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Mechanical properties of Al(Mg) solid solution prepared by solidification under high pressures

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ABSTRACT

Mechanical properties of Al(Mg) solid solution with different Mg solubility prepared by solidification under high pressure were investigated in the present study. The results show that the tensile strength of solid solution increases first, and then decreases with increasing Mg solubility. Fractographic examination reveals that the fracture characteristic transforms from dimple-like fracture to combination of quasi-cleavage plus intergranular fracture with increasing Mg solubility. This trend is believed not only limited to Al(Mg) solid solution, but also to other solute-strengthened alloys.

1. Introduction

The introduction of substitutional solute alloying elements into metals has long been known to have solute strengthening effect. Solute strengthening arises in aluminum 2XXX, 3XXX, 5XXX and 6XXX alloys, which represent important classes of lightweight alloys where solute strengthening is crucial. Al–Mg alloys are one of the most important metallic materials used for commercial wrought and casting alloys due to their high corrosion resistance, mechanical properties and formability. In general, the most relevant mechanisms for substitutional alloying of Al are the elastic interactions due to the size misfit and the modulus misfit between Al and Mg atoms [1]. All of the models of solute strengthening so far are explicitly for dilute Al(Mg) solid solutions with Mg content usually lower than 5 wt.% (all percentages are wt.% unless otherwise stated) [2–5], which assuming that the Mg atoms do not interact with each other. In previous studies, it has been suggested that the yield stress (YS) can be described by an equation as following:

$$\sigma_y = \sigma_{pure} + Kc^n \qquad (1)$$

where σ_y is the yield stress of the alloy, σ_{pure} is the yield stress of a pure metal, c is the solute content, and K and n are constants. Mukai et al. studied high-purity Al–Mg alloys with various Mg contents from 1.8% to 8.4% at a strain rate 2×10^{-3} at room temperature and obtained that $n = 1$, $\sigma_{pure} = 11.8$ MPa, and $K = 13.8$ [6], indicating that the yield stress of Al(Mg) solid solution increases with Mg solubility linearly. Here, an interesting question arises, that is, can the yield stress increase with increasing Mg solubility up to a high value? or whether there is a maximum yield stress of Al(Mg) solid solution with a moderate Mg solubility? This question, which is beneficial to prepare alloys with high mechanical properties, may also exist in other solute-strengthened alloys. Recently, our group has successfully prepared supersaturated Al(Mg) solid solutions with high Mg solubility by solidification under high pressure [7,8], which provides condition for us to study this question. In the present study, we demonstrate that the yield stress of supersaturated Al(Mg) solid solutions increases first, and then decreases with increasing Mg solubility. A maximum yield stress should exist in the Al(Mg) solid solution with a moderate Mg content.

2. Experimental

Al–Mg alloys with different Mg contents (12.07 wt.%, 19.63 wt.%, and 25.62 wt.%) were prepared by conventional casting from 99.99 wt.% pure Al and Mg. The samples for high pressure solidification were cylinders of 20 mm in diameter and 18 mm in length. The experiments were carried out by a tungsten-carbide six-anvil apparatus. Al–12.07Mg and Al–19.63Mg alloys were solidified under 2 GPa, and Al–25.62Mg alloy was solidified under 3 GPa. Details of high pressure solidification are described elsewhere [7]. The phases were characterized by a Rigaku D/max-RB X-ray

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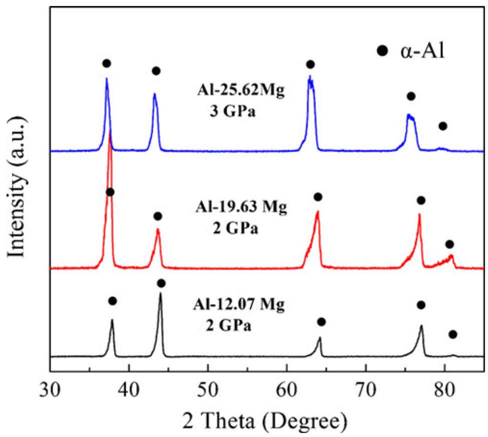

Fig. 1. XRD patterns of samples solidified under different pressures.

diffractometer with monochromatic Cu-K_α radiation. Fractographic analysis and compositional homogeneity were performed on a scanning electron microscope (S4700) equipped with an energy dispersive X-ray spectrometer (EDX). Tensile tests were carried out using an INSTRON 5569 testing machine at a strain rate of 10^{-3} s^{-1}. All of the samples were cut into dog-bone-shaped specimens with a gauge length of 13.0 mm and a cross section of 1.5 mm × 1.0 mm for tensile tests [9]. In order to examine reproducibility, five replicates were used for testing.

