

Postprint: Friction Stir Welding of 7B04 Aluminum Alloy Thin Sheets and Low-Temperature Superplasticity of Joints

Authors: Yang Chao, Wang Jijie, Ma Zongyi, Ni Dingrui, Fu Mingjie, Li Xiaohua, Zeng Yuan-Song

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Abstract

Friction stir welding was conducted on 2 mm thick annealed 7B04 aluminum alloy sheets under three parameter sets: rotational speed 1600 r/min with welding speed 200 mm/min; rotational speed 800 r/min with welding speed 200 mm/min; and rotational speed 400 r/min with welding speed 400 mm/min. The effects of welding parameters on weld quality and microstructure were investigated, and the low-temperature superplastic deformation behavior of the weld nugget zone was analyzed. The results demonstrate that good weld quality can be obtained through parameter control, achieving a joint strength coefficient of 100%. Dynamic recrystallization occurred in the weld nugget zone, generating fine equiaxed grains. The base material grain size was approximately 300 μm, while the grain sizes at rotational speeds of 1600, 800, and 400 r/min were 2, 1, and 0.6 μm, respectively. This fine-grained structure facilitates superplastic deformation in the weld nugget zone. At 300 °C, elongations of 160%~590% were achieved in the weld nugget zone at strain rates of 1×10^{-3} and 3×10^{-4} s⁻¹; at 350 °C and 1×10^{-3} s⁻¹, a maximum elongation of up to 790% was obtained; and the superplastic deformation behavior vanished at approximately 400 °C.

Full Text

Friction Stir Welding and Low-Temperature Superplasticity of 7B04 Aluminum Alloy Sheet

YANG Chao^{1,2}, WANG Jijie^{2}, MA Zongyi^{1}, NI Dingrui^{1}, FU Mingjie^{3}, LI Xiaohua^{3}, ZENG Yuansong^{3}

- 1) Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

- 2) College of Materials Science and Engineering, Shenyang Aerospace University, Shenyang 110036, China
- 3) Metal Forming Technology Department, Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China

Abstract: Annealed 7B04 Al sheets with a thickness of 2 mm were subjected to friction stir welding (FSW) under three parameter sets: rotation rate 1600 r/min with welding speed 200 mm/min, rotation rate 800 r/min with welding speed 200 mm/min, and rotation rate 400 r/min with welding speed 400 mm/min. The effects of welding parameters on weld quality and microstructure were investigated, and the low-temperature superplastic deformation behavior of the nugget zones was analyzed. The results showed that high-quality welds could be obtained by controlling welding parameters, achieving a joint strength coefficient of 100%. Dynamic recrystallization occurred in the nugget zone, producing fine equiaxed grains. While the base material had a grain size of approximately 300 μm , the nugget zones exhibited grain sizes of 2 μm , 1 μm , and 0.6 μm at rotation rates of 1600, 800, and 400 r/min, respectively. This fine-grained structure facilitated superplastic deformation in the nugget zone, which achieved elongations of 160%–590% at 300 °C under strain rates of 1×10^{-3} and $3 \times 10^{-4} \text{ s}^{-1}$. A maximum elongation of $790 \times 10^{-3} \text{ s}^{-1}$, while superplastic deformation capability disappeared at approximately 400 °C.

Keywords: ultra-high strength aluminum alloy, friction stir welding, superplasticity, microstructure

Introduction

In aerospace manufacturing, numerous thin-walled aluminum alloy structures require welding. Some of these welds demand not only adequate strength but also superplastic deformation capability for subsequent forming operations—requirements that conventional fusion welding cannot satisfy. Friction stir welding (FSW), as a novel solid-state joining technology [1,2], effectively avoids defects inherent to traditional fusion welding and enables high-quality joining of high-strength aluminum alloys (such as 2000 and 7000 series) previously considered unweldable [3,4]. Friction stir processing (FSP), developed based on FSW principles, is a versatile plastic deformation technique [5,6] that has attracted increasing attention for fabricating fine-grained/ultrafine-grained aluminum alloys with superplastic properties [5–10]. This suggests that FSW joints may also exhibit superplastic deformation capability similar to FSP-processed zones, as the primary difference lies in joining two plates versus processing a single plate.

Aluminum alloy superplasticity belongs to the fine-grained category. Severe plastic deformation techniques for preparing fine-grained/ultrafine-grained structures, such as thermomechanical processing and equal-channel angular pressing, are either overly complex or limited by workpiece geometry, making

batch processing difficult. Studies [11–14] have demonstrated that FSW/FSP can refine the microstructure in the nugget zone to obtain fine-grained/ultrafine-grained structures, which not only provide excellent comprehensive mechanical properties but also confer superplastic deformation capability [9]. Current research has focused more systematically on FSP aluminum alloys. Ma et al. [8] and Mishra et al. [15] reported that FSP 7075 aluminum alloy with a grain size of $3.8 \mu\text{m}$ achieved over 1250% elongation at 480 °C within a strain rate range of $3 \times 10^{-3} - 1 \times 10^{-2} \text{ s}^{-1}$. Subsequently, Liu and Ma [16] reported that ultrafine-grained FSP 7075 aluminum alloy achieved $540 \times 10^{-2} \text{ s}^{-1}$, realizing low-temperature, high-strain-rate superplasticity. These studies confirm that FSP can produce fine-grained/ultrafine-grained structures in aluminum alloys with excellent superplastic properties.

