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Short communication

Effects of Yb on the mechanical properties and microstructures of an Al–Mg alloy

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ABSTRACT

This paper reported a first study of the effects of Yb on the microstructures and mechanical properties of an extruded Al–Mg alloy. It has been shown that the addition of 0.3 wt.% Yb decreases the mechanical properties of the alloy since Mg- and Yb-containing constituents decrease the concentration of Mg solute atoms in Al matrix, and thus the solution strengthening effect. However, the addition of 1 wt.% Yb substantially improves the mechanical behavior of the alloy because the concentration of Yb solute atoms in Al matrix is high enough to generate solution strengthening effect. The improvement in the mechanical properties is due to the large work-hardening and high dislocation density caused by the interaction between dislocations and Yb and Mg solute atoms. The Yb and Mg atoms inhibit the dynamic recovery and recrystallization of the alloy, thus provide a uniformly distributed dislocation structure with high density.

1. Introduction

Al–Mg alloys have been widely used in aerospace and vehicle industries due to good combined properties, such as medium strength, good corrosion resistance and welding property [1]. In many conditions, the mechanical properties of Al–Mg alloys are required to be further improved. One method to improve the mechanical properties of Al–Mg alloys is applying pre-strain to the alloys. The influence of pre-deformation on the subsequent general mechanical behavior of Al–Mg alloys, such as hardness, yield stress, flow stress and elongation, has been reported by earlier researchers [2–6]. In most cases, the strength increases sharply with pre-strain, and more gradually for larger pre-strain. In some cases, such as 5083 Al [4,6], larger pre-deformations result in a mild lowering of the subsequent flow stress. Dalla Torre et al. [7] attributed this to the increasing misorientation between the subgrains and a decreasing width of the cell wall, leading to a greater effectiveness of boundaries to act as sinks for defects. Another important method to improve the mechanical properties of Al–Mg alloys is microalloying. Previous studies [8–10] showed that the addition of minor Sc to the Al–Mg alloys can substantially improve the yield strength and tensile strength, resulted from the Al_3Sc particles by inhibiting the dynamic recrystallization and dislocations movement. When Sc and Zr are added to Al–Mg alloys simultaneously, the strengthening effect is more obvious due to the finer and more stable $Al_3(Sc,Zr)$ particles [11–13]. However, the key problem of the wide application of the Sc-containing Al–Mg alloys is the high cost of scandium. In a very recent paper, Chen et al. [14] showed that cheaper Yb can moderately improve the mechanical properties of an Al–Zn–Mg–Cu–Zr alloy by inhibiting recrystallization. Based on the work of Chen et al. [14], we reported a first study of the effects of Yb on the mechanical properties and microstructures of an extruded Al–Mg alloy.

2. Experimental

The nominal composition of the alloys in the present study has been shown in Table 1. The alloys were prepared by a casting metallurgy method in a graphite mould. The as-cast ingots were homogenized at 470 °C for 10 h, followed by air cooling to the room temperature. Then the ingots were converted into rods by hot extrusion at 450 °C, with an extrusion ratio of 9:1.

The mechanical properties were tested at room temperature using a smooth dog-bone-shaped tensile specimen that had a gage size of 6 mm in diameter and 40 mm in length at a constant strain rate of $2 \times 10^{-5}\ s^{-1}$ by an Instron-8082 testing machine. All the specimens have an axis along the extrusion direction. Distribution of the constituents and fracture surfaces of the specimens after tensile testing were examined using a scanning transmission microscopy (with EDS). Microstructural analysis used transmission electron microscopy (TEM). The TEM specimens (thin foils) were prepared by twin-jet electro-polishing in a 30% nitric acid and 70%

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Table 1
Chemical composition of the tested alloys (wt.%)

Alloys	Mg	Mn	Zn	Ti	Cr	Yb	Al
1#	5.0	0.35	0.15	0.18	0.15	0	Bal.
2#	5.0	0.35	0.15	0.18	0.15	0.3	Bal.
3#	5.0	0.35	0.15	0.18	0.15	1.0	Bal.

methanol solution at −35 °C and examined using a Tecnai G^2 20 microscopy operating at 200 kV.

