

Study on Thermo-Mechanical Treatment for Strength-Toughness Regulation in Aerospace Al-Li Alloys

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Abstract. Aluminum-lithium (Al-Li) alloys have emerged as critical structural materials for airframe lightweighting, fuel efficiency improvement, and flight performance enhancement due to their exceptional combination of low density, high strength, and superior toughness. Thermo-mechanical treatment plays a pivotal role in tailoring the service performance of Al-Li alloy components, with cold deformation being a key factor determining their strength-toughness balance. This study systematically investigates the effects of cold rolling reduction (0%, 1%, 3%, 5%) and artificial aging (160°C/x h) on the microstructure and mechanical properties of an Al-Li alloy through cold-rolling thermo-mechanical treatment experiments. The results demonstrate that cold rolling significantly accelerates aging kinetics, suppresses the competitive precipitation of δ' and σ phases during aging, and promotes T1 phase nucleation. With increasing cold rolling reduction, the precipitation density of T1 phase increases while its size decreases, accompanied by a gradual transition from transgranular fracture to intergranular fracture. The optimal strength-toughness combination is achieved in the Al-Li alloy subjected to 1% cold rolling followed by aging at 160°C for 20-24 h, exhibiting tensile strength of 594 MPa, yield strength of 552 MPa, and elongation of 7.2%.

Keywords: Aerospace Al-Li alloys; Thermo-mechanical treatment; Strength-toughness; Cold rolling.

1. Introduction

With the rapid development of the aviation industry [1] and the growing demand for a low-carbon economy [2], aircraft are facing increasingly stringent requirements for fuel efficiency. Statistics indicate that fuel costs account for 20–40% of airline operating expenses [3], with airframe weight being a critical factor affecting fuel consumption. A 1 kg reduction in airframe weight leads to an annual fuel savings of 80–120 L (for narrow-body aircraft) to 150–200 L (for wide-body aircraft), resulting in a lifetime cost reduction of \$2,500–7,500 and a 3–6 ton decrease in CO₂ emissions over the aircraft's service life. For instance, the Airbus A350 achieved an 8-ton weight reduction through structural lightweighting [5], extending its range to 15,000 km while improving fuel efficiency by 25% compared to conventional aircraft models.

Aluminum-lithium (Al-Li) alloys, known for their low density, high strength, and excellent toughness, have become the preferred material of choice for lightweight aerospace structures. Airbus extensively employs Al-Li alloys to replace traditional 7xxx-series aluminum alloys in skins, frames, and floor beams (Fig. 1a) [7], yielding significant economic benefits. Similarly, the C919 aircraft utilizes 2060 Al-Li alloy in wing skins and fuselage frames, achieving a 600 kg weight reduction [8]. In military applications, the F-16 fighter jet incorporates 2196 Al-Li alloy in its rear bulkhead [9,10], enhancing maneuverability, while the EH101 helicopter employs Al-Li alloys in its main cabin frame and skin structures (Fig. 1b), reducing weight by 200 kg per aircraft [6,11]. Furthermore, 2195 Al-Li alloy is gradually replacing 2219 aluminum alloy in liquid hydrogen/oxygen fuel tanks for rockets and missiles [12], further improving payload efficiency.

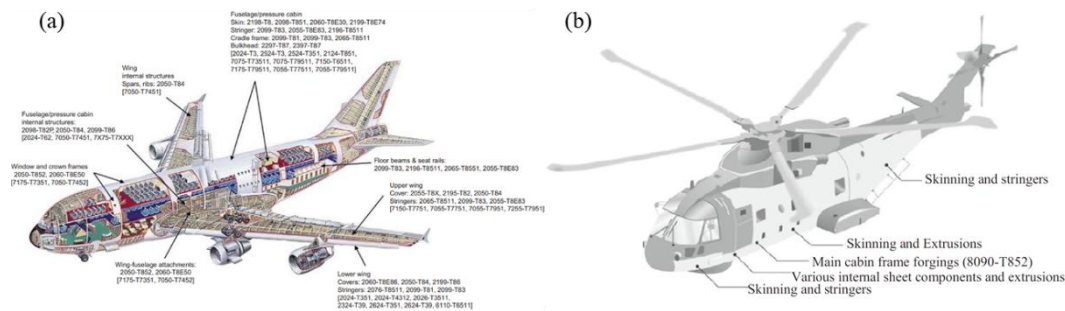


Fig. 1 Applications of Al-Li alloys in aerospace: (a) Airbus A380 [7]; (b) EH101 helicopter [6,11].