3. Results and discussion

Fig. 1 shows the XRD patterns of different samples, and no reflections of second phase can be observed in the samples. The peaks of the α-Al phase shift to the lower angles, indicating that the lattice parameter and Mg solubility of the solid solution increase with Mg concentration. In addition, the reflections of the α-Al phase are asymmetric, which is caused by the inhomogeneous distribution of Mg atoms in the Al(Mg) solid solution [7,8]. The range of Mg solubility in the Al(12.07Mg) and Al(19.63Mg) solid solutions can be estimated to be about 7–16 wt.% [8] and 13–27 wt.% [7], respectively. Fig. 2a shows the backscattered electron (BSE) image of Al-25.62Mg alloy solidified under 3 GPa. The atomic number contrast afforded by the BSE image shows that the Mg concentration in the interdendritic region, increasing gradually from 17 wt.% to about 32 wt.% measured by EDX as shown in Fig. 2b, is higher than that in the dendrite.

Fig. 3 shows the typical tensile stress–strain curves of different samples. The mechanical properties of samples solidified under different pressures are summarized in Table 1. It can be seen that the elongation of samples decreases with increasing Mg content (see Fig. 3a), and the Al(19.63Mg) solid solution has the highest ultimate tensile strength (UTS) of 474.8 MPa and yield stress of 232.8 MPa. The mechanical properties decrease when the Mg content increases up to 25.62%, suggesting that the tensile strength of supersaturated Al(Mg) solid solution cannot increase with increasing Mg solubility, and exhibits a trend that increases first and then decreases. It should be noted that the flow curves of the Al(Mg) solid solutions with different Mg contents are partly serrated, as shown in Fig. 3b, indicating a dynamic strain ageing (DSA) effect which refers to interactions between Mg atoms and mobile dislocations under appropriate conditions [4,10,3,11]. In addition, the Al(19.63Mg) solid solution displays a higher magnitude of stress drop (the difference between the peak stress and the valley stress in each serration) than that Al(12.07Mg) solid solution. According to the solute-dislocation interaction model [12], more of the Mg solute atoms in the Al(19.63Mg) solid solution diffuse to the dislocations during dislocations waiting time and thus the breakaway of the dislocations is more difficult. Therefore, a higher force is needed for dislocation unpinning, resulting in a higher stress drop.

Assuming that the Mg atoms are all in solid solution and distribute homogeneously and extrapolating available experimental quantities determined at low Mg contents according to Eq. (1), the yield strength of Al–12.07Mg, Al–19.63Mg and Al–25.62Mg alloys due to solute strengthening from Mg can be estimated to be 178.4 MPa, 282.7 MPa, and 365.4 MPa, respectively. It can be found that the yield stresses of the samples all deviate the linear correlation between the yield stress and Mg content described by Eq. (1).

In general, the effect of Mg element on strength of non-heat-treatable Al–Mg alloys can be mainly ascribed to solid-solution hardening and grain-size hardening. The effect of grain size on alloy strength is commonly expressed by the well-known Hall–Petch equation [13,14]:

$$\sigma_y = \sigma_0 + kd^{-1/2} \tag{2}$$

where σ_y is the yield stress of the alloy, σ_0 is the fractional stress, d is the average grain size, and k is a constant that characterizes the difficulty of transmitting slip across the grain boundary for a given system. The effect of grain-size on the strength of alloys solidified under high pressures can be negligible due to the large grain sizes. For example, an estimation for the expected variation in the yield strength of Al(19.63Mg) solid solution due to the grain size is about 4.6 MPa or a few percent (calculated on the base of Hall–Petch $k \approx 0.08$ MPa $m^{1/2}$).

One effect which may influence mechanical properties is residual stress formed after relief of high pressure. Normally, the residual stress plays an important role in welding structures, coatings and

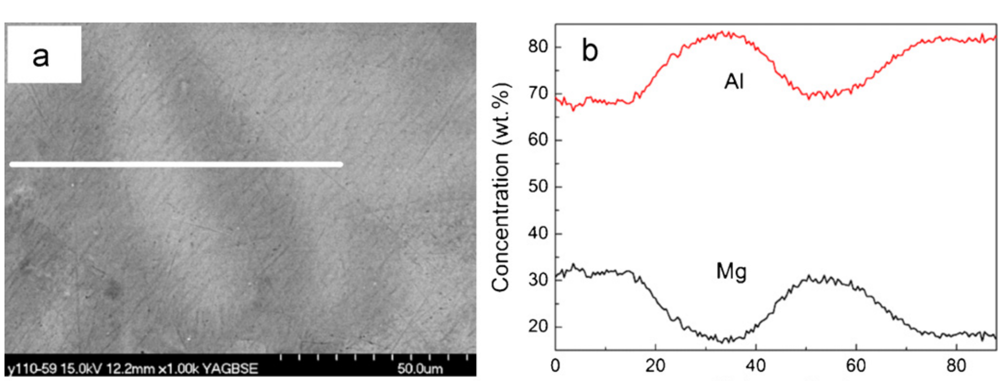

Fig. 2. Microstructure of Al–25.62Mg alloy solidified under 3 GPa and concentration distribution of Mg element. (a) Back scattered electron image and (b) concentration of Mg element cross the interdendritic region.