3. Results

3.1. As-extruded microstructures

Fig. 1 shows the as-extruded microstructures of the tested alloys. It can be seen that all three alloys have similar microstructures after extrusion. The microstructures include high density of dislocations, which are generated during hot extrusion because of working hardening. In general, the dislocation density in alloys 1 and 3 is slightly higher than that in alloy 2. The dislocations in alloys 1 and 2 are distributed "quasi-uniformly" as Taylor lattice, which shows typical dislocation structures in Al–Mg alloys. However, the dislocations in alloy 3 exhibit a structure close to cell structure since cell walls are clearly seen.

3.2. Mechanical properties

Table 2 illustrates the mechanical properties of the extruded alloys. It can be seen that Yb degrades both the yield strength and tensile strength at a low concentration of 0.3 wt.%. However, when the concentration of Yb reaches 1 wt.%, the tensile strength, yield strength and elongation of the alloy have been increased by about 8.6%, 5.2% and 24%, respectively, compared to the alloy without Yb.

3.3. Microstructures after tensile deformation

Fig. 2 illustrates the TEM microstructures of the tested alloys after tensile deformation. It can be seen that the dislocations are still distributed "quasi-uniformly" as Taylor lattice in alloy 1, a typical structure in Al–Mg alloys. However, in alloys 2 and 3, the dislocations are distributed non-uniformly, exhibiting characteristic of cell structures. Typically, the dislocation densities are very high in all three alloys, especially in alloy 3 (see Fig. 2c and d). The increase in dislocation density is due to the work-hardening. The most important feature of the alloys is that the dislocation density increases as the Yb content increases, which indicated that work-hardening level of the alloy during deformation increases as the Yb content increases. However, it should be noted the dislocations are distributed more uniformly in alloy 3 than in alloy 2. Small amount of the stable Al_8Mg_5 (β) particles can be observed in the matrix. During tensile deformation, the dislocation and vacancy densities increase, and thus accelerate the precipitation of β phase.

Table 2
Mechanical properties of the tested alloys[a]

Alloys	σ_b (MPa)	$\sigma_{0.2}$ (MPa)	δ (%)
1#	374	211	18.3
2#	339	207	18.0
3#	406	222	22.7

[a] All the data are the average values of five experiments, and the maximum error is less than 10%.