The primary strengthening phase in Al-Li alloys is the T1 phase (Al₂CuLi). To achieve optimal strength-toughness balance, structural components made of Al-Li alloys require heat treatment after forming to induce T1 phase precipitation. The predominant nucleation sites for T1 phase are dislocations and subgrain boundaries [13]. Cold deformation can significantly enhance T1 phase nucleation efficiency and accelerate age-hardening kinetics [14]. Xie [15] compared the mechanical properties of 2195 Al-Li alloy under T6 (solution quenching + artificial aging) and T8 (solution quenching + cold deformation + artificial aging) conditions, demonstrating that the peak-aged strength of T8-treated alloy was 60-80 MPa higher than that of T6-treated counterparts. This strong dependence of T1 phase precipitation on dislocations makes the heat treatment process highly sensitive to cold deformation, where variations in deformation amount can lead to substantial differences in mechanical properties. Rodgers [16], Wang [17], and Lv [18] systematically investigated the effect of cold deformation amount on T1 phase precipitation. Their studies revealed that with increasing cold deformation, the precipitation density of T1 phase increases while its average length decreases, resulting in gradual strength enhancement. Notably, when cold deformation is below 3%, precipitation strengthening dominates the strength contribution; beyond 3% deformation, dislocation strengthening becomes increasingly significant.

For cold deformation processing of aerospace aluminum alloy components, three primary methods have been reported: stretching [19], compression [20], and rolling [21]. From an engineering perspective, cold compression suffers from poor strain uniformity, making it less suitable for dislocation-density-sensitive Al-Li alloys. Cold stretching typically requires heavy-duty tension machines, compromising both production continuity and cost-effectiveness. In contrast, cold rolling offers distinct advantages in continuous production efficiency and economic feasibility, showing great potential for industrial applications. However, research on cold rolling for mechanical property regulation in Al-Li alloys remains limited. Therefore, this study focuses on thermo-mechanical treatment via cold rolling in Al-Li alloys, aiming to provide guidance for strength-toughness optimization and further promote their aerospace applications.

2. Experimental and Materials

The experimental material was a 2195 Al-Li alloy forging with a nominal composition of Al-4.1Cu-1.0Li-0.44Mg-0.3Ag-0.1Zr-0.05Fe (wt%) and dimensions of approximately 150×100×28 mm. Solution heat treatment was performed at 500°C for 4 h followed by water quenching (transfer time <10 s, water temperature 15°C). Cold rolling with reductions of 0%, 1%, 3%, and 5% was completed within 1 h after quenching using a two-high cold rolling mill. Two tensile specimens were extracted from both the surface and center layers along the rolling direction of each cold-rolled sample. The specimens were then subjected to aging treatments at 160°C with different durations (0-40 h, 4 h interval). The gauge sections of tensile specimens were ground with 180-grit sandpaper prior to testing. Tensile tests were conducted on a CMT5105GL universal testing machine according to GB/T 228.1-2010 standard. Transmission electron microscopy (TEM) was employed to examine Al-Li alloy specimens subjected to different aging conditions. Fracture

surface analysis of different tensile specimens was carried out using a scanning electron microscope (SEM).

