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Influence of electric field on microstructure and mechanical properties of an Al-Cu-Li alloy during ageing

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ABSTRACT

The effect of an electric field on the microstructure and mechanical properties of an Al-Cu-Li alloy was investigated by optical microscopy (OM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), microhardness tests, electric conductivity tests, and tensile tests. The results show that the field-aged sample exhibited a shorter stable hardening plateau period and an earlier peak-aged stage than the field-free-aged sample. Also, the hardness and conductivity of the field-aged sample during the hardening plateau interval were generally greater than that of the field-free-aged sample. This might be due to the fact that the electric field promoted the precipitation of the β'/δ' phase and accelerated the growth of the θ' phase. The improvement in mechanical properties of the field-aged sample was caused by the segregation of the T_1 phase at the subgrain boundaries and the grain boundaries. A vacancy-atom complex diffusion model successfully explains the microstructure evolution and the change in mechanical properties of the alloy during the ageing process accompanied by an electric field.

1. Introduction

The Al-Cu-Li alloys are extensively used in the aerospace industries and in military aircraft due to their low density, high specific strength, excellent property stability, and good damage tolerance [1–3].These alloys can contain a wide variety of precipitates, depending upon the heat treatment conditions, including Guinier-Preston (GP) zones, θ″, θ′, θ (Al_2Cu), δ′ (Al_3Li), β′ (Al_3Zr), T_1 (Al_2CuLi), and possibly Ω and S′ (Al_2CuMg) as well [4–6]. Proper control of the species, size, orientation, and distribution of grain boundary precipitates and matrix precipitates is critical to obtain the highest strength as well as good ductility in these alloys [7,8].

In Al-Cu-Li alloys, the T_1 (Al_2CuLi) phase is known to be the dominant strengthening phase [9]. Usually it exhibits a hexagonal structure and has a thin platelet-like morphology aligned semi-coherently on $\{111\}_{Al}$ planes [10,11]. Cold working prior to the final ageing treatment has long been known to promote precipitation of the T_1 phase [12,13].

Conventional T8 [4,13,14] heat treatment is widely used in Al-Cu-Li alloys and provides them with an optimal combination of strength, fracture toughness, and fatigue resistance, but at the price of decreasing ductility; moreover, for some parts with complex shapes and sizes, it is difficult to improve their mechanical properties by the cold work subsequent to solution treatment. Recently, an innovative way to tailor the microstructure of alloys and improve their mechanical properties is applying external physical fields during heat treatment.

During the past 30 years, many researchers [15–23] have found that the mechanisms of diffusion and vacancy migration in some metals and alloys could be influenced by an external electric field. In particular, the process of recovery and recrystallization in Al and Cu, the super-plastic deformation behavior and grain growth of some ceramics and alloys, and the hardenability of some low carbon steels can be changed by applying an electric field. These experimental results provide a new way to change the microstructure of some materials and thereby improve their mechanical properties. For this purpose, a large amount of exploratory research has been performed. Liu et al. [24] improved the ductility of an Al-Li alloy with no decrease of the strength properties during a solid solution treatment accompanied by an electric field. Liu and Cui [25], by prolonging the duration of the homogenization treatment in an electric field, found that T_1(Al_2CuLi) precipitates distribute more homogeneously in the matrix and their volume fraction dramatically increases, thereby improving the strength of 2091 Al-Li alloy. Zhou et al. [26] studied the fatigue crack behavior of an Al-Cu-Mg alloy and found that the applied electric field refines S′ phase precipitates and forces vacancies to move toward grain boundaries. Meanwhile, improved fatigue crack propagation resistance was found in the alloy aged with an electric field because of higher energy for dislocation movement caused by the dispersed S′(Al_2CuMg) phases and low stored energy in defects. Conrad et al. [27] reported that an electric field applied during solution heat treatment and during natural ageing treatment has a significant effect on precipitates and yield stress of an Al-Mg-Si alloy; not only the

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size of the precipitates, but also the yield stress was improved by using field treatment.

Even though the influence of an electric field on the mechanical properties of Al alloys has been confirmed by various researchers, there has been little prior research on the influence of an electric field on the microstructure evolution and mechanical properties of Al-Cu-Li alloys during the ageing process. In the present study, the ageing treatment accompanied by an electric field in a third generation Al-Cu-Li alloy, containing less than 2% Li, was investigated. The aim of the study is to explore the effects of an electric field on the mechanical properties and microstructure of a third generation Al-Cu-Li alloy, and to elucidate the relevant mechanisms.

2. Materials and methods

The experimental Al-Cu-Li alloy, whose composition is Al-2.8Cu-1.3Li-0.3Mn-0.1Zr (in wt.%), was provided by the AVIC Beijing Institute of Aeronautical Materials (BIAM) in the form of cold-rolled 6-mm-thick sheets with a fully unrecrystallized microstructure, and the optical microstructure of the initial material is shown in Fig. 1. The test sheets were first cold rolled to a thickness of 2.5 mm; then the samples were solution treated at 530 °C for 1 h and water quenched. Directly after water quenching, the samples were artificially aged at 175 °C with or without an electric field of 5 kV/cm. The samples were connected to the positive pole of the high voltage source as shown in Fig. 2.