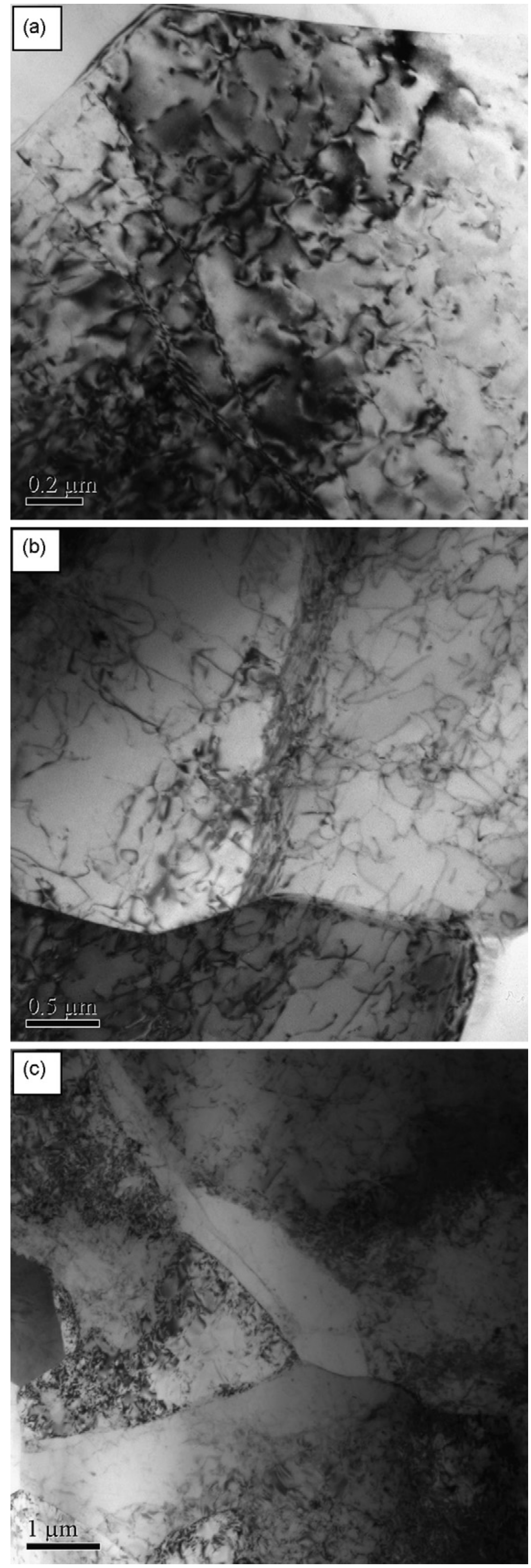

Fig. 1. TEM images of as-extruded microstructures of the tested alloys: (a) without Yb, (b) with 0.3 wt.% Yb and (c) with 1.0 wt.% Yb.