3. Results and Discussion

3.1 Effect of Cold Rolling Reduction on Age Hardening of Al-Li Alloy

The age-hardening behavior and mechanical properties of 2195 Al-Li alloy under different thermo-mechanical treatment conditions are shown in Fig. 4. For the T6 condition (0% cold rolling), age hardening progressed slowly without a distinct peak aging point. The strength gradually increased with prolonged aging time, while the elongation decreased steadily. After aging at 160°C for 40 h, the tensile strength reached 573 MPa, yield strength 535 MPa, and elongation 5.6%. The introduction of cold rolling significantly accelerated age-hardening kinetics. With 1% cold rolling + aging at 160°C, the tensile strength increased linearly to 557 MPa after 8 h aging, then rose slowly to 608 MPa by 40 h. The elongation decreased from 21.5% (0 h) to 7.2% (16 h), remained stable at 6.8-7.2% between 20-34 h, and further dropped to 4.2-5% at 36-40 h. For 3% cold rolling, age hardening was further enhanced. High strength (tensile strength: 560 MPa, yield strength: 518 MPa) was achieved after only 4 h aging. The tensile strength stabilized at 590-598 MPa during 8-40 h aging. The initial elongation of 19.2% (unaged) decreased rapidly to 6.5% after 12 h aging, with the inflection point occurring earlier than in 1% cold-rolled samples. Elongation remained at 6.4-6.7% from 12-34 h before decreasing to 5.1-5.3% at 36-40 h. With 5% cold rolling, the tensile strength maintained 586-598 MPa during 12-36 h aging but dropped to 581 MPa at 40 h. The elongation showed no stable period, decreasing continuously from 17.6% (0 h) to 4.9% (40 h).

The mechanical properties of Al-Li alloy were highly sensitive to cold deformation. Without cold rolling (0%), age hardening was slow without peak aging. At 1% cold rolling, age hardening was significantly accelerated, producing a clear peak aging stage and strength plateau. Higher cold rolling reductions had limited effects on peak strength but markedly reduced ductility: higher reductions resulted in lower initial elongation (unaged) and faster ductility loss during aging.

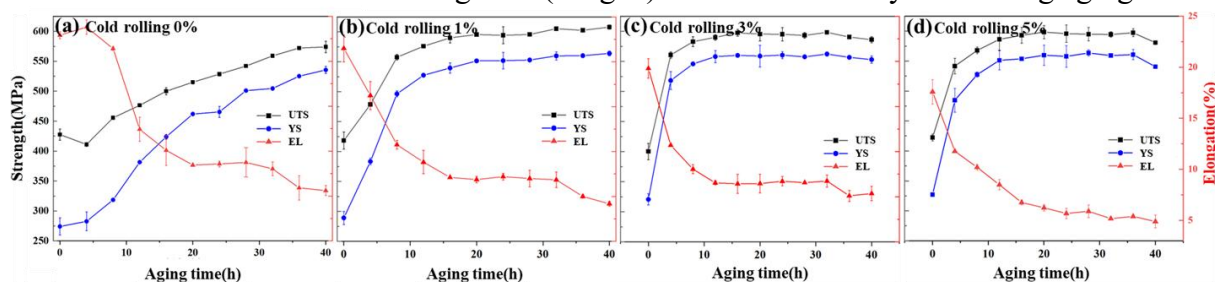


Fig. 2 Age-hardening curves of Al-Li Alloy under different cold rolling reductions: (a)0% , (b)1%, (c)3%, (d)5%.

3.2 Effect of Cold Rolling Reduction on Precipitation Behavior in Al-Li Alloy

Figure 3 shows the precipitation morphology along the $\langle 110 \rangle_{\text{Al}}$ direction of 2195 Al-Li alloy after different cold rolling reductions followed by aging at 160°C for 24 h. In the 0% cold-rolled sample (T6 condition), TEM analysis revealed four typical precipitates: (1) needle-shaped T1 phase (Al_2CuLi) with an average length of ~ 200 nm, (2) θ' phase (Al_2Cu) precipitates (~ 79 nm in length), (3) spherical δ' phase (Al_3Li), and (4) blocky σ phase ($\text{Al}_5\text{Cu}_6\text{Mg}_2$) [23]. These precipitates exhibited low number density and random distribution.

After 1% cold rolling, the precipitation pattern changed to predominantly T1 phase with minor θ' phase, as evidenced by strong T1 diffraction spots and weak θ' spots in the selected area diffraction pattern. The T1 phase showed significantly increased number density while its average length decreased to 102 nm, whereas θ' phase length increased to 128 nm. With 3% cold rolling, diffraction spots from θ' and δ' phases disappeared, and the T1 phase density further increased with

reduced average length (79 nm). At 5% cold rolling, the microstructure remained T1-dominated, showing the highest precipitation density and shortest average length (62 nm).

