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Precipitation hardening behavior of dilute binary Al−Yb alloy

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Abstract: The precipitation hardening behavior in dilute Al−Yb alloys upon annealing at different temperatures was investigated to shed light on the mechanism of micro-alloying element in aluminum alloys. When aging at different temperatures, the samples showed their corresponding peak hardness in the range of 400−416 MPa due to the precipitation of Al_3Yb with L12 crystal structure. The coarsening kinetics of the Al_3Yb precipitates obeyed the LSW theory, which indicated that the coarsening process was controlled by the diffusion of Yb. The coherence between Al_3Yb particles and matrix was maintained until the particle size reached 11 nm. When the particle size increased to about 2 nm, the shearing mechanism started to change to Orowan mechanism.

Key words: aluminum alloy; microalloying; ytterbium; aging; coherency; precipitation hardening

1 Introduction

A continuing goal in aluminum alloy development is to improve the strength, ductility, thermal stability and weldability so as to obtain a good comprehensive performance. Intensive past research has been conducted, and it was found that coherent intermetallic precipitating, especially for the $L1_2$ structured intermetallic particle, is an effective approach for strengthening [1]. However, only a limited number of possibilities exist in Al-based alloys for the formation of coherent strengthening particles that are thermodynamically stable and have the ordered $L1_2$ structure [1,2]. Of the possibilities, additions of Sc, Er and Yb have been most commonly studied [2−4]. Extensive research has established that Al–Sc solid solution decomposes to form a fine dispersion of homogeneously nucleated, equilibrium precipitates of a stable $L1_2$ phase, Al3Sc, which can produce a significant age hardening [5]. Moreover, the Al3Sc dispersoids can stabilize the grain structure of the alloy and prevent recrystallization after hot rolling by pinning grain and subgrain boundaries [6,7]. Similar to Sc, the heavy rare-earth element Er exhibits an Al−Al3Er eutectic reaction with Al3Er exhibiting a stable $L1_2$ crystal structure [8]. DALEN et al [8] and WEN et al [9] had investigated the solubility of Er in aluminum and the isochronal aging behavior of Al−0.045(mole fraction, %)Er. LI et al [10] and NIE et al [11] carried out intensive research on the influence of Er on the microstructure and mechanical properties of commercial aluminum alloy and found that Er addition is capable of strengthening and nanoscale Al3Er dispersions can inhibit recrystallization. There are investigations on precipitation strengthening in Al−Zr−Yb alloys, which illustrates significant precipitation strengthening and thermal stability [4]. However, there is no systematic investigation on the precipitation hardening behavior of Al−Yb binary alloy. In this work, we will investigate the precipitation hardening behavior of an Al−0.3(%)Yb aged at temperatures of 250, 300, and 350 °C to shed light on the mechanism of micro-alloying element in aluminum alloys.

2 Experimental

An Al−0.3(mass fraction, %)Yb alloy was prepared by diluting commercially pure aluminum with an Al−30(mass fraction, %)Yb master alloy. Its chemical composition was verified using inductively coupled plasma-atomic emission spectroscopy. The melt was poured into an iron mold at about 720 °C to produce a

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15 mm × 100 mm × 200 mm plate. Heat-treatments consisted of homogenization in air at 625 °C for 24 h, water quenching to room temperature, and aging in air at temperatures of 250, 300 and 350 °C for 5 min and 130 h, which was terminated by water quenching. Vickers microhardness was measured on polished samples using the average value from at least 10 independent measurements with a load of 1.96 N and a dwell time of 10 s. The common used unit of Vickers hardness is HV, but the unit is MPa in this work for comparing with other references [8,9]. The conversion of HV into MPa can use the equation HV_1=9.8 MPa. Slices for transmission electron microscopy (TEM) samples were cut from the plate, and were subsequently ground to less than 100 μm and punched into 3 mm discs. Thin foils for TEM observation were prepared by twin-jet polishing with an electrolyte solution consisting of 30% HNO_3 and 70% methanol below −30 °C. TEM observation was carried out by JEOL 2100 microscope with an operating voltage of 200 kV. The average precipitates radii, $\langle R(t)\rangle$, were measured from dark field images taken by the L12 superlattice reflections. To obtain statistically reliable data, more than 200 particles were analyzed on more than three micrographs for each aging condition.