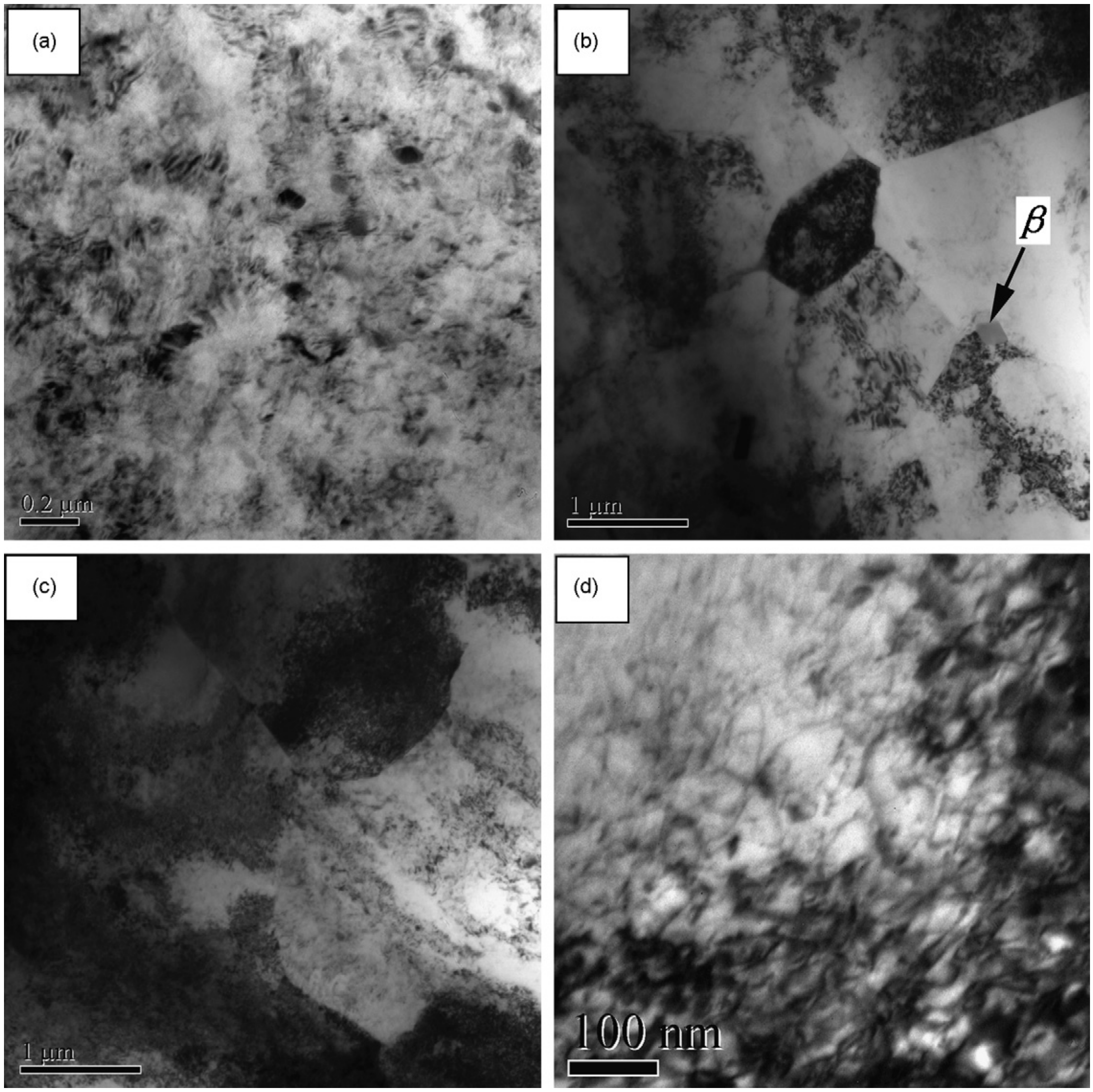

Fig. 2. TEM microstructures of the alloys after tensile testing: (a) without Yb, (b) with 0.3 wt.% Yb and (c) with 1.0 wt.% Yb; (d) high dislocation density in the alloy with 1.0 wt.% Yb.

3.4. Fracture surfaces

Fig. 3 shows the fracture surface morphologies of all the tested alloys after tensile deformation to fracture. All specimens failed in a ductile manner, consisting of numerous dimples over the entire surfaces. It can be seen that the dimple size in Yb-free alloy is only several microns. The dimples should be a result of the void nucleation and subsequent coalescence by strong shear deformation and fracture process on the shear plane. However, the average dimple size increases dramatically and becomes about tens of microns with the addition of Yb. It should be noted that the fractured Yb- and Mg-containing constituents (see the EDS results in Fig. 3) are clearly seen in the center of some larger-sized dimples. Thus, the increase in the dimple size by the addition of Yb can be explained by work-hardening and the fragmentation of the constituents caused by high stress concentration.

4. Discussion

In most applications of Al–Mg-based (5XXX) alloys both work-hardening and solution strengthening are important contributors to the strength. Compared to most other solute atoms in Al, Mg atoms have large radius and exhibit large internal friction in Al matrix. This large internal friction affects dislocation distributions, microband formation, strain localization and shear band formation [15–18]. Magnesium additions in solid solution are known to increase considerably the work-hardening ability of aluminum [19–21]. For a typical polycrystalline Al–Mg alloy, serrated flow is generally observed [22,23]. The dynamic strain aging, which is microscopically controlled by dynamic interactions between the mobile dislocations and diffusing solute atoms (Mg atoms), has been proposed to be a primary mechanism associated with the serrated flow in polycrystalline Al–Mg alloys [22,23]. In general, the dislocation motion can be arrested more effectively by solute atoms at a low strain rate than that at a high strain rate.

It is believed that Yb also exhibits large strengthening effect as Mg since the mechanical properties of alloy 3 is substantially higher than those of alloy 1. In principle, Yb solute atoms can generate large internal friction and inhibit the cross-slip of the dislocations, which results in large work-hardening and solution strengthening since the radius of Yb atom is very large. Fig. 2d illustrates a uniform distribution of the dislocations with very high density in alloy 3, indicating a high work-hardening in 1 wt.% Yb-containing alloy, compared to the alloy without Yb. However, it should be noted that the concentration of Yb must be high enough to generate strengthening effect since alloy 2 with 0.3 wt.% Yb has relatively lower mechanical properties than alloy 1 without Yb. This is probably due to the formation of the Yb- and Mg-containing constituents. Fig. 4 shows the SEM images of the Yb- and Mg-containing constituents in alloys 2 and 3. It can be seen that the size (about 10 μm), shape, distribution and volume fraction of the Yb- and Mg-containing constituents are similar for both alloys with 0.3 and 1 wt.% Yb. In general, the constituents in aluminum alloy have low fracture strength and nucleate microcracks during

