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Effect of Mn on fracture toughness in Mg–6Al–1 wt.%Zn alloy

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Abstract

The effect of Mn content on fracture toughness and strength is investigated in Mg–6 wt.%Al–1 wt.%Zn alloy. As a result, the addition of 0.1–0.15 wt.% of manganese, which is close to the solubility limit of manganese is the most effective to avoid a significant reduction of fracture toughness and takes advantage of solution strengthening at the same time. The addition of Mn above the solubility resulted in the reduction of fracture toughness due to the formation of Mn-bearing particles. We defined the minimum size of void-nucleating particles and found that this minimum size increased with decreasing fracture toughness due to the formation of Mn–Al particles by the excessive manganese addition. In such a case, the reduction of the size of the second-phase particles is effective in improving the fracture toughness.

Keywords: Magnesium alloy; Strength; Fracture toughness; Manganese content; Second-phase particle; Minimum size

1. Introduction

Due to the strong demand for weight reduction in vehicles for better fuel efficiency, there have been considerable research interests in the application of Mg-alloys to various structural components of automobiles and aircrafts [1–3]. For a wider application of Mg-alloy, the improvement of its mechanical properties such as strength and ductility is required.

Fracture toughness is known as one of the parameters, that represents the reliability and safety of materials. In Mg-alloy, very few studies have been carried out to clarify the fracture behavior [4–6]. Since the evaluation of plane-strain fracture toughness could not be examined properly in wrought Mg-alloy, we firstly applied the stretched zone analysis and found that it was effective to evaluate plane-strain fracture toughness properly [7]. In order to broaden the application of Mg-alloy, there are strong needs to clarify the detailed microstructure–fracture toughness relationship for the improvement of fracture toughness. Recently, the number of reports concerning the fracture behavior of wrought Mg-alloy reported the low fracture toughness of Mg-alloys and also clarified the unique microstructure–fracture relationships such as that between the grain size, texture and fracture toughness [8–13].

As to the fracture mechanism of wrought Mg-alloy, ductile fracture induced by void nucleation, growth and coalescence is a dominant fracture mechanism. This fracture mode has been widely observed in many commercial alloys [14–17]. During the past several decades, there have been a considerable number of investigations of the ductile fracture characteristics [14–37]. Void nucleation and growth are known to have several mechanisms depending on the given microstructure condition [18,19]. In particular, most of the studies have been focused on to clarify the relationship between the dispersion of second-phase particles, void nucleation and growth behavior since microvoids generally nucleate at inclusions as has been known by the pioneering work of Tipper [20]. In the very early stage of ductile fracture, void nucleation takes place and exhibits the low-strain-range nucleation behavior. It is characterized by interfacial separation around large inclusions, internal cracking of large elongated particles, and separation between closely spaced particles. After this stage, microvoids nucleate at a certain point late in the strain history by decohesion along the interfaces between average-sized particles and the matrix [21]. The order of the fracture toughness is entirely determined by the void nucleation in these stages. Thus, one of the reports about the particle–fracture relationship indicates that the size reduction of second-phase particles is effective to improve the fracture toughness [22]. Although the second-phase particle–fracture relationship is not

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studied very well in Mg-based alloy, some articles reports the very small particle with a diameter of even few microns can be a nucleus of the microvoid in the determination of fracture toughness [8,38]. Up to now, many trials have been made to correlate the particle features such as size, interparticle spacing and volume fraction with fracture toughness not only experimentally but also theoretically [23–37,39,40]. However, all the particle features obtained from the experiments were expressed as averaged values. Knowing the critical parameter can also be one of the best ways to suggest clear guidelines for materials design. In the present study, we investigated the effect of Mn on mechanical properties such as strength and fracture toughness and also tried to clarify the minimum size of void-nucleating particles in Mg-alloy. Mn is generally added to the Mg-based alloy in order to separate out the harmful heavy metals from the melt by forming intermetallic compounds with Al [41]. Although the residual large second-phase particles are thought to degrade the mechanical properties, very few studies have been carried out about the effect of Mn addition on mechanical properties [42,43]. At the same time, in Mn-containing alloy, it is very easy to investigate the effect of the dispersion of particles on fracture characteristics since Mn easily forms an intermetallic compound with aluminum [41]. This also makes it very easy to investigate the effect of the particles on fracture toughness. In the present study, commercial Mg–6Al–1 Zn (wt.%) extruded alloy with systematic addition of Mn was used since fracture toughness needs to be evaluated in this alloy system.

