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Letter

High strength and good ductility of casting Al–Cu alloy modified by Pr_xO_y and La_xO_y

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ABSTRACT

A modified Al–Cu alloy with high tensile strength and ductility of about 574.0 MPa and 10.4%, respectively, was obtained by adding multiple rare earth oxides (Pr_xO_y and La_xO_y) as modifier. Compared with the unmodified Al–Cu alloy, the tensile strength and ductility of the modified sample were increased by 24.3% and 42.5%, respectively. The improvement both in the strength and ductility may attribute to the finer crystal grains and dendrites, more homogeneously distributed θ′ phase precipitates and the intermetallic compounds formed at the crystal grain boundaries as well as in the space of the dendrites.

1. Introduction

Due to the desirable combination of high strength, favorable ductility, light weight, low density, good workability and corrosion resistance, Al alloys are used more often than other metals except the steel for industry applications such as aeronautical, automobile and military structural materials [1–3]. Recently, the microstructures and mechanical properties of different types of Al alloys have been investigated for the further commercial requirements. The effects of the casting temperature on the microstructure and mechanical properties of the squeeze-cast Al–Zn–Mg–Cu alloy were investigated by Fan et al. [4], and Liu et al. reported the microstructure evolution of Al–Cu–Mg–Ag alloy during the homogenization [5]. Moreover, Sherafat reported the compression and tensile properties of Al/Al7075 two-phase material [6]. Among the various Al alloys, casting Al–Cu alloys are widely used in industry because of their excellent mechanical properties. However, the use of the Al–Cu alloys has been limited because their strength and ductility could not be enhanced simultaneously. An effective approach aimed at overcoming the limitation is the addition of rare earth (RE) metals (such as La, Y, Nd, Ce and Sc) into the melting Al [7–11]. Zhao et al. reported that the high tensile strength and the ductility of the casting Al–Cu alloy modified by Pr_xO_y were about 520 MPa and 13.5%, respectively, and the corrosion resistance of the alloy was also improved evidently [12,13]. Moreover, high creep resistance behaviour of the casting Al–Cu alloy modified by the addition of La was obtained by Yao et al. [14]. The achievements mentioned above are gained through using single rare earth metal or oxide as modifier. However, the works on using the multiple rare earth oxides as modifier are less. In this study, the casting Al–Cu alloy with the high tensile strength about 574.0 MPa and the strain of 10.4% was obtained by adding Pr_xO_y and La_xO_y. The microstructure and the mechanical property of the alloy were studied in detail.

2. Experimental

The compositions of raw casting Al–Cu alloy (in wt.%) were 5.2 Cu, 0.3 Ti, 0.45 Mn, 0.2 Cd, 0.2 V, 0.15 Zr, 0.04 B, and balance Al. The alloys were melted at 750–800 °C in the graphite crucible in the electric resistance furnace. Rare earth oxides (0.2 wt.% Pr_xO_y and 0.6 wt.% La_xO_y) were wrapped in aluminum foils and added into the melting Al liquid. The liquid was then held at that temperature for about 20–30 min. After mixed round, the liquid was poured into a steel die of 200 mm × 60 mm × 12 mm. After T6 heat treatment (solution at 510 °C for 15 h and aging at 165 °C for 10 h), the samples were cut into sheets and incised to tensile dog-bone shaped samples with a gauge cross section of 5.0 mm × 2.0 mm and a gauge length of 50.0 mm. Subsequently, these tensile samples were mechanically polished. Tensile tests were performed at a constant strain rate of $5.0 \times 10^{-4}\ s^{-1}$ using a servo-hydraulic materials testing system (MTS, MTS 810, USA) at room temperature. Microstructures were investigated by Olympus optical microscope (OM, Olympus PMG3, Japan), scanning electron microscope (SEM, JSM-5310, Japan) coupled with energy-dispersive spectrometry (EDS, Woyager-3105, UK), and transmission electron microscope (TEM, JEM-2100F, Japan). The fracture surface morphologies were observed by SEM.

