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Effect of precipitate morphology evolution on the strength–toughness relationship in Al–Mg–Si alloys

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Experimental results show that the gradual evolution of precipitate morphology in Al–Mg–Si alloys, from spherical to rod-/needle-shaped, leads to an increase in ductility but a decrease in both yield strength and fracture toughness. The strength–ductility relationship reported here is similar to general observations but the strength–toughness relationship is distinctly different from the conventional one. These relationships are rationalized by considering a competition between dislocation–precipitate interaction and precipitate–matrix deformation discrepancy as the dominant strain localization mechanism, which is modulated by the evolution of precipitate morphology.

Keywords: Aluminum alloys; Fracture toughness; Precipitate; Morphology evolution

Both high strength and superior fracture toughness are required for heat-treatable aluminum alloys used in transportation fields such as in aircraft and automobiles [1–12]. The relationship between strength and fracture toughness has been a permanent focus of research into aged aluminum alloys. First, it is very useful for industrial purposes if toughness can be easily deduced from a tensile test using unnotched specimens and simple measurements. Second, a good understanding of this relationship can be favorable for artificially controlling the aging treatment to achieve a good combination of strength and fracture toughness. In general, the toughness of metals decreases as the strength is raised by alloying and heat treatment. The trade-off between strength and fracture toughness in heat-treated aluminum alloys is usually the result of aging treatment. From the under-aged conditions up until the peak-aged point, the increasing nucleation and growth of precipitates causes a successive enhancement in the strength. At the same time, the fracture toughness degrades gradually because the presence of fine precipitates induces local shear instability. In the over-aged conditions, where precipitates coarsen via Ostwald ripening, strength goes down and the fracture toughness can either go up or be almost unchanged, depending on the composition and fracture mode (intergranular or intergranular fracture) [5]. The known strength–fracture toughness relationships in aged aluminum alloys have mainly been explained based on the evolution of precipitate content and precipitate size with aging treatment [2–5]. However, the influence of precipitate morphology or precipitate shape on the strength–fracture toughness relationship is still unclear.

Most recently, the evolution of precipitate morphology, from spherical to predominantly rod- and needle-shaped, has been obtained in an Al–Mg–Si alloy by the present authors [13,14] using a two-step aging treatment. It has been found that the strength and ductility of the alloy were clearly affected by the evolution of precipitate morphology. In this paper, the influence of precipitate morphology evolution on the fracture toughness is investigated and the relationships between the mechanical properties, i.e. the strength–ductility and the strength–toughness relationships, are discussed in terms of this evolution.

The Al–Mg–Si alloy used in the present investigation is extruded rod 18 mm in diameter. The composition is 1.12 Mg, 0.57 Si, 0.25 Cu, 0.22 Cr (wt.%), and balance Al. The alloy had been solution-treated at 703 K for 30 min followed by water quenching and had then been

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pre-aged at 373 K for 20 min. After storage at room temperature for 50 months, the alloys were secondarily aged at 473 K for a series of aging times (t) from 2 to 40 h. Yield strength (σ_y), reduction in area (RA%) and strain to fracture (ε_f) were measured in tension testing and details can be found in our previous paper [13,14]. Fracture toughness (KIC) was determined using three-point bending sample and J-integral measurement. The samples, 18 mm in width and 9 mm in thickness, have a L–R orientation (L, extrusion direction and R, radial direction) and the V-notch is normal to the extrusion direction. An initial crack was machined by spark erosion and subsequently grown by fatigue to an a/W value of 0.55–0.65 (a, crack length and W, sample width). Since the sample thickness is too small to obtain a valid KIC according to the ASTM standard, the ductile fracture toughness JIC was determined using the multiple-sample technique outlined by ASTM E813. An equivalent KIC, denoted KJC, was then derived from the JIC measurement using the relationship [15]:

$$K_{JC} = \left(\frac{J_{IC}E}{1-\nu^2}\right)^{1/2}, \quad (1)$$

where E (70 GPa) and ν (0.33) are the Young's modulus and Poisson's ratio of aluminum. For microstructural analyses, transmission electron microscopy (TEM) was used to determine the size and volume fraction of the precipitates. Details can be found in our previous papers [11,12,16,17].

