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Microstructure and property of stress aged Al−Cu single crystal under various applied stresses

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Abstract: The stress aging behavior of Al−Cu alloy under various applied stresses, i.e., elastic stress, yield stress and plastic deformation stress, was investigated using single crystals. The resulting microstructures and the yield strength were examined by transmission electron microscopy (TEM) and compression tests, respectively. The results indicate that an elastic stress of 15 MPa is high enough to influence the precipitation distribution of θ' during aging at 180 °C. The applied stress loading along $[\bar{1}16]_{\text{Al}}$ direction results in increased number density of θ' on $(001)_{\text{Al}}$ habit planes. This result becomes more significant with increasing applied stress and leads to lower yield strength of Al−Cu single crystals during aging. Moreover, the generation of the preferential orientation of θ' was discussed by the effect of the dislocation induced by applied stress as well as the role of the misfit between the θ'-precipitate and Al matrix. The results are in agreement with the effect of the latter one.

Key words: Al alloy; single crystal; stress aging; θ' phase; microstructure; property

1 Introduction

Owning the superiority of high specific strength, excellent fatigue resistance and ease of formability, aluminum alloys are ideal materials to perform the creep age-forming technique that can finish the age-hardening treatment and stress-induced deformation simultaneously. This creep age-forming technique has been utilized in the manufacturing process of large integrally stiffened lightweight structures for aerospace applications [1−3]. However, application of an external stress during aging can strongly affect the precipitate distribution and generate preferential orientation of precipitates in several age-hardenable alloy systems. This preferential orientation of precipitates structure or aligned precipitate structure was usually called the stress-orienting effect.

The plate-shaped θ' phase, of nominal stoichiometry Al_2Cu, is one of the most common and effective strengthening precipitate phases in aluminum alloys [4], and provides significant contribution to the yield strength of parts of 2000 series aluminum alloys. The stress-orienting effect in Al alloy system was firstly reported in binary Al−Cu alloy [5], i.e the θ'-plate, which may be attributed to its special habit planes of $\{100\}_{\text{Al}}$ and elongation directions of $\langle 001\rangle_{\text{Al}}$. Thus, it was usually used to study the conditions of generating the stress-orienting effect [5−8], or the precipitation distribution structure induced by the stress aging [9−11]. Additionally, with the development of the creep age-forming technique, the researchers are more concerned with the effect of stress aging or creep aging behavior on the strength property [12−15]. It has been reported that the stress-orienting effect may reduce the yield strength and deteriorate the strength anisotropy [16,17]. However, what degree of the stress may affect the precipitation distribution of θ', and how it further affects the strength property are not clearly understood.

Furthermore, regarding the mechanism of the stress-orienting effect, LI [18] first explained it with classical nucleation theory in which external work by the applied stress compensates the strain energy due to the lattice misfit of coherent precipitate nuclei, and it was widely employed to explain the stress-orienting effect [5−9].

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However, since SANKARAN's explanation [19] took into account the preferred nucleation on the stress-oriented dislocation structures, there were also some studies proposed that the dislocation affected or even dominated the precipitation of the precipitates during stress aging [20,21]. In the present study, we described the results of our investigation on Al−2%Cu single crystal that was aged without stress and with various applied compressive stresses, i.e., elastic stress, yield stress and plastic deformation stress, which are determined by the stress−strain curve of the Al−Cu single crystal. The resulting microstructures and the yield strength, as well as the relationship between the microstructures and the strength property, were examined in detail. Based on the dispute about the explanations of the stress-orienting effect, both the effect of the dislocation induced by applied stress and the effect of the role of the misfit between the precipitate and the Al matrix on the precipitation of θ' were discussed.

2 Experimental

The material (Al−2%Cu) and the procedures (heat treatments and single crystal preparation) used for the present experiments were as described in a previous publication [22]. In order to apply different compressive stress magnitudes, the biggest one chosen from single crystals was cut into four parts with different dimensions. The orientations (rolled surface) of the single crystal were determined by an automated electron back-scattered diffraction (EBSD) system mounted in a FEI Nova 230 Nanolab scanning electron microscope (SEM), and performed at 20 kV and 10 mm scan steps. The preparation procedures of the samples for EBSD measurement and post-processing analysis of the orientation maps could refer to Ref. [15]. Analysis of the result showed that the plane orientations of the single crystals were $(\bar{1}16)_{\rm Al}$. Additionally, one of these four single crystals was subjected to determine the stress−strain curve of the Al−Cu single crystal by compression tests using a strain rate 10^{-2} s^{-1} in a CSS44110 machine, and the other three single crystals were subjected to stress aging. One additional single crystal sample with random orientation was subjected to conventional aging (aging without stress) for microstructure comparison. These four single crystal samples were solution-treated at 525 °C for 2 h and quenched in water, and the stress-aging samples were loaded with compressive stresses in a specially designed fixture with three sample space, which was made according the Ref. [17]. Subsequently, all single crystal samples were aged at 180 °C for 66 h together. The applied stress magnitudes were approximately 15, 40, 60 MPa, respectively.

The yield stresses of aged samples were determined at 0.2% offset from the elastic response of compression tests on specimens using a strain rate 10^{-2} s^{-1} in a CSS44110 machine. The precipitate structure in the samples aged with and without stress was characterized by means of high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) and TEM. The TEM specimens were prepared by twin-jet polishing at 20 V using a solution of 50 mL HNO$_3$ and 150 mL methanol cooled at −25 to −30 °C. The TEM images and HAADF-STEM images were observed by FEI Titan G2 60-300 transmission electron microscope (TEM) operating at 300 kV. The features of the precipitates including the average diameter and the number density were determined by quantitative analysis of 5−10 TEM images for each sample.

3 Results

3.1 Stress−strain curve of Al−Cu single crystal before aging

As the stress aging samples of Al−Cu single crystal were subjected to applied stress prior to aging treatment, the applied stress may lead to a certain plastic deformation strain. In order to clearly understand the effect of the applied stress on aging behavior of Al−Cu single crystals during stress aging, it is necessary to determine the nature of the applied stress via the stress−strain curve of the Al−Cu single crystal. Figure 1 shows the stress−strain curve of the Al−Cu single crystal before aging (as-quenched condition). The resulting plastic deformation strain induced by corresponding applied stress are determined as shown in Table 1 based on Fig. 1. It can be found that the applied stresses during stress aging in present study are exactly located in different deformation stages, i.e., elastic stress $\varepsilon_{\rm p}$=0.02% (15 MPa), close to yield point stress $\varepsilon_{\rm p}$=0.3% (40 MPa), and plastic deformation stress $\varepsilon_{\rm p}$=3.5% (60 MPa), respectively.

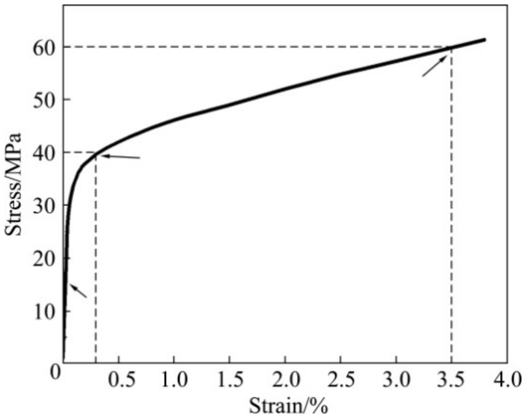

Fig. 1 Stress−strain curve of Al−Cu single crystal before aging (as-quenched condition)