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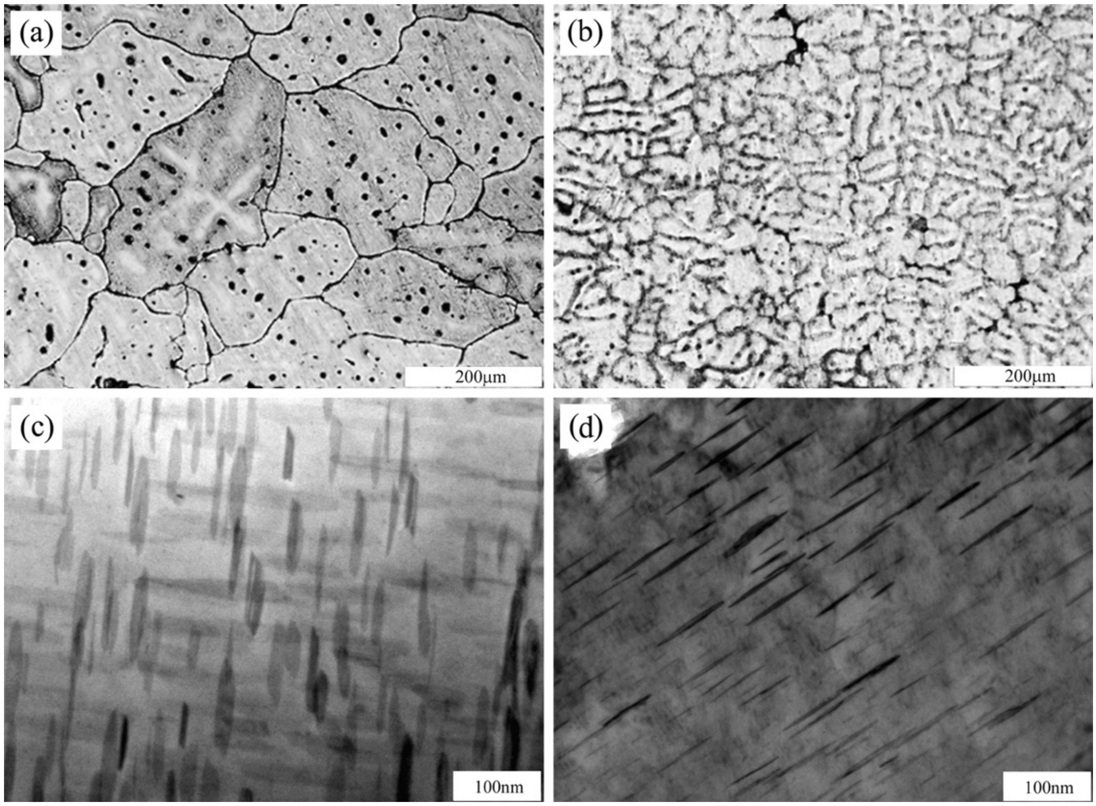

Fig. 1. OM images of as-cast microstructures of (a) the UA and (b) MA samples; and TEM images of microstructures of (c) the UA and (d) MA samples.

3. Results and discussion

Fig. 1 shows the OM images of microstructures of the as-cast (a) unmodified alloy (UA) and (b) modified alloy (MA) as well as the TEM images of microstructures of (c) the UA and (d) MA samples. It is clear that the crystal grains and dendrites in the MA sample (about 50 μm) are finer and more homogeneous than those (150–200 μm) in the UA sample. As can be seen from Fig. 1(c) and (d), the nano-scale θ′ phase precipitates (Al_2Cu) in the UA sample are coarser, less in number and more inhomegeneous than those in the MA sample. The average width and length of the θ′ phase precipitates in the UA sample are about 15–20 nm and 80–100 nm, while those in the MA sample are about 5 nm and 70 nm, respectively. Fig. 2 shows the EDS analysis of the intermetallic compounds in the MA sample. According to the EDS analysis, it can be seen clearly that the elements of Pr, La, Al and Cu have been detected, and the rare earth elements Pr and La are rich in these compounds (Fig. 2(a) and (b)). The results of the two EDS line analyses of the different parts (Fig. 2(c) and (d)) show that main elements of the intermetallic compounds are Al, Cu, La and Pr., which demonstrated that the original rare earth oxides addition (Pr_xO_y and La_xO_y) have decomposed to the free state [Pr], [La] and [O], which is similar with the former reports [10,13–15]. It can be deduced that the intermetallic compounds are formed by RE ([Pr] and [La]) with [Al] and [Cu]. Fig. 3 shows the engineering tensile stress–strain curves of the MA and UA samples. It can be seen that the ultimate tensile strength and the fracture strain of the MA sample are 574.0 MPa and 10.4%, respectively, which are increased by 24.3% and 42.5% than those of the UA sample (461.7 MPa and 7.3%).

