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The inhibiting effect of dislocation helices on the stress-induced orientation of S' precipitates in Al–Cu–Mg alloy

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ABSTRACT

The phenomenon of restrained stress-induced preferential orientation of S' precipitates is investigated using a single-crystal of Al–1.23Cu–0.43 Mg alloy. Al–1.23Cu–0.43 Mg single-crystal specimens are subjected to stress aging, and the microstructure is analyzed by transmission electron microscopy (TEM). It is found that the stress-induced preferential orientation of S' precipitates is restrained owing to the dislocations produced by a higher stress. The effect of dislocations on the oriented precipitates depends on the total length of the intersection lines for precipitate habit planes and dislocation glide planes. This investigation not only provides important insight into solving the anisotropy problem attributed to precipitation strengthening, but also offers a benchmark for choosing the appropriate stress range in manufacturing of Al–Cu–Mg alloys.

1. Introduction

The anisotropy of mechanical properties plays an important role in aluminum alloys for aerospace applications [1–3]. In the manufacture of aluminum products, anisotropy in mechanical properties has been attributed to strengthening precipitates as well as to the development of crystallographic texture [4,5]. In T8 temper of certain classes of aluminum alloy, a plastic deformation prior to aging promotes the heterogeneous nucleation of precipitates on dislocations. However, application of an elastic stress during aging can significantly affect the orientation distribution of precipitates. This stress aging treatment has direct relationship with the “creep age forming” (CAF) technique, which has been utilized in manufacturing processes of integrally stiffened lightweight structures [6,7].

Previous investigations of aluminum alloys [8–10] have indicated that a stress applied within the elastic deformation regime during aging can significantly affect the distribution of the orientations of the precipitates [9–12]. Hosford and Agrawal [8] first studied the stress-orienting in Al–4Cu alloy single crystals and found that θ' precipitates on habit planes perpendicular to the applied compressive stress were generated preferentially. But Eto et al. [9] found the contrary results when Al–4Cu alloy single crystals were stress-aged under a lower temperature, where θ' precipitates were preferential orientation on habit planes parallel to the applied compressive stress. Based on the relationship between misfit inclusion and the applied stress, they explained the stress-orienting effect. Later, Skrotzki et al. [11] found that there was a threshold value (16–19 MPa) of the applied stress that

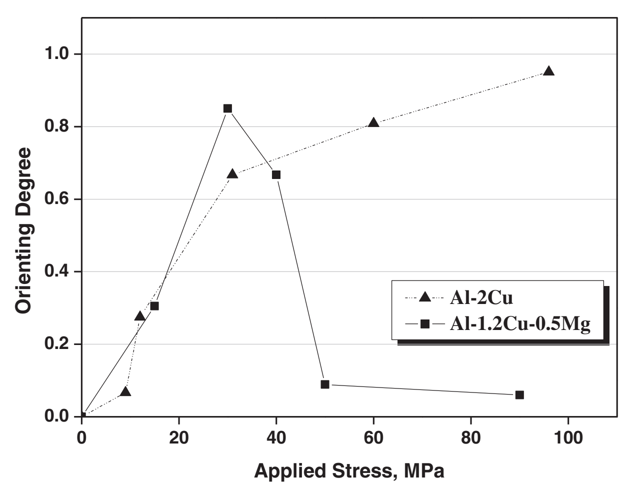

Fig. 1. Degree of orientation Γ' versus the applied compressive stress for aging of samples of single-crystal Al–4Cu [22] and Al–1.23Cu–0.43 Mg alloys.