Unlike FSP, the oxide film on the faying surfaces during FSW is stirred into the nugget zone, which can affect joint mechanical properties to some extent [17]. However, research on the superplasticity of 7000 series aluminum alloy welded joints remains scarce. Motohashi et al. [18] reported that 7075-T6 aluminum alloy after FSW (1500 r/min, 300 mm/min) developed a fine-grained microstructure in the weld, with the nugget achieving 440% elongation at 400 °C and $1 \times 10^{-3} \text{ s}^{-1}$. 7B04 is a high-strength aluminum alloy widely used in aerospace applications for aircraft skins, upper and lower wing spar webs, and cabin walls [19,20], with thin sheets comprising a significant proportion of its usage. This demands excellent comprehensive properties, particularly good superplasticity in welded joints to meet subsequent forming requirements. Superplasticity in the nugget zone is a prerequisite for achieving superplastic forming of welded joints. While a few studies on FSW of 7B04 aluminum alloy have been reported [21,22], research on the superplastic deformation behavior of FSW joints remains unpublished.

This work conducted FSW butt welding on 2 mm thick annealed 7B04 aluminum alloy sheets, analyzing the effects of welding parameters on weld quality, microstructure, and mechanical properties, with particular emphasis on investigating the low-temperature superplasticity of the nugget zone and its deformation mechanisms.

1. Experimental Methods

The material used in this study was annealed 7B04 aluminum alloy sheet with dimensions of 400 mm × 95 mm × 2 mm. The main chemical composition (mass fraction, %) was: Zn 3.17, Mg 0.15, Cu 0.67, Fe 0.15, Si 0.05, Mn 0.05, Al balance.

Welding was performed using an FSW-5LM-020 CNC friction stir welding machine. A steel welding tool was employed with a shoulder diameter of 10 mm and a tapered threaded pin (M4) with a length of 1.65 mm. Three parameter sets were selected for butt welding: rotation rate 400 r/min with welding speed

400 mm/min (sample designated 400-400), rotation rate 800 r/min with welding speed 200 mm/min (sample 800-200), and rotation rate 1600 r/min with welding speed 200 mm/min (sample 1600-200).

Microstructural analysis was conducted using a MEF4A optical microscope (OM), Quanta 600 scanning electron microscope (SEM), and Tecnai F20 transmission electron microscope (TEM). Metallographic samples were sectioned perpendicular to the weld. After grinding and mechanical polishing, specimens were etched with Keller's reagent (volume ratio $\text{HNO}_3:\text{HCl}:\text{HF}:\text{H}_2\text{O} = 2.5:1.5:1:95$) for OM observation. TEM specimens were extracted from the weld center, ground to 60 μm thickness, and thinned using a twin-jet electropolishing unit with a solution of 25% HNO_3 and 75% CH_3OH at -35°C and 17 V. Phase analysis of the base metal (BM) and the nugget zone of sample 400-400 was performed using a D/MAX2400 X-ray diffractometer (XRD).

Tensile specimens were cut perpendicular to the welding direction, with dimensions of 140 mm length, 6 mm width, and 1.5 mm thickness, and a gauge length of 40 mm [Figure 1: see original paper]. BM longitudinal tensile specimens had identical dimensions. Three specimens were tested for each condition, with results averaged. Tensile tests were conducted on a SANS-CMT5205 universal testing machine at an initial strain rate of $1 \times 10^{-3} \text{ s}^{-1}$.

Superplastic tensile specimens were cut along the weld direction from the weld center, with a gauge length of 2.5 mm and width of 1.4 mm. Samples were ground and polished to approximately 1 mm thickness. Superplasticity tests were performed on an INSTRON 5848 micro-tensile tester at temperatures ranging from 200°C to 400°C . Specimens were held at temperature for 15 minutes prior to testing, with initial strain rates of 1×10^{-3} and $3 \times 10^{-4} \text{ s}^{-1}$.

2.1 Joint Mechanical Properties

Table 1 presents the tensile properties of the annealed 7B04 aluminum alloy base metal. The tensile strength was approximately 210 MPa in both longitudinal and transverse directions relative to the rolling direction. Table 2 shows the tensile properties of the FSW joints. The joint tensile strength was approximately 213 MPa, comparable to that of the base metal, indicating that equal-strength welding was achieved under the selected process parameters.