3 Results and discussion

3.1 Age hardening behavior

The average hardness value of our specimens after homogenization and quenching but before aging is 240 MPa, which is higher than the hardness of about 180 MPa for pure Al [12], as expected from the presence of ytterbium in solid solution and primary Al_3Yb at the grain boundary. Figure 1 shows the TEM image of some typical primary Al_3Yb phases at the grain boundary and its corresponding selected area diffraction (SAD) pattern. It should be formed by divorced eutectic reaction as that of the primary Al_3Yb in Yb-containing alloys [13]. During solidification, supersaturated Yb atoms were expelled from the grain and accumulated at the front of the interface between solid and liquid. When Yb concentration approaches the eutectic point, Al_3Yb will form as part of the eutectic structure.

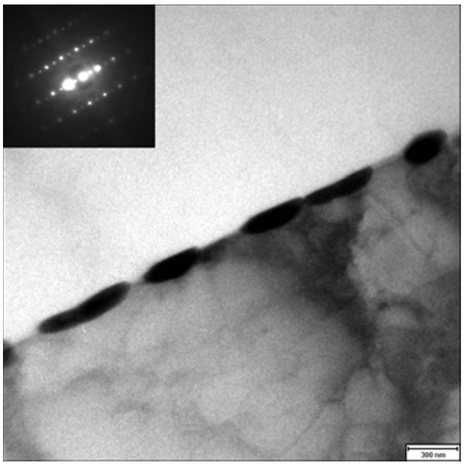

Fig. 1 TEM image of primary Al_3Yb phase and its corresponding SAD pattern

The homogenized alloy was aged at temperatures of 250, 300 and 350 °C, respectively. The microhardness as a function of the aging time is presented in Fig. 2. For a given aging temperature, with the increasing of the aging time, there is aging hardening behavior, which exhibits four different regions: 1) an incubation period; 2) a short transient period with a rapid increase in hardness values; 3) peak aging, a plateau at high hardness values; and 4) overaging, a decrease of the hardness [12]. The incubation period is very short, and the hardness increases immediately after aging treatment. The peak aging hardness values are similar to each other; however, the time taken to reach the maximum hardness decreases and the rate of hardness drop after peak aging increases as the aging temperature increases. The maximum hardness obtained is 415 MPa after aging at 250 °C for 1 h and this hardness level is retained for about 50 h. The maximum hardness of 350 °C aging is 400 MPa, which is obtained after aging for 5 min, and this hardness decreases quickly with overaging. This aging behavior is similar to that of the Al−Sc alloy, while the peak aging hardness is larger than that of the Al−Sc alloy with the same composition [12,14].

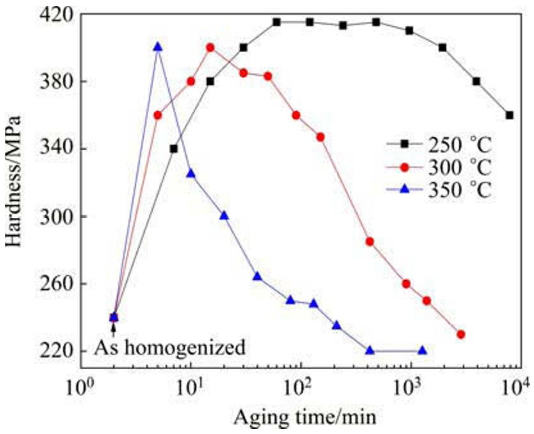

Fig. 2 Vickers microhardness as function of aging time at temperatures of 250, 300, 350 °C

The age hardening effect must be accommodated by precipitation of a secondary phase. From the Al−Yb equilibrium phase diagram, the supersaturated Al−Yb solid solution will decompose to form Al_3Yb phase [15]. TEM observations were carried out to investigate the hardening precipitates and four typical samples were selected to exhibit the precipitation characteristic. Figures 3(a) and (b) show the TEM micrographs of the

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