The high strength and good ductility of the MA sample may be attributed to the refined crystal grain and dendrite, the precipitation second-phase, and the intermetallic compound at the grain boundaries as well as in the space of the crystal dendrites. The refined grains could reduce the nucleating flaws and increase the resistance to crack propagation, leading to a higher fracture stress and ductility. More boundaries are formed because of the refined crystal grains and dendrites in the MA sample. The high boundary concentration and the rosebush-like dendrites play a role as barriers to the transmission of the dislocations, which is helpful to improve the strength and ductility. On another hand, the refined grains can also offer a higher resistance to shear localization and shear fracture, and thus stabilize the hydrostatic triaxial stress. Then, the ductile fracture through microvoid nucleation and coalescence can be promoted by this, according to the former studies [16,17]. The rosebush-like microstructure makes it harder for the transgranular fracture. Even when the fracture mode is intergranular, the rosebush-like dendrites microstructure can also improve the strength and ductility by extending the crack propagation path. The intermetallic compound formed at the grain boundaries as well as in the space of the crystal dendrites can block the transmission of the dislocations and impede the crack propagating. According to the TEM analyses, much more dispersed finer nano-scale θ′ phase precipitates were investigated in the MA sample compared with the UA sample (as shown in Fig. 1(c) and (d)). This suggests that the precipitation strengthening, which results from the ability of the nano-scale second-phase precipitates to restrict and impede dislocation actuation and movement by forcing dislocations to circumvent the

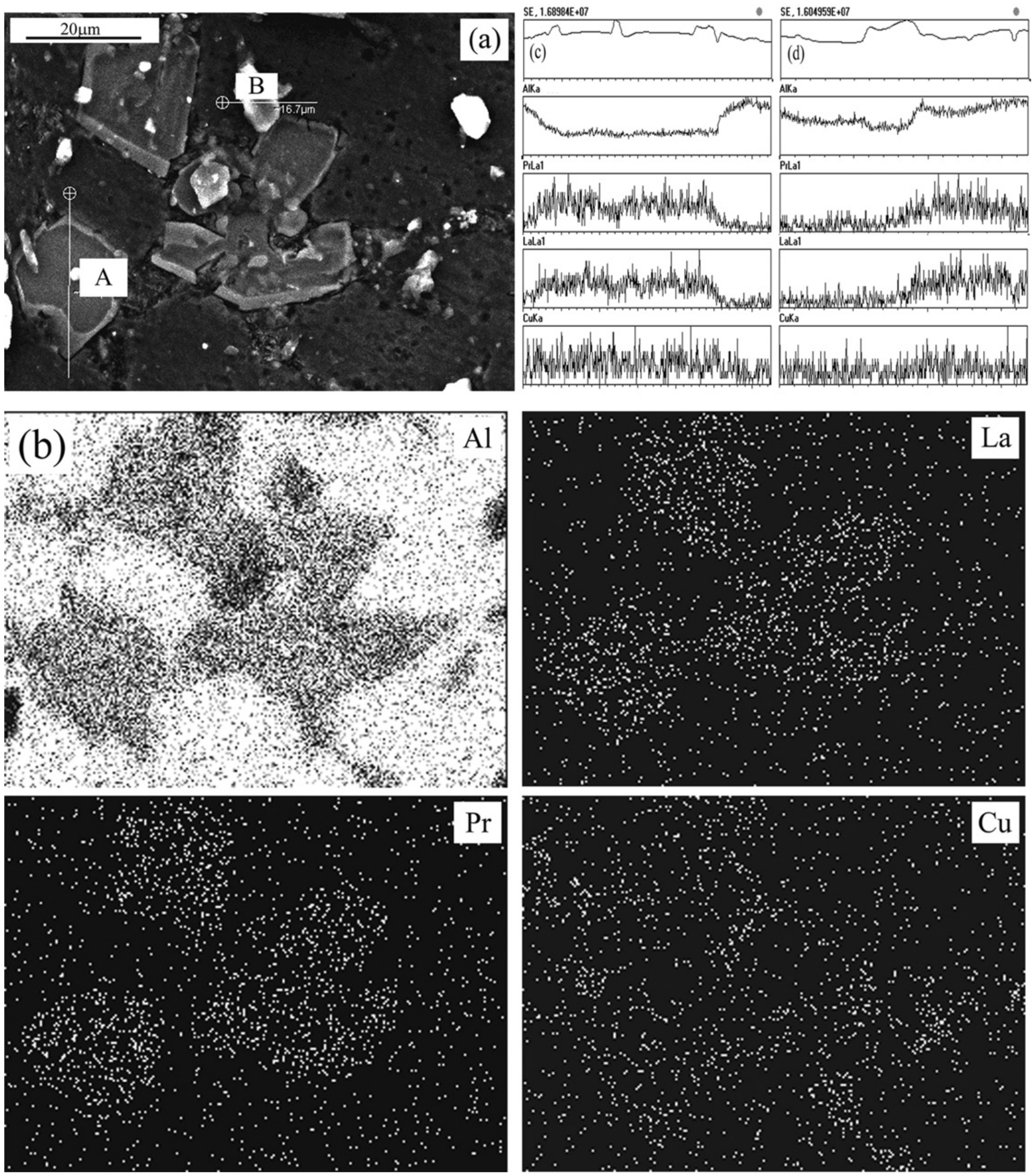

Fig. 2. (a) SEM images of microstructure of the MA sample; (b) map EDS analysis of the MA sample; EDS line analysis of the elemental composition of (c) zone A and (d) zone B.