2.2 Joint Microstructure

Figure 2a–c [Figure 2: see original paper] shows macroscopic OM images perpendicular to the welding direction, with the right side of the nugget being the advancing side (AS) and the left side the retreating side (RS). Figures 2d–f display photographs of the macroscopic weld appearance under the three welding

parameters. Smooth, defect-free welds were obtained in all cases, with no macroscopic defects observed in the weld zones and complete nugget formation. Figure 3 [Figure 3: see original paper] presents the metallographic microstructure of the 7B04 aluminum alloy base metal, revealing coarse, elongated plate-like grains aligned along the rolling direction, with an average grain width of approximately 20 μm and length of approximately 300 μm .

Figure 4 [Figure 4: see original paper] shows TEM images of the 7B04 aluminum alloy base metal and the FSW nugget zones. The base metal contained numerous coarse, rod-shaped MgZn_2 precipitates within the grains, with an aspect ratio of approximately 4:1. All three parameter sets produced fine-grained microstructures in the nugget zones (Figs. 4b–d), with grain size increasing with rotation rate from 0.6 μm at 400 r/min to 2 μm at 1600 r/min. Fine precipitates were distributed within grains and at grain boundaries, becoming more numerous with decreasing rotation rate, though the nugget zone contained significantly fewer precipitates than the base metal. Unlike the coarse rod-shaped precipitates in the base metal, the nugget zone precipitates were fine and uniformly distributed.

XRD spectra of the 7B04 aluminum alloy base metal and the nugget zone of sample 400-400 are shown in Figure 5 [Figure 5: see original paper]. In addition to Al matrix diffraction peaks, the base metal exhibited distinct MgZn_2 precipitate peaks. In contrast, the nugget zone showed primarily Al matrix peaks with significantly weaker precipitate peak intensities, indicating precipitate dissolution in the nugget zone. This observation aligns with the TEM results showing reduced precipitate density. During welding, the nugget zone experienced intense thermal cycling, causing partial dissolution of precipitates followed by re-precipitation of a small number of fine particles with much lower density and size than the strengthening phases in the base metal, resulting in very weak diffraction peaks.

2.3 Superplastic Tensile Results of Joints

Figure 6a [Figure 6: see original paper] shows the initial strain rate versus elongation curves for the 7B04 aluminum alloy base metal and different nugget zones at 300 $^\circ\text{C}$. All three nugget zones exhibited superplasticity across strain rates of 10^{-10} to 10^{-4} s^{-1} , achieving maximum elongations of 590%, 407%, and 324% at an initial strain rate of 3×10^{-4} s^{-1} . At 1×10^{-3} s^{-1} , the maximum elongations were 530% and 324%.

The effects of initial strain rate and temperature on superplasticity were evaluated for the base metal and the high-performance sample 400-400. Figure 6b [Figure 6: see original paper] shows elongation versus temperature at a constant initial strain rate of 3×10^{-4} s^{-1} . For sample 400-400, elongation increased with temperature, reaching a maximum of 590% at 300 $^\circ\text{C}$, then de-

creased with further temperature increase, disappearing at 400 °C. The base metal showed no significant variation in elongation with initial strain rate or temperature (Figs. 6a and b) due to its coarse, non-equiaxed grain structure (Fig. 3) and poor plastic deformation capability.

Figure 6c [Figure 6: see original paper] presents the initial strain rate versus elongation curves for sample 400-400 at 300 and 350 °C. The optimal initial strain rate for maximum elongation increased with temperature: $3 \times 10^{-4} \text{ s}^{-1}$ at 300 °C and $1 \times 10^{-3} \text{ s}^{-1}$ at 350 °C, where a remarkable elongation of 790% was achieved.

The strain rate sensitivity index m was determined from the slope of double-logarithmic plots of flow stress versus strain rate at a true strain of 0.1 (Fig. 6d [Figure 6: see original paper]). Previous studies [23] indicate that superplastic deformation requires $m \geq 0.3$. In this work, sample 400-400 exhibited m values ranging from 0.02 to 0.59 across all test temperatures and strain rates, with m values of 0.32–0.59 corresponding to conditions of maximum elongation, demonstrating good superplastic behavior.

Figure 7 [Figure 7: see original paper] shows the post-deformation morphologies of nugget zone specimens tested under maximum elongation conditions. All specimens exhibited relatively uniform superplastic deformation characteristics. SEM examination of the surface morphology near the fracture tip for the fine-grained, high-performance sample 400-400 revealed grain elongation features indicative of grain boundary sliding [16] (Fig. 8 [Figure 8: see original paper]), confirming that grain boundary sliding was the dominant deformation mechanism during superplastic deformation.

