Microstructure and mechanical properties of Mg-6Al magnesium alloy with yttrium and neodymium

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Abstract: The effects of rare earth (RE) elements Y and Nd on the microstructure and mechanical properties of Mg-6Al magnesium alloy were investigated. The results show that a proper level of RE elements can obviously refine the microstructure of Mg-6Al magnesium alloys, reduce the quantity of β-Mg17Al12 phase and form Al2Y and Al2Nd phases. The combined addition of Y and Nd dramatically enhances the tensile strength of the alloys in the temperature range of 20–175℃. When the content of RE elements is up to 1.8%, the values of tensile strength at room temperature and at 150℃ simultaneously reach their maximum of 253 MPa and 196 MPa, respectively. The main mechanisms of enhancement in the mechanical properties of Mg-6Al alloy with Y and Nd are the grain refining strengthening and the dispersion strengthening.

Key words: Y; Nd; Mg-6Al magnesium alloy; microstructure; elevated mechanical properties

Magnesium alloy is the lightest constructional material, which has lower density, higher specific strength and hardness, better cast characteristics, higher electric conductivity, and better thermal conductivity than steel and aluminum alloys. So it is widely used in automobile industry, electronic industry and 3C product. However, its relatively low strength and creep strength at elevated temperature lead to the poor heat resistance of magnesium alloy, which is the main factor limiting its applications at elevated temperatures [1−3].

Rare earth (RE) elements are typically active metallic elements, which can enhance the binding force of magnesium atoms, and reduce the diffusion velocity of atoms. RE elements can effectively improve the heat resistance of magnesium alloy because they can form the high-melting point compounds with other elements and refine the grains. RE elements have been used in magnesium alloys for many years, but the alloys within the Mg-Al-RE system were developed just recently. Some investigation was conducted on the precipitation, morphology, structure, thermal stability and strengthening mechanisms of intermetallic phases when adding RE to Mg-Al alloys. In some studies, RE were added to magnesium alloys as misch metal since RE elements have similar effect, while other studies were based on single RE elements. However, no systematic research about the effects of Y and Nd on Mg-Al alloys has been reported [5−6]. The effects of Y and Nd on the microstructures and mechanical properties of Mg-6Al magnesium alloy were studied in this work.

1 Experimental details

High-purity Mg (99.95%) and Al (99.98%), Mg-Y and Mg-Nd master alloys were used as raw materials. The studied alloy was designed as Mg-6.0Al-xRE, where x is the total content of RE elements, x=0, 0.9, 1.8, 2.7, 3.6, respectively. The mass ratio of Y to Nd is 2:1. The designed compositions of the alloys are listed in Table 1.

<table>
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<th>Table 1 Designed compositions of alloys (wt.%)</th>
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<td>Alloy No.</td>
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All the raw materials had been dried at 200℃ before the melting started. The alloys were melted in a vacuum induction furnace with graphite (99.9%) crucible under the mixed atmosphere of CO2 and SF6 with the ratio of 100:1. The molten metals were held for 15 min at 720℃, then poured into a metal mold (φ18 mm × 200 mm) at 690–700℃. At last, the as-cast samples of alloys covered with MgO powders were heated for solid solution treatment at 420℃ for 10 h and followed by aging treatment at 250℃ for 8 h.

The tensile tests were carried out at a strain rate of 1 mm/min on a SHIMADZU AG-I 250 kN precision universal
material test machine at room temperature (20°C), 150°C and 175°C, respectively. Three test samples were tested for each condition. For the elevated temperature tensile tests, the alloys were held for 15 min at their corresponding temperatures. Microstructures, fracture surface morphologies and compositions of these alloys were analyzed using optical microscopy and scanning electron microscopy (SEM) (JSM-5610LV) equipped with energy dispersive spectroscopy. Phase analyses were performed with an X’pert X-ray diffractometer.

2 Results

2.1 Microstructure

X-ray diffraction patterns are shown in Fig. 1. The microstructure of Mg-6Al alloy corresponding to Fig. 1(a) mainly consists of α-Mg basal phase and β′-Mg12Al12 phase. When the content of RE is up to 1.8%, the microstructure of Mg-6Al alloy as shown in Fig. 1(b) is mainly consists of α-Mg, β′-Mg12Al12, Al2Y and Al2Nd phases.