Hardness tests were carried out on the HV-10B Vickers Microhardness tester with a 0.5 kg loading for 15 s. For each sample, at least seven indentations were performed to obtain an average value of hardness. Electrical conductivity measurements were performed on the FQR7501 electrical conductivity meter; a total of five measurements were taken on every sample and the average is reported as the conductivity. Tensile tests were carried out on a MTS-858 test machine; three tensile specimens were tested and the average value of the results was adopted to evaluate the strength and ductility of the alloy.

Fracture morphologies and microstructures were examined using optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Leica DM ILM metallographic microscope was employed for side-view observation of fracture surface. SEM analysis was performed using a Sirion 200 scanning electron microscope. TEM specimens were first mechanically polished into thin slices of 100 μm and then electro-polished by using a twin-jet system in a solution of 25% nitric acid in methanol at −20 °C and 15 V. The observation of the microstructures was carried out on a Tecnai G^2 F20 transmission electron microscope operating at 200 kV.

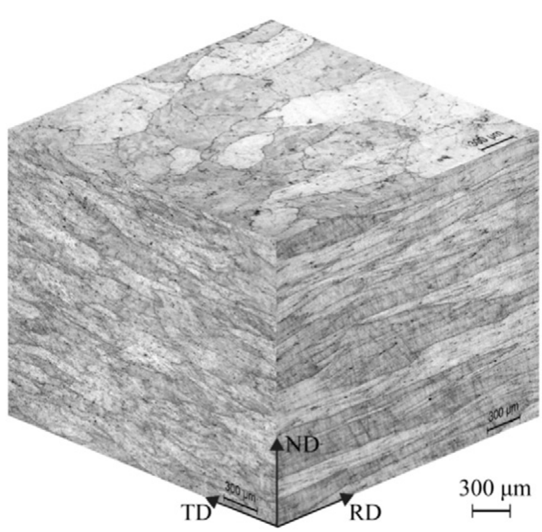

Fig. 1. Three-dimension microstructures of the initial alloy. RD: rolling direction; TD: transverse direction; ND: normal direction.

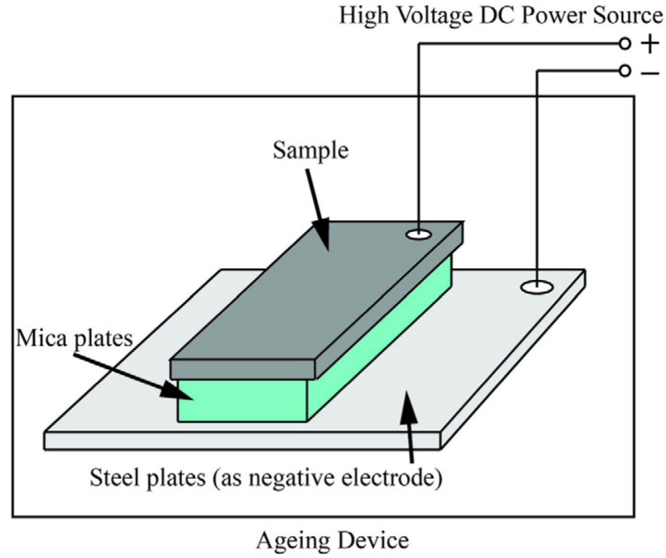

Fig. 2. Schematic of sample ageing with electric field.

3. Experimental results

3.1. Evolution of hardness and electrical conductivity

Fig. 3 shows the hardness of Al-Cu-Li alloy aged at 175 °C as a function of ageing time with and without the presence of an electric field; the general shape of the curves is consistent in both cases. The age hardening curves of Al-Cu-Li alloy are divided into five stages: the primary hardening stage, stable hardening plateau, secondary hardening stage, peak-aged stage, and over-aged stage. However, the main difference between the field-free-aged sample and field-aged sample on the curves occurred during the hardening plateau and peak-aged stage. As can be seen, the field-aged sample exhibits a shorter stable hardening plateau period and an earlier peak-aged stage than the field-free-aged sample. Also, the hardness of the field-aged sample during the hardening plateau is generally greater than that of field-free-aged sample.

The comparison of the two curves indicates that the electric field significantly influenced the duration time of the hardening plateau and caused the peak-aged time to occur earlier; however, the electric field

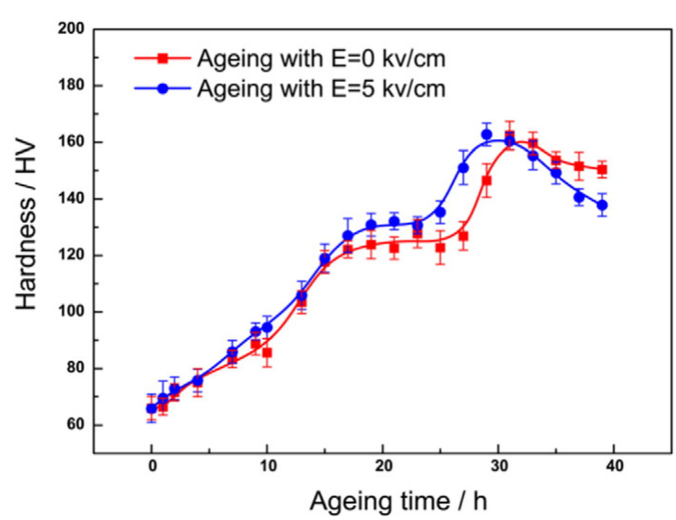

Fig. 3. Hardness of Al-Cu-Li alloy aged at 175 °C for various ageing times.