The highly alloyed 2195 Al-Li alloy exhibits complex competitive precipitation during aging. The T1 phase, as the primary strengthening phase, requires dislocations for nucleation. Without cold rolling (0%), weak precipitation kinetics and competitive formation of other phases (consuming Cu atoms) resulted in slow strength development and low peak strength. After 1% cold rolling, introduced dislocations provided nucleation sites for T1 phase while suppressing σ and δ' phase formation. At 3% cold rolling, higher dislocation density promoted further T1 nucleation but caused size reduction due to competitive growth. The 5% cold-rolled sample showed the highest T1 density with the smallest size.

Mechanical properties correlated with precipitation analysis reveal that: (1) precipitate types significantly affect strength - multi-phase precipitation reduces strength potential, while T1-dominant microstructure with minor θ' phase yields optimal strength; (2) although higher cold rolling increased T1 density and reduced size, the peak strength remained unchanged, suggesting limited influence of these factors on strength; (3) increased dislocation strengthening at higher rolling reductions appears to compensate for reduced precipitation strengthening contribution [16].

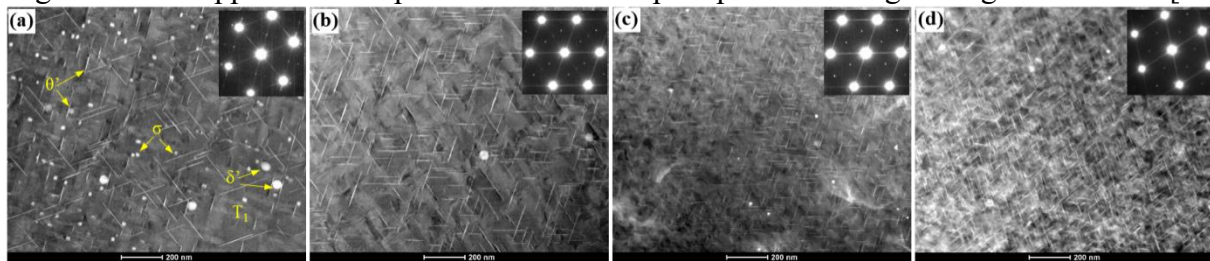


Fig. 3 Effect of cold rolling reduction on Al-Li Alloy precipitation: (a) 0% , (b) 1%, (c) 3%, (d) 5%.

3.3 Effect of Cold Rolling Reduction on Fracture Behavior of Al-Li Alloy

Figure 4 shows the fracture evolution of 1% cold-rolled samples during aging. The unaged specimen (0 h) displayed typical ductile transgranular fracture with numerous dimples (10-24 μm) and tear ridges, corresponding to 21.5% elongation. After 8 h aging, a mixed-mode fracture appeared, combining reduced dimples/ridges with emerging intergranular facets, coinciding with decreased elongation (8.8%). Complete transition to intergranular fracture occurred after 24-40 h aging, with elongation dropping to 5-6.8%.

The as-rolled fracture characteristics are shown in Figure 5. The 0% cold-rolled specimen exhibited pronounced tear ridges and dense small dimples (8-15 μm), yielding 22.9% elongation. With 1% cold rolling, slight work hardening reduced ridge height and elongation (21.5%). Further reduction to 3% rolling produced flatter surfaces with occasional grain facets (19.2% elongation). At 5% cold rolling, minimal ridges remained (17.6% elongation).

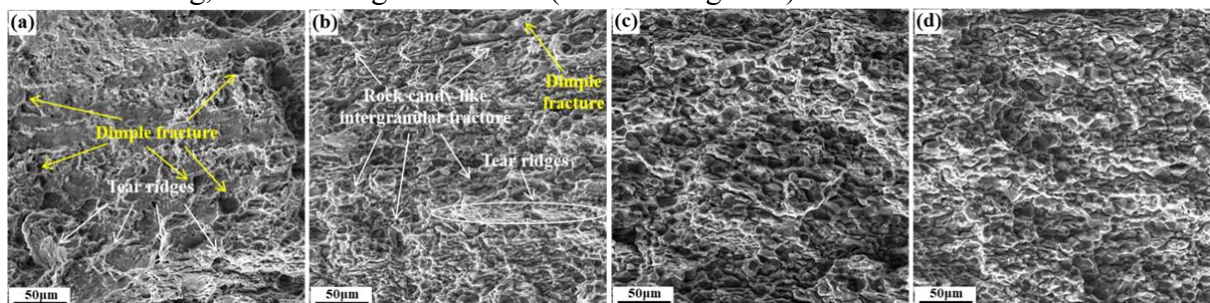


Fig. 4 Fracture surface evolution of 1% cold-rolled specimens during aging at 160°C: (a) 0 h, (b) 8 h, (c) 24 h, (d) 40 h