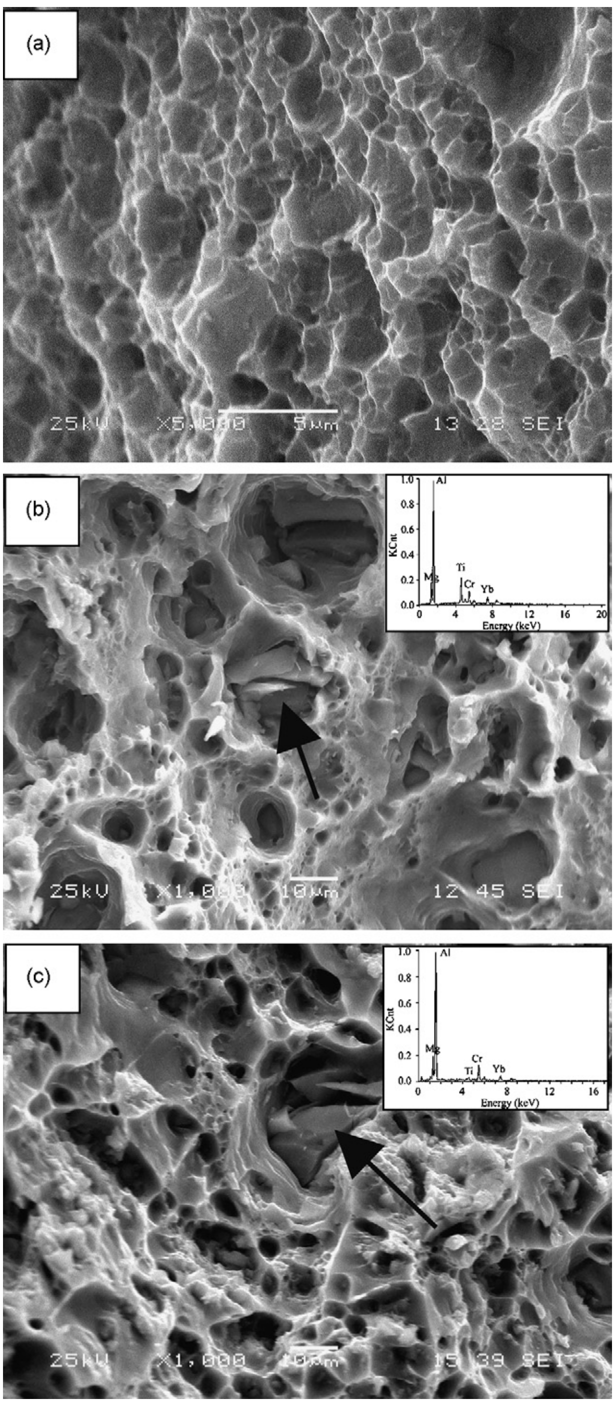

Fig. 3. SEM images of the fracture surfaces of the tested alloys: (a) without Yb, (b) with 0.3 wt.% Yb and (c) with 1.0 wt.% Yb.