2. Experimental procedure

Mg–6Al–1 Zn (wt.%) alloys with different Mn content were received in the form of extruded bars. The chemical composition of each sample is listed in Table 1. Since the grain size in each extruded sample differed considerably from each other in as-received condition, each sample was subjected to heat treatment to obtain comparable grain sizes. The heat treatment conditions were as follows: 673 K for 1.8×10^3 s for sample A–C and 723 K for 1.44×10^4 s for sample D. The grain size after heat treatment is also summarized in Table 2.

In order to evaluate the tensile properties of these samples, tensile test was carried out at a strain rate of $1.0 \times 10^{-3}\ s^{-1}$ using round-bar specimens with a gauge length of 5 mm and a diameter of 1.25 mm.

Fracture toughness evaluation is carried out by stretched zone analysis, which analyzes the plane-strain fracture toughness by analyzing stretched zone appearing on fracture surface. In order to obtain fractured specimen, plane-strain fracture toughness tests were carried out on the extruded bars following the procedure outlined in ASTM E-399 [44]. The fracture toughness test specimens were three point bending samples with the size of 62 mm × 15 mm × 5 mm in length, width and thickness, respectively. The fracture toughness test specimens were machined directly from the extruded bars. The V-notch was introduced normal to the extrusion direction. Before the plane-strain fracture toughness test, fatigue pre-crack was introduced to the specimen so that the length of fatigue pre-crack is in the range from 0.45 to 0.55W, where W is the width of 15 mm. The plane-strain fracture toughness tests were carried out at a cross-head speed of 1 mm/min. In order to analyze the stretched zone, which is a trace of the blunt crack tip, the fractured specimens were observed with scanning electron microscopy, SEM. From the stereo analysis of the stretched zone, the critical crack-tip opening displacement ($CTOD_C$), δ, was analyzed. Details about the analysis of $CTOD_C$, δ from the stretched zone analysis can be referred to our previous report [7]. From the calculated $CTOD_C$, the plane-strain fracture toughness, K_{1C}, was calculated using the following equation [24]:

$$K_{1C} = \sqrt{\frac{\delta \lambda E \sigma_{ys}}{1 - \nu^2}} \quad (1)$$

where λ is the constant (=2 [45]), E the Young' s modulus (=42.93 GPa in pure-Mg [46]), σ_{ys} the yield strength, and ν is the Poisson ratio (=0.28 in pure-Mg [41]).

Microstructural observation was carried out by SEM and electron probe microanalysis (EPMA), to investigate the relationship between the microstructural features of the alloys and the fracture toughness.

Table 2
Grain size in each sample before and after heat treatment

	Grain Size (d/μm)	
	As-extruded	Annealed
Sample A	25.5	69.6
Sample B	9	60.4
Sample C	9.7	60.2
Sample D	9.6	57.9

3. Results and discussions

3.1. Microstructure

Fig. 1(a)–(c) shows the secondary electron images of sample A, sample B and sample D observed from the normal direction, respectively. The arrow in Fig. 1(a) shows the extrusion direction. In each image, globular inclusions with white or

Table 1
Chemical composition of the specimens

Sample	Al (wt.%)	Zn (wt.%)	Mn (wt.%)	Fe (wt.%)	Si (wt.%)	Mg (wt.%)
Sample A	6.2	1.07	<0.01	<0.02	<0.02	Bal.
Sample B	6.15	1.05	0.14	<0.02	<0.02	Bal.
Sample C	6.19	1.07	0.17	<0.02	<0.02	Bal.
Sample D	6.2	1.08	0.25	<0.02	<0.02	Bal.