The aforementioned analysis reveals that underaged 2195 Al-Li alloy predominantly fails through transgranular fracture, where higher tear ridge density corresponds to greater elongation. The transition to intergranular fracture modes results in reduced ductility, a characteristic inherent to this alloy system. The high reactivity of lithium leads to elevated hydrogen content during casting,

increasing grain boundary embrittlement. In unaged and underaged conditions, lower intragranular strength relative to grain boundary strength promotes crack nucleation and propagation within grains, resulting in ductile transgranular fracture. More pronounced tear ridges indicate superior matrix ductility. As the alloy approaches peak aging, intensive precipitation of strengthening phases within grains enhances their strength, shifting deformation localization to grain boundaries. The inherent brittleness of these boundaries facilitates rapid crack propagation, leading to diminished elongation. Cold rolling induces preliminary work hardening, with greater reductions exacerbating this effect and consequently reducing fundamental plasticity. Thus, in peak-aged conditions, increasing cold rolling reductions progressively decrease elongation. Optimal strength-ductility balance (tensile strength: 594 MPa, yield strength: 552 MPa, elongation: 7.2%) is achieved through 1% cold rolling combined with aging at 160°C for 20-24 h. This treatment effectively enhances T1 phase precipitation kinetics while maintaining acceptable ductility levels.

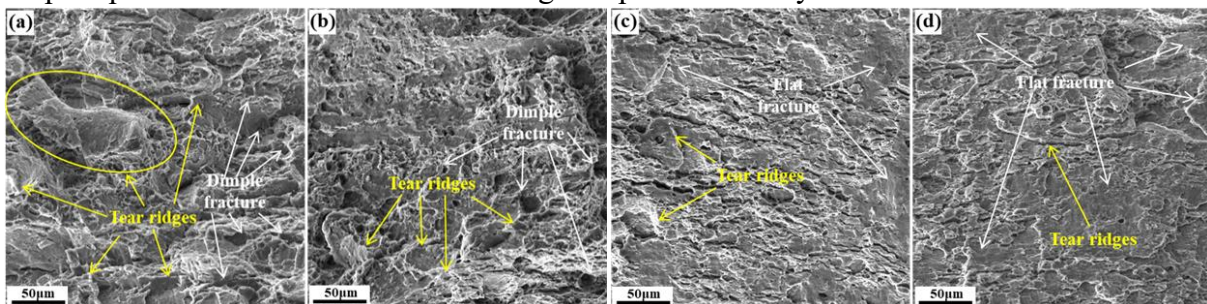


Fig. 5 Fracture morphology of as-rolled specimens before aging: (a) 0%, (b) 1%, (c) 3%, (d) 5%.

4. Summary

- 1) Cold rolling prior to aging significantly accelerates precipitation kinetics and reduces peak aging time. For 1% cold-rolled samples, peak strength was achieved after only 16 h aging - 19 h shorter than required for T6 treatment. Further increasing cold rolling to 3-5% reduced the peak aging time to just 12 h.
- 2) Compared to non-rolled condition (0%), 1% cold rolling promoted T1 phase precipitation while suppressing competing non-strengthening phases (δ' and σ), resulting in over 66 MPa strength enhancement at peak aging. Although higher cold rolling reductions (1-5%) produced denser T1 precipitates with smaller average sizes, their influence on ultimate tensile and yield strengths was marginal.
- 3) The underaged 2195 Al-Li alloy exhibited transgranular fracture, with intergranular fracture proportion increasing during age hardening. Higher cold rolling reductions accelerated ductility loss during aging and caused greater elongation reduction at peak aging. The optimal strength-ductility combination (tensile strength: 594 MPa, yield strength: 552 MPa, elongation: 7.2%) was achieved through 1% cold rolling followed by 160°C/20-24 h aging.

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