3. Analysis and Discussion

FSW parameters and the initial temper of heat-treatable aluminum alloys significantly influence joint strength. Wang et al. [22] investigated the effect of rotation rate (750, 950, 1150, and 1500 r/min) at a fixed welding speed (95 mm/min) on the tensile properties of 2 mm thick T74B-temper (solution-treated + overaged) 7B04 sheet FSW joints. Their results showed smooth weld surfaces at low rotation rates but rough surfaces with numerous particles at high rotation rates. The joint strength reached 97.4% of the base metal tensile strength (487 MPa) at 750 r/min, decreasing to 50–60% of the base metal strength at higher rotation rates due to coarsening and partial dissolution of strengthening phases from excessive heat input [24]. In contrast, the annealed material used in this work contained no strengthening phases susceptible to coarsening, enabling equal-strength welding (Table 2).

Welding parameters significantly affect nugget zone grain size and precipitate morphology. The base metal exhibited coarse plate-like grains (Fig. 3), while the nugget zone underwent significant grain refinement through dynamic recryst-

tallization (Fig. 4). Grain size increased with rotation rate from 0.6 μm at 400 r/min to 2 μm at 1600 r/min, as higher rotation rates increase heat input and promote post-recrystallization grain growth. The nugget zone contained fine, uniformly distributed precipitates due to intense thermal cycling during the high-speed tool rotation and friction, which caused initial dissolution of precipitates into the matrix followed by uniform precipitation of fine particles [17,25].

Low-temperature superplastic deformation offers advantages including reduced energy consumption, longer die life, better surface quality, and improved mechanical properties of formed components [26,27]. However, achieving true low-temperature superplasticity in aluminum alloys is extremely challenging, with only a few processed fine-grained aluminum alloys reported to exhibit superplasticity below 200 $^{\circ}\text{C}$. Consequently, superplasticity below 350 $^{\circ}\text{C}$ is generally considered low-temperature superplasticity [27]. In this study, the nugget zone developed a fine-grained microstructure through dynamic recrystallization during FSW, enabling superplasticity under certain conditions (Fig. 6). Sample 400-400 demonstrated excellent low-temperature superplasticity at 300 $^{\circ}\text{C}$, achieving 530% and 590% elongation at 1×10^{-3} and $3 \times 10^{-4} \text{ s}^{-1}$, respectively—superior to the $440 \times 10^{-3} \text{ s}^{-1}$, and comparable to the $530 \times 10^{-3} \text{ s}^{-1}$. This confirms that fine-grained aluminum alloys can achieve excellent superplasticity at low temperatures and low strain rates. The disappearance of superplasticity at 400 $^{\circ}\text{C}$ resulted from grain coarsening at elevated temperatures [16].

The annealed 7B04 aluminum alloy base metal exhibited no superplasticity (Figs. 6a and b) due to its coarse, non-equiaxed grain structure (Fig. 3) and poor plastic deformation capability, demonstrating that FSW can refine the weld zone microstructure and enable superplasticity under appropriate conditions. In Fig. 6b, the base metal showed higher elongation than sample 400-400 at 200 $^{\circ}\text{C}$. This occurs because superplastic deformation is a special deformation mode requiring specific conditions to activate grain boundary sliding, the primary mechanism for aluminum alloys. Generally, grain sizes must be smaller than 10 μm , and only when temperature and deformation rate satisfy the conditions for this mechanism can superplasticity be exhibited. Otherwise, deformation properties may be inferior to conventional materials—for instance, ultrafine-grained and nanocrystalline materials often show lower ductility at room temperature than conventional materials.

Conclusions

1. High-quality butt joints were obtained in 2 mm thick annealed 7B04 aluminum alloy under all three welding parameter sets, with FSW joint tensile strength of approximately 213 MPa, achieving equal-strength welding.
2. The annealed 7B04 aluminum alloy base metal exhibited a rolled mi-

microstructure with coarse plate-like grains approximately 20 μm wide and 300 μm long along the rolling direction, containing coarse precipitates within grains. The FSW nugget zone underwent dynamic recrystallization, producing fine-grained microstructures with grain sizes of 2 μm , 1 μm , and 0.6 μm at rotation rates of 1600, 800, and 400 r/min, respectively, with fine precipitates dispersedly distributed within grains.

3. At 300 $^{\circ}\text{C}$, the elongation of all three nugget zone specimens increased with decreasing initial strain rate.
4. For sample 400-400 at an initial strain rate of $3 \times 10^{-4} \text{ s}^{-1}$ and temperatures of 200–400 $^{\circ}\text{C}$, elongation first increased with temperature, reaching a maximum at 300 $^{\circ}\text{C}$, then decreased with further temperature increase, disappearing at 400 $^{\circ}\text{C}$. The optimal initial strain rate for maximum elongation increased with temperature. The dominant deformation mechanism for superplasticity in the nugget zone was grain boundary sliding.

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