Figure 1 shows the precipitate evolution with aging time (t) during the secondary aging treatment. At $t = 0$ or before the secondary aging treatment, the alloy contains spherical strengthening particles (Fig. 1b), which were determined to be the metastable pre-β″ phase of $AlMg_4Si_6$ [16], and were precipitated during the first aging treatment and subsequently grew during the subsequent storage period. In the secondary aging treatment, the spherical pre-β″ precipitates dissolved gradually. On the other hand, two other kinds of strengthening second-phase particles were precipitated, which are rod-shaped precipitates and needle-shaped precipitates, examples of which are shown in Figure 1c and d, respectively. The rod-shaped precipitates, which were determined to be the metastable β″ phase of Mg_5Si_6, formed in situ on the pre-β″ phase and grew by consuming the pre-β″ phase, while the needle-shaped strengthening particles, which were determined to be the metastable β′ phase of Mg_2Si, were precipitated from the matrix. The precipitation sequence is in good agreement with previous results [18]. During the entire secondary aging treatment, the volume fraction of spherical pre-β″ phase reduces progressively, while the volume fraction of rod-shaped β″ phase and needle-shaped β′ phase rises (Fig. 1a). However, there is not much change in the total volume fraction (about 1%) of the three kinds of precipitates. This means that, although the precipitate morphology changes gradually from fully spherical to predominantly rod- and needle-shaped, the evolution of precipitate morphology can simply be regarded as a conserved process because there is little change in the overall content.

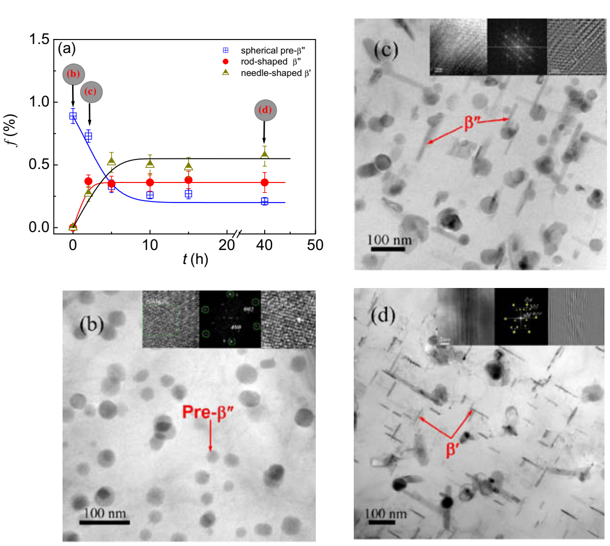

Figure 1. Evolution of precipitate volume fraction (a) and precipitate morphology (b–d) with aging time t. (b), (c) and (d) are typical TEM images of the alloy aged at $t = 0$, 2 and 40 h, respectively, to show the precipitate evolution from spherical pre-β″ precipitates of $AlMg_4Si_6$, to rod-shaped β″ precipitates of Mg_5Si_6 and needle-shaped β′ precipitates of Mg_2Si. Inserts in these images are structural analyses [14] for the three precipitates, respectively.

Table 1 summarizes the measurements of the mechanical properties. Variations in all these mechanical properties are obvious, along with the evolution of precipitate morphology. Prolonging the aging time or increasing t causes σ_y and K_{JC} to decrease while RA% and ε_f increase. The relationships between these mechanical properties will be discussed in detail by taking account of the evolution of precipitate morphology.

The strengthening effect in aged aluminum alloys mainly derives from precipitates. It is well known that raising the precipitate content and reducing the precipitate size can promote the strengthening effect. Furthermore, computer simulations have also revealed that precipitates with different shapes should have different strengthening responses [19]. According to our previous result [13,14], compared to rod-/needle-shaped precipitate, spherical precipitate has a stronger interaction with dislocation.

Strength and ductility are often mutually exclusive in a material. The pinning of dislocations, which induces strengthening, will cause local strain/stress concentration and degrade the deformation capability. A similar trend is found in the present aluminum alloys (Table 1), i.e. ductility increases while yield strength decreases, with the precipitate morphology changing from spherical to rod- and needle-shaped. Here, the parameters used to characterize ductility are ε_f and RA%, both derived from the measurement of area change. RA% is an important parameter, especially in industry, because it has significant implications in regard to bending and collapse. Lloyd [20] has proposed, based on a macroscopic model, that there exists a scaling relationship between RA% and σ_y in aluminum alloys. This scaling relationship was clearly found in 6000 series Al–Mg–Si alloys [20], where strength was varied by aging. Some data from 2000 series Al–Cu–Mg [11] and 6000 series Al–Mg–Si alloys [20] are shown in Figure 2a as square dots. RA% increases with reducing σ_y, and the relation-