The microstructures of the alloys after solution and aging treatment are shown in Fig. 2. As can be seen in Fig. 2(a), α-Mg12Al12 phases of Mg-6Al magnesium alloy precipitate both inside grains and at grain boundaries after solid solution and aging treatment. These precipitates are scattered at the grain boundaries in coarse bulk and inconsecutive network, while inside the grains are in fine particle structure. From the phase diagram of Mg-Al binary system [7–8], it can be explained that when Mg-6Al magnesium alloys are heated for solid solution treatment at 420°C, the supersaturated α-Mg solid solutions of the alloys are first formed, then the solid solutions directly form incoherent equilibrium phase in the course of aging treatment, while no other precipitates and transition phases are formed [9–11]. The microstructure of the alloy with RE elements (Y+Nd) is shown in Figs. 2(b)-(e). The quantity of α-Mg12Al12 phases after aging treatment decreases obviously with the addition of RE. When the content of RE is up to 1.8%, almost no α-Mg12Al12 phase is observed in Fig. 2(c). The electronegative differences between Y, Nd and Mg, Al determine that Y and Nd are easier to form compound with Al than Mg. Therefore, Al2Y and Al2Nd are easier to form after solid solution treatment. The Al2Y and Al2Nd
phases distribute in the grains and at the grain boundaries dispersively. However, when the content of RE is up to 2.7%, the quantity of Al\textsubscript{2}Y and Al\textsubscript{2}Nd phases increases, the grains are coarsened, and their distribution shows a tendency of non-equilibrium segregation (Figs.2(d) and (e)). The average grain sizes of alloys after solid solution and aging treatment are shown in Fig. 3. With the addition of RE, the grain size of Mg-6Al magnesium alloy obviously decreases.

2.2 Mechanical properties
The tensile properties of the alloys with solid solution and aging treatment are shown in Figs.4 and 5. It can be seen in Fig.4 that, with the increase of the RE content, the tensile strength values of the alloys both at room temperature and at 150°C first increase, then decrease. When the content of RE elements is at 1.8%, the values of tensile strength at room temperature and 150°C reach their maximum simultaneously, at 253 MPa and 196 MPa, respectively. As compared to the Mg-6Al alloy without RE elements, the strengths of the alloys are increased by 35% and 63%, respectively. When the content of RE elements is over 2%, the strength of alloys drops, which is consistent with the result of phase transformation. Based on the above analysis, it can be known that proper content of RE elements (i.e. 1.2%Y, 0.6%Nd) can enhance the strength of the alloys both at room temperature and at applicable elevated temperatures.

2.3 Fracture behavior observation
SEM fractographs at room temperature are shown in Fig.6. The fracture pattern of the Mg-6Al alloy without RE elements (Fig. 6(a)) indicates quasi-cleavage steps and tearing ridges, with the quasi-cleavage being the main characteristic. The Mg-6Al alloy with the characteristic of brittle fracture has low elongation. When the content of RE elements is up to 0.9%, fractures of the alloys clearly show tearing ridges, a few local circular dimples and the formation of quasi-cleavage and ductile fracture characteristics (Fig. 6(b)). When the content of RE elements is up to 1.8%, the photograph of the alloy shows typical ductile fracture (Fig. 6(c)) with a large number of dimples and tearing ridges of connected dimples, and obvious necking phenomenon in tensile test. The corresponding elongation is 13%. When the content of RE elements is up to 2.7%, the fracture of the alloys demonstrates brittle nature with low corresponding elongation, as shown in Fig. 6(d). Based on the above analysis, the plasticity of the alloys can be enhanced considerably when the content of RE elements is at 1.8% (i.e. 1.2%Y, 0.6%Nd).

3 Discussion
For Mg-Al based alloys, \(\beta\)-Mg\textsubscript{17}Al\textsubscript{12} phase is the main strengthening phase at room temperature. But the \(\beta\)-Mg\textsubscript{17}Al\textsubscript{12} phase with a melting point only at 437°C has poor thermal stability and low strength at elevated temperatures due to easy breaking-down, and therefore, it worsens the mechanical properties of Mg-6Al alloy at elevated temperatures \[12\]. In this work, the main reasons for the enhancement of mechanical properties of Mg-6Al alloys with Y and Nd are the functions of...
3.1 Grain refining strengthening

Solute with high segregation tendency and particles functioning as effective crystal nucleus are the absolutely necessary factors for grain refinement. The segregation of solute can easily lead to the supercooling in the front of liquid-solid interface, which can hinder the growth of fir tree crystal and provide the power of activating the crystal nucleus in the area of supercooling. And the capability of forming crystal nucleus determines the quantity of effective crystal nucleus in the area with supercooling when alloy begins to solidify.

The effect of solute elements is expressed through Growth Restriction Factor (GRF) listed in reference [13]:

\[
GRF = \sum_i m_i c_{i0} (k_i - 1)
\]

Where \( m_i \) is the slope of liquidus, \( c_{i0} \) is the initial concentration, \( k_i \) is the solute distributing coefficient. The greater the GRF is, the stronger the refining ability.

