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The effect of stress-aging on dimensional stability behavior of Al-Cu-Mg alloy

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ABSTRACT

The stress-aging method is proposed to improve the dimensional stability of Al-Cu-Mg (2024 aluminum) alloy. Both the reduction of residual stress and the acceleration of precipitates are investigated during the stress-aging process. It is observed that some S′ particles precipitate in the alloy during stress-aging. With the external stress increase to 100 MPa, the residual stress and thermal strain (ε_c) decrease, while the micro-yield strength increases significantly. This is attributed to that the dislocations are effectively pinned by the uniformly distributed precipitates and the stored elastic energy diminishes remarkably, which leads to a considerable improvement of the dimensional stability of 2024 aluminum alloy. However, when further increases the external stress to 150 MPa, due to the coarsened precipitates, the residual stress and thermal strain increase, while the micro-yield strength decreases slightly.

1. Introduction

Due to the excellent structural properties, such as low density, high fracture toughness and fatigue strength, 2024 aluminum alloy has become an attractive light-weight material for inertial instruments and aircrafts [1–6]. However, the alloy has the relatively high coefficient of thermal expansion and the low micro-yield strength, which may lead to dimensional instability when the alloy is in the alternating temperature field or under the stress [4–6]. The dimensional instability of the alloy would bring about navigation errors for the guide instruments and catastrophic failures of structural components, resulting in satellite deviation and air crashes [4,5].

In recent years, much attention has been drawn to improve the dimensional stability of aluminum alloys [6–11]. The precipitates and residual stress are the two key features to affect the dimensional stability of these materials [6–15]. Wang et al. [6] reported that the uniformly dispersed precipitates could increase the micro-yield strength and enhance the dimensional stability of 2024 aluminum alloy. Furthermore, Elgallad et al. [12] claimed that a two-stage aging treatment could considerably improve the dispersion of the precipitates, the precipitation of Guinier-Preston (GP) zones could be observed during the first stage and then GP zones are subsequently transformed into effective θ″ strengthening precipitates during the second stage. Kim et al. [13] investigated the relationship between the clustering behavior during natural aging and the two-step aging, and found that Si-rich clusters formed during natural aging are thermally stable during the two-step aging. Schueller et al. [14] stated the nucleation mechanism of the secondary phase in squeeze-cast aluminum matrix composites. It was found that the existence of excess Si (approximately 0.5 wt %) in the matrix is determined to be responsible for nucleation of these secondary phases. Furthermore, the residual stress is related to the elastic energy stored during the fabrication process, which could be relaxed via the cryogenic and mechanical treatments [8,15]. Senthilkumar et al. [8] developed two types of cryogenic treatment on the residual stress of alloy. It is demonstrated that the shallow cryogenic treatment could decrease more residual stress than deep cryogenic treatment. Koc et al. [15] studied three different cold working treatments on reducing the residual stress of quenched 7050 aluminum alloy. It is reported that the single-strike compression of aluminum alloy is an efficient and cost-effective method for reduction of the residual stress, and only 10% of the residual stress remains in the alloy.

Stress-aging combined the advantage of aging-precipitating and stress-relieving methods, is a relatively novel technique for

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dimensional stability. The stress-aging method plays a key role in the precipitation of second phase [16,17]. Chen et al. [16] illustrated that the distribution of S′ phase can be changed by the loading orientation of applied stress. Liu et al. [18] studied the effects of stress-aging processing on the precipitation behavior of Al-Cu-Mg alloy, and pointed out the distribution and dimension of aging precipitates are sensitive to the aging temperature and external stress. Zhu et al. [19] demonstrated the stress-aging strengthening effects on the Al-Cu alloys, and illustrated that the external stress could promote the aging precipitates of the Al-Cu alloys. Liu et al. [17] emphasized the precipitation of the second phase is accelerated with external stress. Furthermore, the stress-aging process also plays a significant role in the reduction of residual stress [20]. The compressive residual stress on the surface is developed during the quenching process. After the reverse tensile stress is added, the residual stress can be relieved. However, to the best of our knowledge, there is no report regarding the stress-aging method for dimensional stability of 2024 aluminum alloy in the open literature. The question remains that, whether and what extend the stress-aging can improve the dimensional stabilities of 2024 aluminum alloy, and what the stabilizing mechanisms are. The aim of this paper is to develop a new method to stabilize 2024 aluminum alloy, evaluate the dimensional stability, and identify the underlying stabilizing mechanisms.

2. Materials and methods

2.1. Raw materials

In the present work, the commercial cold-rolled 2024 aluminum alloy with a dimension of 1200 mm × 500 mm × 5 mm (Southwestern Aluminum Co. Ltd.) was used as raw materials. The composition of 2024 aluminum alloy was shown in Table 1.