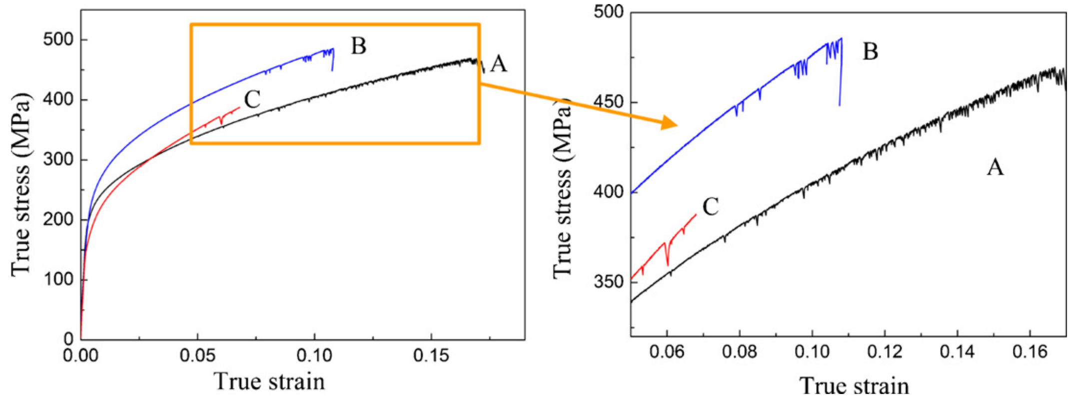

Fig. 3. (a) True tensile stress–strain curves of different samples, and (b) the high magnification of serrated flow of tensile curves, (A) Al–12.07Mg, (B) Al–19.63Mg, and (C) Al–25.62Mg.

Table 1
Mechanical properties and grain sizes of different samples.

Samples	Grain size (mm)	UTS (MPa)	YS (MPa)	Elongation (%)
Al–12.07Mg	1.0 ± 0.2	458.5 ± 19.3	203.7 ± 6.1	18.2 ± 1.0
Al–12.07Mg, homogenized	1.1 ± 0.4	420.2 ± 7.7	185.8 ± 2.9	17.4 ± 1.1
Al–19.63Mg	0.3	474.8 ± 11.0	232.8 ± 6.6	11.1 ± 0.5
Al–25.62Mg	0.4	386.2 ± 8.5	180.7 ± 4.8	6.8 ± 0.5

extrusions [15–17]. The samples in the present study were heated and melted under relatively homogeneous pressures. The effect of residual stress is trivial and can be neglected. Another effect which may influence the yield stress is the inhomogeneous distribution of Mg atoms in the solid solution, which is formed during solidification process. In order to investigate the influence of inhomogeneous distribution of Mg on the mechanical properties, tensile testing of the Al–12.07Mg alloy homogenized at 430 °C for 17 h and quenched in iced water which can make Mg atoms distribute in the solid solution homogeneously was conducted. It should be noted that the homogenized samples are cut from the Al–12.07Mg alloy solidified under 2 GPa, to make sure that they are as dense as the samples solidified under 2 GPa. The mechanical properties, together with their grain sizes are summarized in Table 1. It can be seen that the yield strength of homogenized samples is 185.8 MPa, which is a little more than 178.4 MPa calculated from Eq. (1). The reason may be that the samples solidified under high pressure are denser and have less casting defects, compared with that prepared by conventional casting under normal pressure. Thus, the yield stress of homogenized Al(12.07Mg) solid solution obeys Eq. (1). But the yield strength of Al–12.07Mg alloy solidified under 2 GPa is 203.7 MPa, which is higher than that of the homogenized samples. It can be seen that the inhomogeneous distribution of Mg in Al–12.07Mg solid solution can improve its yield strength. The exact reason for enhanced yield strength due to the inhomogeneous distribution of Mg solutes is not fully understood yet. Therefore, the inhomogeneous distribution of Mg solutes in the supersaturated Al(19.63Mg) solid solution should also improve its yield strength. So Eq. (1) is not valid when the Mg concentration in the solid solution is extended up to 19.63%. The yield stress of Al–25.62Mg alloy solidified under