GRF of Y in magnesium alloy is 1.70 \[14\]. Based on the phase diagrams of Mg-Y binary system and Mg-Nd binary system \[6\], the GRF of Nd in magnesium alloy is bigger than that of Y. According to the significant grain refining function of Y in magnesium alloy \[14\], the grains of Mg-6Al alloy can be obviously refined with the addition of Y and Nd.

Active elements Y and Nd have the normal segregation in magnesium alloy and decrease the liquidus temperature. Y and Nd segregation in the front of liquid-solid interface leads to the supercooling condition when Mg-6Al alloy solidifies, which forms the \( \alpha \)-Mg crystal nucleus of well proportioned nucleus. So the grains of Mg-6Al alloy are obviously refined. Furthermore, the compounds of Al\(_2\)Y and Al\(_2\)Nd with high-melting point can precipitate in the area of fir tree crystal, largely hindering the growth of \( \alpha \)-Mg crystal and refining the grains in Mg-6Al alloy \[15\].

The diameter of grain to describe the yield strength (Hall-Petch formula) is generally expressed as \[16\]:

\[
\sigma_y = \sigma_0 + Kd^{\alpha/2}
\]

Where \( \sigma_y \) is the yield strength, \( \sigma_0 \) is a constant, \( K \) is a parameter of influence extent of grain boundaries to yield strength, \( d \) is the average diameter of grain. The value of \( K \) becomes bigger with the increase of Thaler modulus, which usually increases with the decrease of glide system. Magnesium alloys, which have the hcp structure, have fewer glide systems than the metal of the bcc structure, so magnesium alloys have larger value of \( K \). Therefore, the grain refining can obviously enhance the yield strength of magnesium alloys.

3.2 Dispersion strengthening

The Al\(_2\)Y and Al\(_2\)Nd phases with high-melting point can be formed with the addition of Y and Nd, which strengthens the Mg-6Al alloy at elevated temperature. A majority of the Al in Mg-6Al alloy are used up because of the formation of Al\(_2\)Y and Al\(_2\)Nd, which can reduce the quantity of Mg\(_{17}\)Al\(_{12}\) phases. In conclusion, the above two effects can availably enhance the properties of Mg-6Al alloy at room and elevated temperature. The Mg\(_{17}\)Al\(_{12}\) phases and the Al\(_2\)Y and Al\(_2\)Nd
phases can hinder the slippage of dislocation, which can improve the mechanical properties of Mg-6Al alloy deformed at room temperature. With the rise of deforming temperature, the Al2Y and Al2Nd phases of primary dispersion distribution have higher thermal stability than β-Mg12Al17 phase at grain boundaries in Mg-6Al alloy, which can lock the near grain motion at elevated temperatures and effectively resist the movement of grain boundaries and dislocations. The effect of RE elements on heat resistant properties of the alloys also shows that RE elements minimize the permeability between phase boundary and grain boundary, slow the agglomeration of phase boundary, limit the movement of dislocation during the whole course, reduce the defect of metal-oxide on surface and change the crystalline lattice parameters, making the alloys have good oxidation resistance.

When the content of RE is excessive, a lot of unsymmetrical distribution conglomerations of Al2Y and Al2Nd phases appear in the microstructure of the alloys, which makes the distribution of particle phase (Al-RE) non-uniform, weakening the dispersion strengthening effect, causing composition segregation and microstructure un-uniformity of the alloys, arousing stress concentration, and leading to the decline of the elevated temperature mechanical properties of the alloys.

4 Conclusions

(1) With the addition of RE elements (Y+Nd), the microstructure of Mg-6Al is remarkably refined, and the quantity of β-Mg12Al17 phase is reduced. Meanwhile, phases of Al2Y and Al2Nd with high-melting point are formed.

(2) After solid solution and aging treatment, with the increase of RE element content, the tensile strength and elongation of the Mg-6Al alloys increase first, and then decrease at all selected temperatures of ambient, 150°C and 175°C. The main mechanisms of enhancement in the mechanical properties of Mg-6Al alloy with Y and Nd are the grain refining strengthening and the dispersion strengthening.

(3) When the content of RE elements is at 1.8%, the values of tensile strength at room temperature and 150°C reach their maximum simultaneously, at 253 MPa and 196 MPa, respectively. The elongation of Mg-6Al alloy can also be enhanced. At the 1.8% RE element content (i.e. 1.2%Y, 0.6%Nd), the values of elongation at room temperature and at 150°C also reach their maximum simultaneously, 13% and 15%, respectively.

References