joints welded at 800 r/min were subjected to artificial aging treatment at 150°C for 20 h followed by furnace cooling to room temperature.

Post-weld samples were sectioned perpendicular to the welding direction. The joint interfaces were etched using Keller' s reagent (1 mL HF + 5 mL HNO + 3 mL HCl + 190 mL H O) and examined using an OLYMPUS-MG3 optical microscope (OM) to observe the lap joint interface morphology. Microhardness profiles across the weld were measured at a depth of 0.6 mm from the surface using an HMV-2 microhardness tester with a load of 1.96 N and dwell time of 15 s.

Peel tests were conducted on an INSTRON 3300 universal testing machine using specimens measuring 44 mm × 10 mm × 30 mm. The peel test fixture is schematically illustrated in [Figure 1: see original paper], with a loading speed of 0.5 mm/min. Fracture surfaces were examined using a VEGA-II scanning electron microscope (SEM).

2.1 Lap Interface Morphology

[Figure 2: see original paper] shows the microstructure of 2099-T83/2060-T8 FSW lap joints under different welding conditions, while [Figure 3: see original paper] presents detailed views of the local bonding interface in the weld zone. The weld nugget zone exhibited a basin shape, similar to the macroscopic morphology observed in other aluminum alloy FSW joints [15], with a distinct bonding interface visible between the weld nugget zones. At a rotation speed of 600 r/min, welding speed of 400 mm/min, and pin length of 3 mm, the bonding interface was smooth and continuous ([FIGURE:2a and 3b]). The advancing side interface exhibited severe downward bending deformation, with obvious porosity defects near the bottom 2060-T8 alloy side ([Figure 3a: see original paper]), while the retreating side interface bent upward with less severe deformation ([Figure 3c: see original paper]). Under these conditions, weak bonding (kissing-bond) defects formed at the bonding interfaces near both the advancing and retreating sides of the weld zone. [Figure 2b: see original paper] shows the interface morphology at 800 r/min, 400 mm/min, and 2.5 mm pin length, where the bonding interface exhibited a "serrated" interlocking morphology ([Figure 3e: see original paper]). The bending of both advancing and retreating side interfaces was less pronounced ([FIGURE:3d and 3f]), with smaller kissing-bond defects formed on the retreating side. No significant changes in interface morphology were observed after artificial aging treatment, as shown in [Figure 4: see original paper].

When using a 3 mm pin length, the pin penetrated deeply into the bottom 2060-T8 sheet, resulting in a large frictional contact area but relatively weak thermo-mechanical stirring intensity directly at the initial contact interface between the upper and lower sheets. This led to insufficient interface fragmentation and poor material flow, producing a smooth bonding interface. On the advancing side, the thermoplastic softening of metal was more extensive during welding, creating a larger softened zone that caused the plasticized metal to flow downward under relatively small rotational shear stresses, forming a downward-bending interface. On the retreating side, the smaller thermoplastic softened region provided insufficient flow channels, obstructing the backfilling path of plasticized metal from the advancing side and causing accumulation, extrusion, and upward flow. Combined with the shear stresses from tool rotation, this resulted in an upward-bending interface and porosity defects on the advancing side.

Increasing the tool rotation speed enhanced heat input while reducing the pin length to 2.5 mm decreased the penetration depth into the bottom 2060-T8 sheet. This intensified the thermo-mechanical stirring action directly at the initial contact interface, achieving more complete interface fragmentation and sufficient vertical flow of thermoplastic softened metal to form a serrated interlocking interface. Additionally, the bottom 2060-T8 sheet exhibited a smaller thermoplastic softened region with higher softening degree and better flowability, resulting in less pronounced interface bending at both the advancing and retreating sides [5,6]. The initial interface with lower softening degree adjacent to the weld zone was drawn into the weld ends, forming kissing-bond interfaces.

These results demonstrate that increasing tool rotation speed (ensuring sufficient heat input for adequate metal softening) while decreasing pin length not only enhances the thermo-mechanical stirring action directly at the initial contact interface of the lap joint, intensifying turbulent flow of nearby thermoplastic softened metal and achieving complete fragmentation of the initial sheet surfaces, but also effectively reduces vertical flow of plasticized metal along the pin length direction while promoting horizontal flow. This effectively suppresses the formation of micro-voids and kissing-bond defects, resulting in a serrated interlocking interface with thorough fusion of the upper and lower sheets in the weld nugget zone. Furthermore, interface bending at the advancing and retreating sides was reduced, hook defect size decreased, and the effective load-bearing sheet thickness in the weld zone increased, thereby improving lap joint performance. Previous studies [5,6,10,11] have indicated that modifying pin geometry or employing multi-pass welding can increase the bonding interface width and improve interface structural characteristics, enhancing joint mechanical properties.