2.2. Samples preparation

Stress-aging experiments were performed in an RDL30 electronic creep system in the air. In each stress-aging experiment, a specimen was firstly heated to 515 °C for 1 h, and then quenched into the water bath. Water was used as quench medium and kept at a constant temperature of 25 °C. Thereafter, the specimens were initially stress-aged at 110 °C for 8 h (first aging stage) and then stress-aged at 190 °C for 24 h (second stage aging) according to the literature data [21], when the tensile stress was 0 MPa, 50 MPa, 100 MPa and 150 MPa respectively. The stress-aged samples were tested 5 times in each condition, and the average values were reported.

2.3. Characterization of materials

The microstructures of the samples were examined using the Tecnai G^2 F20 transmission electron microscope (TEM). Thin disks (3 mm in diameter) of stress-aged 2024 aluminum alloy were initially polished by the sand paper to a thin slice of 80 μm, and then polished by the twin-jet electro polishing machine with a solution of 25% nitric acid in methanol at −30 ~ −20 °C and 15–20 V.

The thermal cycling experiments were carried out on the Netzsch DIL402 C instrument. Fig. 1 schematizes a diagram of a thermal strain-temperature plot depicting a hysteresis loop formed during thermal cycling and the descriptive parameter. In order to evaluate the level of strains induced in this work, elastic strain (ε_c) was determined as the strain range over the evaluated temperatures. In the thermal cycling tests, the samples, with a dimension of 25 mm × 5 mm × 5 mm, were stabilized at 40 °C for 0.5 h to eliminate external disturbance (environment temperature) and then cycled for 3 times where the temperatures ranged between 40 °C and 300 °C with a heating and cooling rate of 5 °C/min [7]. Three samples were tested in each condition, and the average values were reported. The micro-yield strength of the stress-aged samples was measured by a continuous loading method via the Instron 8032 electron tensile system at room temperature. When the stress-strain ($\sigma-\varepsilon$) curve was obtained in the test, the residual plastic strain (ε_p) could be calculated according to the following equation [6,22]:

$$\varepsilon_p = \varepsilon - \sigma / E \tag{1}$$

where ε_p is the residual plastic strain, ε is the strain, σ is the stress, and E is the elasticity modulus. And then, the stress corresponding to $\varepsilon_p = 10^{-6}$ on the plotted ($\sigma-\varepsilon_p$) curve was defined as the micro-yield strength in this work. Three samples were tested in each condition, and the average values were reported. The surface residual stress of alloys was analyzed by the side inclination and fixed ψ methods via the HD-D/Max 2550 VB+/PC X-ray diffraction with Cu-kα radiation in the tube voltage and current of 20 kV and 5 mA, respectively. Aluminum alloy (3 1 1) was selected as the diffraction plane, while the ψ (°) was set as 0.0, 24.2, 35.3, 45.0, respectively. Five samples were tested in each condition, and the average values were reported.

3. Results

3.1. Micro-structural characterization

The typical TEM micrographs of 2024 aluminum alloy after stress-aging treatment and the ED patterns of Al are illustrated in Fig. 2. It can be seen from Fig. 2(a) that a large number of needle-shape and rod-like precipitates are distributed in 2024 aluminum alloy. The rod-like particles are T phase which precipitate from

Table 1
The composition of 2024 aluminum alloy (in wt.%).

Element	Al	Si	Mg	Mn	Fe	Cu
Content	Bal.	0.5	1.6	0.6	0.5	4.1

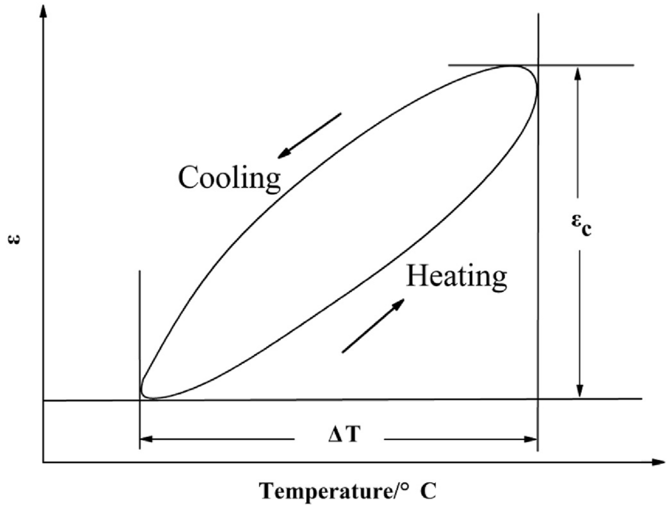

Fig. 1. Schematic diagram of a thermal strain-temperature plot showing a hysteresis loop formed during thermal cycling and the descriptive parameter.