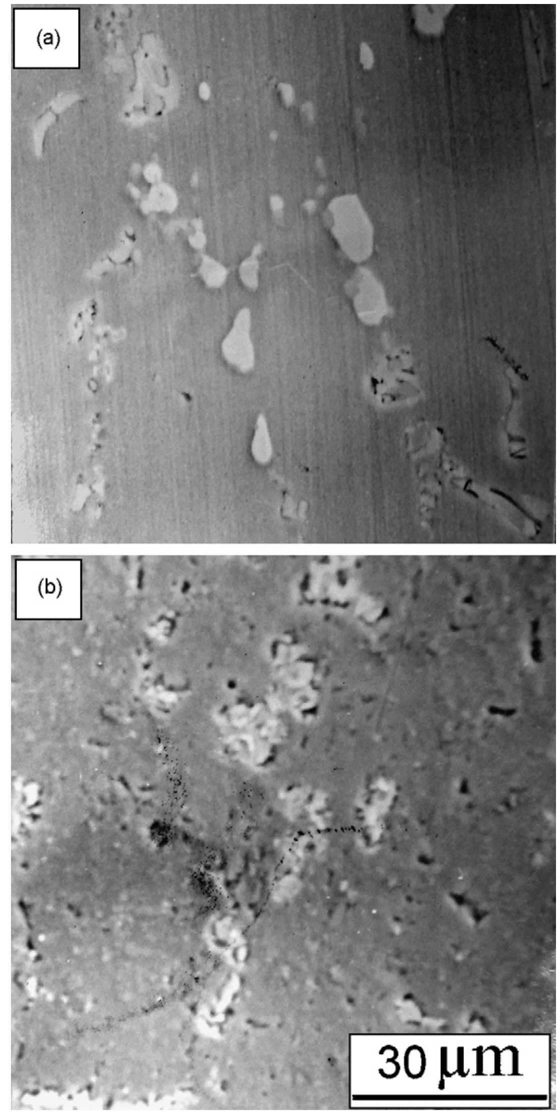

Fig. 4. SEM images showing the size and distribution of the constituents in alloys (a) 2 and (b) 3.

deformation [24,25]. In this case, it is believed that the Yb- and Mg-containing constituents may not generate obvious strengthening effects because of the large size and low fracture strength. It is known that Mg has large solubility in Al, about 17.4 % at eutectic temperature. The formation of Yb- and Mg-containing constituents decreases the solute degree of Mg in the Al matrix. Although some Yb atoms have also to be dissolved in matrix before the formation of the constituents, the increase in the strength caused by Yb solute atoms cannot compensate the decrease in the strength caused by the decrease in the Mg solute atoms in alloy 2 with 0.3 wt.% Yb. However, it should be noted that the concentration of Yb solute atoms in the Al matrix is high enough to generate obvious solution strengthening to compensate the decrease in the strength caused by the decrease in the Mg solute atoms in alloy 3 with 1 wt.% Yb.

In this work, the extrusion temperature is 450 °C, which is high enough for the dynamic recovery and recrystallization. In general, dynamic recovery and recrystallization have important effects on dislocation distributions and thus the mechanical behaviors [26]. The improvement of the strength by Yb addition is probably due to the interaction between dislocations and Yb solute atoms, which substantially inhibits the dynamic recovery and recrystallization. This is in agreement with Fig. 2, in which a much higher dislocation density has been observed for Yb-containing alloys.

An important feature of this study is that the 1 wt.% Yb-containing alloy exhibits large elongation as well as yield strength and tensile strength than those of the alloy with 0.3 wt.% Yb. In general, the variations in the elongation are affected by both the solute atoms and the constituents. Solute atoms can increase the elongation by inhibiting the movement of dislocations, while the constituents in the matrix may result in a decrease of the elongation by stress concentration. Fig. 4 shows that the size, distribution and volume fraction of Yb- and Mg-containing constituents are similar for alloys with 0.3 and 1 wt.% Yb, which indicates that the constituents have similar effects on the elongation of both alloys 2 and 3. However, since alloy 3 has more Yb solute atoms in the matrix than alloy 2, it has larger elongation than alloy 2, indicating that the ductility of the alloy increases with increasing Yb content.

5. Conclusions

In this paper, we studied the effects of Yb element on the microstructures and mechanical properties of an Al–Mg alloy. The results indicated that the addition of 0.3 wt.% Yb decreases the mechanical properties of the alloy since Mg and Yb form constituents, which decrease the concentration of Mg and Yb solute atoms in Al matrix, and thus, degrade the solution strengthening effect of Mg and Yb atoms. However, the addition of 1 wt.% Yb can substantially improve the yield strength, tensile strength and elongation of the alloy since the concentration of Yb solute atoms is high enough in Al matrix. Yb solute atoms inhibit the dynamic recovery and recrystallization of the alloy, and increase the wok-hardening, thus provide a uniformly distributed dislocation structure with high density. The interaction between dislocations and solute Yb atoms improves the mechanical properties of the alloy.

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