2.2 Microhardness Distribution

[Figure 5: see original paper] presents the microhardness distribution across the cross-section at 0.6 mm below the surface of FSW lap joints. The microhardness exhibited a W-shaped profile, similar to distributions observed in other heat-treatable aluminum alloy FSW joints [15,17,25]. The weld nugget zone hardness was significantly lower than the base material, decreasing to a minimum at the boundary between the thermo-mechanically affected zone and heat-affected zone with increasing distance from the weld center, then gradually rising to the base material hardness. This trend aligns with microhardness distributions in 2017-T351 aluminum alloy FSW joints, where the maximum softening region appears at the interface between the weld nugget zone and thermo-mechanically affected zone [18]. When the welding speed remained constant, increasing the tool rotation speed to 800 r/min and decreasing the pin length to 2.5 mm narrowed the weld nugget zone and significantly reduced its hardness, while shifting the hardness minimum closer to the weld center. After artificial aging treatment, the microhardness of the 2099-T83/2060-T8 FSW lap joints increased noticeably, with the maximum softening zone remaining at the interface between the weld nugget zone and thermo-mechanically affected zone.

For precipitation-strengthened aluminum alloys, hardness is primarily related to the shape, size, and distribution of precipitated phases [19]. Studies [19-21] have shown that dissolution of strengthening precipitates progressively increases in the heat-affected zone and thermo-mechanically affected zone, reaching maximum dissolution in the weld nugget zone. Increasing tool rotation speed raises welding heat input, enhancing precipitate dissolution in the weld nugget zone and reducing hardness. Therefore, microhardness should continuously decrease from the base material to the weld nugget zone, reaching a minimum in the weld nugget zone. However, incomplete dynamic recrystallization occurs in the weld nugget zone under intense thermo-mechanical stirring, forming fine grains and high-density low-angle grain boundaries that slightly increase microhardness [18,22,23]. This creates a discontinuous hardness distribution at the weld nugget zone/thermo-mechanically affected zone interface, representing the most severely softened region of the joint. Lithium exhibits high solubility in aluminum with significant temperature dependence, giving Al-Li alloys pronounced age-hardening effects. During aging, metastable phases precipitate as dispersed particles that strongly impede dislocation motion [25], resulting in increased microhardness in the weld zone after artificial aging treatment.

2.3 Joint Strength

[Figure 6: see original paper] shows typical macroscopic fracture morphologies of peel test specimens for 2099-T83/2060-T8 lap joints welded at 600 r/min with 3 mm pin length. The results indicate that increasing tool rotation speed and decreasing pin length enhanced the thermo-mechanical stirring action at the initial contact interface, reduced welding defects, and significantly improved joint performance. The lap joints welded at 800 r/min with 2.5 mm pin length achieved an average failure load of 654 N, which is 2.1 times higher than the 312 N average failure load obtained at 600 r/min with 3 mm pin length. All lap joints fractured in the transition region between the thermo-mechanically affected zone and weld nugget zone on the advancing side of the bottom 2060-T8 sheet.

The heat input during friction stir welding can be expressed by:

$$Q = \alpha\mu P\frac{N}{V}\cdot 2\pi R$$

where Q is heat input, is the heat input coefficient, is the friction coefficient, P is pressure, N is tool rotation speed, R is shoulder radius, and V is welding speed.

At constant welding speed, the 600 r/min condition produced lower heat input than 800 r/min according to equation (1), resulting in lower thermoplastic softening and less softened metal in the weld zone. With the 3 mm pin length penetrating deeply into the bottom 2060-T8 sheet, the thermo-mechanical stirring action at the initial contact interface between the sheets was weak, leaving remnants of the original contact interface that formed kissing-bond defects. Poor material flow created porosity defects on the advancing side, while the long pin promoted substantial vertical flow of weld metal, causing severely bent weak-bonding interfaces at both the advancing and retreating sides. These defects not only reduced the effective load-bearing thickness of the bottom sheet but also created stress concentration sites that significantly degraded joint performance [5,6,11,24]. As shown in [Figure 2a: see original paper], the lap joint fractured along the weak bonding interface on the advancing side under relatively low peel loads.