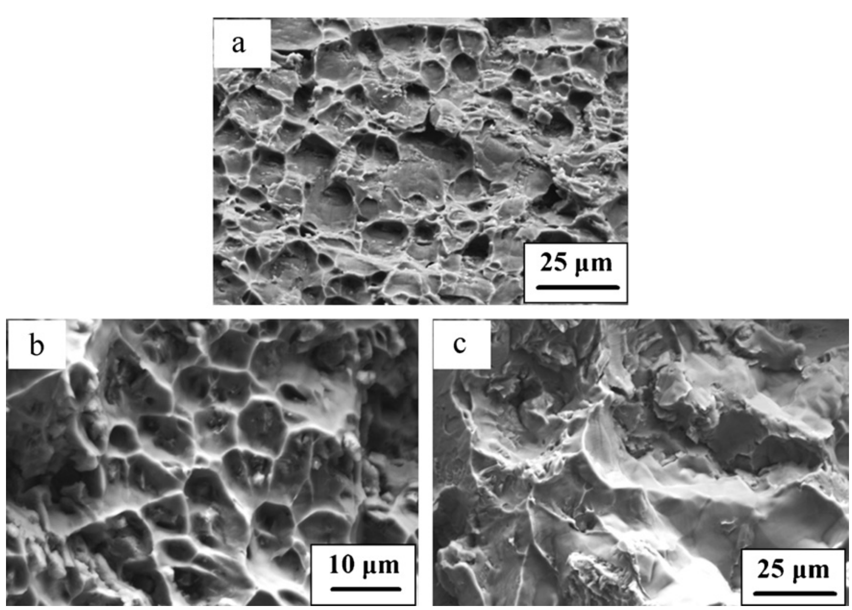

Fig. 4. Fractographs of the tensile samples, (a) Al–12.07Mg, (b) Al–19.63Mg, and (c) Al–25.62Mg.

3 GPa is only 180.7 MPa, which further confirms that the yield stress of Al(Mg) solid solution with high Mg solubility does not increase with increasing Mg content linearly.

Fig. 4 shows the fracture surfaces of different samples. It can be seen that the fracture surfaces of Al–12.07Mg and Al–19.63Mg samples are characterized mainly by extensive dimples (see Fig. 4a and b), resulting in their relatively high mechanical properties. The Al–25.62Mg alloy appears to exhibit a combination of quasi-cleavage plus intergranular fracture, and few dimples can be observed (Fig. 4c), indicating that the fracture mechanism of Al(Mg) solid solution is greatly changed with increasing Mg solubility.

The crucial mechanism of solute strengthening is that substitutional Mg atoms interact with mobile dislocations, leading to pinning of the dislocations and thus requiring higher applied stresses to move the dislocations [18,19]. However, clusters of Mg atoms coherent with the Al matrix, i.e. GP zones, can be formed in the Al(Mg) solid solution with high Mg solubility during natural ageing at very low temperature, which is already proven by DSC observation (not shown here). The Vickers hardness curves for an Al–12Mg solid solution aged at 0 °C and 20 °C for different times have been measured and the results showed that the hardness remained invariable or increased slightly [20]. The Vickers hardness is about three times of the yield stress [21]. Thus, it can be concluded the formation of GP zones or clusters of Mg atoms is not responsible for the decrease of the yield strength of Al(Mg) solid solution with increasing Mg solubility. The relative Al:Mg atoms ratio will be 2:1 to 3:1 in the Al lattice when the solid solution contains too many Mg substitutional atoms, such as Al–25.62Mg. The formation and movement of dislocations, as well as the fracture mechanism (see Fig. 4) of the Al(Mg) solid solution may be greatly changed, and some behaviors may be similar to intermetallic compound. The authors believe that it should be mainly responsible for the decrease of yield strength, and a full understanding of too many substitutional Mg atoms on mechanical properties of Al(Mg) solid solution requires more theoretical and experimental studies. This trend of yield stress with solute solubility is believed to be not just limited to Al–Mg alloy but also to other solute-strengthened alloys. The yield stress should increase first, and then decrease with increasing solute solubility. The maximum yield stress introduced by solute-strengthening should correspond to a moderate solute solubility, above which the yield stress decreases due to the impact of substitutional solute atoms on formation and movement of dislocations in the solid solution.

4. Conclusions

The mechanical properties of supersaturated Al(Mg) solid solution with different Mg solubility in Al were investigated in the present study. The results show that the yield stress of solid solution increases first and then decreases with increasing Mg solubility. It suggests that the maximum yield stress of Al(Mg) solid solution should correspond to a proper Mg solubility, which is not high enough. Fractographic examination reveals that the fracture characteristic transforms from dimple-like fracture to combination of quasi-cleavage plus intergranular fracture with increasing Mg solubility.

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