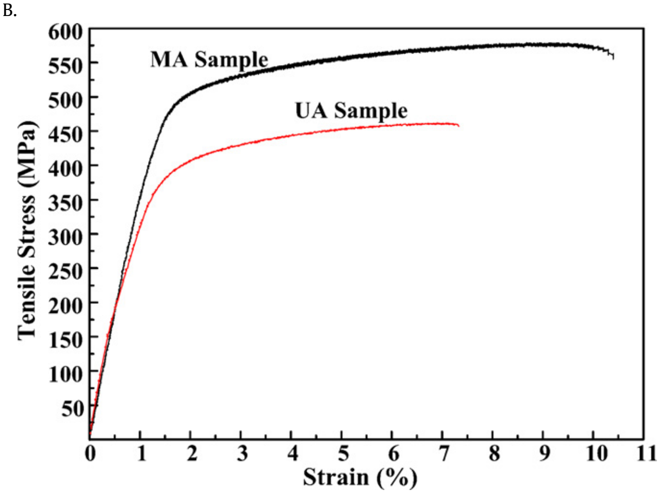

Fig. 3. Tensile stress–strain curves of the UA and MA samples.

nano-scale precipitates, makes a significant contribution to the strength enhancement. On another hand, the increase in the number of the second-phase precipitations is beneficial to the dislocation accumulation and significantly hinders dynamic recovery, which increases the dislocation storage capability and the work-hardening. In fact, the increase in the work-hardening is responsible for the enhanced fracture strain, as reported by the former work [18–20]. Fig. 4 displays the fracture morphologies of the UA and MA samples. For the UA sample (Fig. 4(a)), the main tensile fracture mode is intergranular, and there are few shallow ductile dimples with coarse and blocky Al_2Cu phases in them. However, the fracture mode of the MA sample is both intergranular and transgranular, and many regular, minute and deep ductile dimples exist with relatively finer Al_2Cu phases in them (as shown in Fig. 4(b)), indicating that the mechanical properties of the MA sample are better than those of the UA sample.

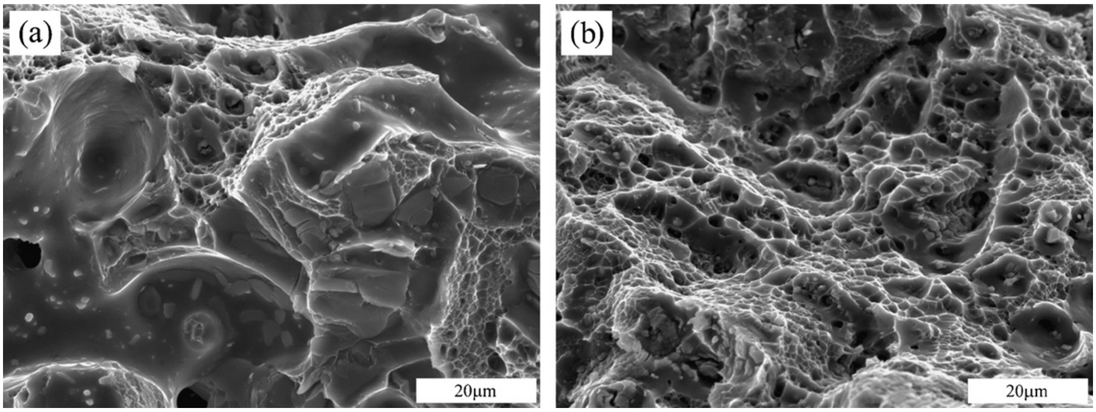

Fig. 4. Fracture morphologies of (a) the UA and (b) MA samples.

4. Conclusions

The high tensile strength (574.0 MPa) and good ductility (10.4%) of the casting Al–Cu alloy were obtained by adding rare earth oxides (Pr_xO_y and La_xO_y) into the melting Al liquid as modifier. The tensile strength and ductility of the MA sample were increased by 24.3% and 42.5% than those of the UA sample, respectively. The tensile fracture mode of the modified sample is both intergranular and transgranular, while that of the unmodified sample is mainly intergranular. Simultaneous increasing in strength and ductility of the modified casting Al–Cu alloy could be induced by the refined crystal grains and dendrites, more homogeneously distributed nano-scale θ′ phase and the intermetallic compounds formed at the grain boundaries as well as in the space of the crystal dendrites.

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