Increasing heat input enhanced thermoplastic softening and promoted sufficient metal flow, suppressing porosity formation. Reducing pin length decreased vertical flow amplitude while increasing horizontal flow at the bonding interface, effectively limiting interface bending at both sides. The stronger thermo-mechanical stirring action of the shorter pin on the initial contact interface significantly improved kissing-bond defects, as shown in [Figure 2b: see original paper], thereby enhancing joint strength. After artificial aging treatment, the 2099-T83/2060-T8 FSW lap joints exhibited an average failure load of 523 N, representing a 20% reduction compared to the as-welded condition. Artificial aging increased the microhardness difference between the weld nugget zone and thermo-mechanically affected zone, creating stress concentration in this weak-bonding interface region during peel testing and reducing its coordinated deformation capability, thereby decreasing load-bearing capacity. This phenomenon aligns with findings reported by Ren et al. [17] and Steuwer et al. [26].

2.4 Fracture Morphology

[Figure 7a: see original paper] shows the peel fracture morphology of a 2099-T83/2060-T8 FSW lap joint welded at 600 r/min with 3 mm pin length. The high-magnification image of area A in [Figure 7a: see original paper] ([Figure 7b: see original paper]) reveals a smooth, flat fracture surface corresponding to the kissing-bond interface on the advancing side of the bottom 2060-T8 sheet. The high-magnification image of area B ([Figure 7c: see original paper]) shows numerous dimples, indicating a ductile fracture mode. However, the presence of the kissing-bond interface significantly reduced the effective load-bearing area and degraded joint performance.

[Figure 8a: see original paper] presents the peel fracture morphology of a joint welded at 800 r/min with 2.5 mm pin length. No kissing-bond interface was observed, increasing the effective load-bearing area and improving joint performance. The high-magnification image of area A ([Figure 8b: see original paper]) shows numerous tear ridges with large tear lips, characteristic of quasi-cleavage fracture. Area B ([Figure 8c: see original paper]) exhibits extensive dimples, indicating ductile fracture. The overall fracture mode was mixed ductile-brittle.

[Figure 9a: see original paper] shows the peel fracture morphology of a joint welded at 800 r/min with 2.5 mm pin length after artificial aging treatment. Comparing [Figure 8a: see original paper] and [Figure 9a: see original paper], the macroscopic fracture morphology changed significantly after aging. The high-magnification image of area A ([Figure 9b: see original paper]) shows a relatively smooth, flat fracture surface corresponding to a kissing-bond defect. Area B ([Figure 9c: see original paper]) exhibits obvious cleavage facets, indicating brittle fracture.

3 Conclusions

(1) Distinct bonding interfaces were observed in the weld nugget zone of 2099-T83/2060-T8 Al-Li alloy friction stir welding (FSW) lap joints. The interface morphology transformed from smooth to "serrated" interlocking with increasing tool rotation speed and decreasing pin length. Under lower rotation speed (600 r/min) and longer pin length (3 mm), the bonding interfaces near both the advancing and retreating sides exhibited pronounced bending in opposite directions, with large kissing-bond and porosity defects formed at the interface ends. Under higher rotation speed (800 r/min) and shorter pin length (2.5 mm), interface bending was less pronounced with smaller kissing-bond defects.

(2) The microhardness in the weld nugget zone of 2099-T83/2060-T8 FSW joints decreased significantly with increasing rotation speed and decreasing pin length, while joint performance improved substantially. Peel fractures occurred in the transition region between the thermo-mechanically affected zone and weld nugget zone on the advancing side of the bottom 2060-T8 sheet, with the fracture mode changing from ductile to mixed ductile-brittle. After artificial aging treatment, the microhardness of the weld zone increased, while the average peel failure load decreased by 20% compared to the as-welded condition, with a brittle fracture mode.

(3) With sufficient welding heat input, pin length played a dominant role in determining the bonding interface morphology of lap joints. A shorter pin was beneficial for reducing vertical flow and enhancing horizontal flow of interfacial plasticized metal, effectively suppressing welding defects and improving the mechanical properties of FSW lap joints.

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