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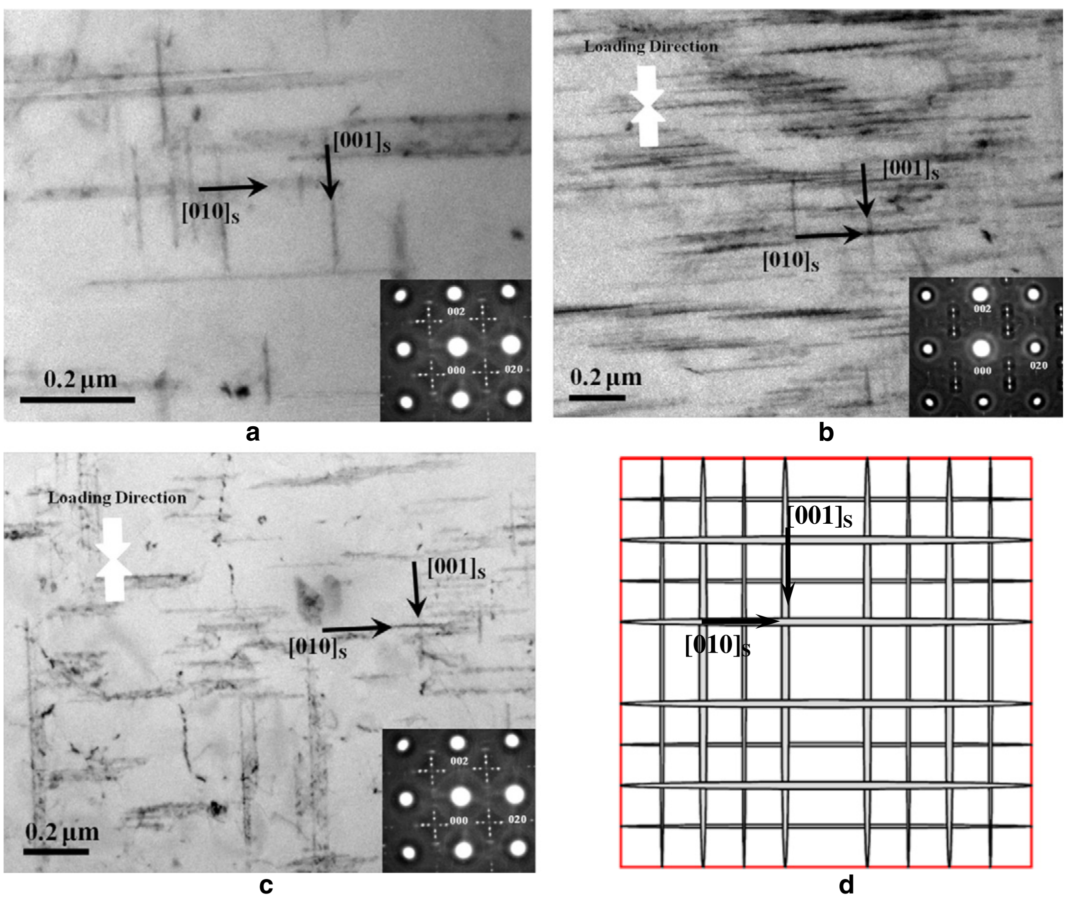
must be exceeded to form the preferential oriented θ′ precipitates in the 160 °C stress-aged Al–5Cu alloys samples. They explained the phenomenon with experiments and calculations in which stress induced the θ′ precipitates having negative misfit with the Al matrix nucleate preferentially on variants under compression. In order to model the precipitation strengthening of stress-aged Al–Cu alloys, Zhu et al. [10] have studied the dependence of applied stress, temperature and alloy composition on stress-aged Al–Cu alloy single crystals systematically. They found that the stress-orienting effect of θ′ precipitates increased with the increasing of applied stress and the yield stresses of the stress-aged specimens were lower than those of stress-free aged specimens. This stress aging treatment increases the alloy's anisotropy, which results in poor mechanical properties [13,14], especially in the Al–Cu–(Mg) series alloys.

The main precipitates of Al–Cu–(Mg) series alloys are S′ ($CuMgAl_2$) phase and θ′ ($CuAl_2$) phase. The S′ phase has an orthorhombic Cmcm structure with the lattice parameters $a = 0.404$ nm, $b = 0.925$ nm and $c = 0.718$ nm [15,16], which forms on $\{012\}_{Al}$ habit planes and grows along the $<100>_{Al}$ directions [17]. The S′ precipitates commonly observed are lath-shaped. But the θ′ phase has different habit planes, which always forms on {100} planes along the $<100>_{Al}$ directions. Previous investigations of Al–Cu–Mg alloys [18,19] indicated that the S′ precipitates were preferentially orientated during stress aging. However, the orientation of the S′ precipitates was not observed in other studies [20,21]. Owing to the difficulty in preparing single-crystal specimens of Al–Cu–Mg alloy for stress aging, no definitive conclusions have been drawn. Therefore, the present study aims to investigate the mechanisms for the preferential orientation of S′ precipitates using single-crystal specimens of Al–Cu–Mg alloy.

2. Materials and methods

Single-crystal Al–1.23Cu–0.43 Mg (wt.%) specimens were prepared, and grains up to 10 mm in diameter were grown by pulling bars cut from the alloy plate to 0.5–1.0% strain, followed by annealing at 525 °C for 24 h and then repeating the cycle 8–10 times. The orientations of the single crystals were determined by electron backscatter diffraction (EBSD). Six pairs of single-crystal specimens with the orientation of



Aging Conditions	$[010]_S : [001]_S$ ratio	The value of parameter Γ
0 MPa (Stress-free aging)	431 : 409 (~1 : 1)	0.018
30 MPa (Stress aging)	905 : 50 (~18 : 1)	0.851
50 MPa (Stress aging)	388 : 300 (~5 : 4)	0.089
0 MPa (Theoretical simulation)	8 : 8 (= 1: 1)	0

e

Fig. 2. TEM micrographs with the incident beam along the $[100]_{Al}$ zone axis and the corresponding selected-area electron diffraction (SAED) pattern showing the cross S′ precipitates $[010]_S$ and $[001]_S$ in the single-crystal Al–1.23Cu–0.43 Mg alloy aged at 180 °C for 66 h. (a) Conventional stress-free aging; (b) compressive-stress-aging at 30 MPa; (c) compressive-stress-aging at 50 MPa; (d) theoretical simulation of the S′ precipitates in the $[100]_{Al}$ TEM micrographs; (e) the proportion of precipitates along $[010]_S$ and $[001]_S$ counted in the $[100]_{Al}$ TEM photos (15–18 photos) for the different aging conditions in (a), (b), and (c) and the proportion directly obtained from (d).