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Effect of erbium on microstructures and properties of Mg-Al intermetallic

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Abstract: The effect of the rare earth element Er on the microstructures and properties of Mg-Al intermetallic were studied in this experiment. Metallographic and X-ray diffraction (XRD) results showed that the microstructures of Mg-Al-Er alloys varied with Er content. The Mg-44Al-0.5Er and Mg-43.8Al-1.0Er alloys were both composed of $Mg_{17}Al_{12}$ matrix and Al_3Er phase, whereas Mg-43Al-3.0Er and Mg-42Al-5.0Er were composed of $Mg_{17}Al_{12}$ matrix, Al_3Er phase, and Mg-$Mg_{17}Al_{12}$ eutectic. The Mg-42Al-5.0Er alloy showed the highest microhardness, and the values remained nearly stable as Er content increased from 1.0 wt.% to 5.0 wt.%. The dispersed second phase Al_3Er caused the grain refinement of the Mg-Al-Er alloy, which was the main reason for the improvement in microhardness. The corrosion resistance of the Er-containing alloys initially increased and then decreased with increasing Er content. All the Er-containing alloys had the ability to suppress hydrogen evolution, which was the main reason for the higher corrosion resistance of the modified alloys than that of the Mg-44.3Al alloy. Considering the higher hardness and dispersity of the Al_3Er phase, Mg-43.8Al-1.0Er exhibited higher wear resistance than the as-cast Mg-44.3Al alloy.

Keywords: Mg-Al intermetallic; precipitates; electrochemical characterization; wear; X-ray diffraction; rare earths

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Similar to the other intermetallic compounds, cast intermetallic $Mg_{17}Al_{12}$ (i.e. Mg-44.3Al alloy) has high hardness and high corrosion resistance but poor room-temperature ductility[1,2]. A previous study has shown that the ductility of the single-phase polycrystal Mg-44.3Al alloy was poor at temperatures lower than 523 K; an obvious yielding phenomenon was observed in Mg-44.3Al alloy at 573 K[1]. As an intermetallic with low density and high corrosion resistance, Mg-44.3Al alloy has a number of potential applications. However, its mechanical and other properties should be improved.

Thus far, several methods, such as micro/macro-alloying[3,4], microstructure control[5,6], and fiber reinforcement[7], have been used to improve the ductility of intermetallics[8]. Rare earth elements have been used in many alloys for performance improvement. Rare earth element addition can decrease the content of impurity elements in the melt to improve the corrosion resistance of the casting[9]. These rare earth elements are also combined with other elements to form new phases, which tend to precipitate first during the cooling process and result in grain refinement[10]. Rare earth elements have also been used to improve the properties of intermetallics. Sun et al. showed that Nd addition could improve the tensile strength of TiAl at room temperature and at 900 °C, as well as its creep resistance[11]. Y addition causes a grain refinement effect on the intermetallic TiAl, thereby improving its mechanical properties[12]. Guo et al. studied the effect of Y, Ce, Nd and Dy on the mechanical properties of NiAl alloy. Their results showed that all four elements can improve the room-temperature mechanical properties of NiAl, with Nd exhibiting the best performance among the said elements[5]. The effect of Nd on the mechanical properties of NiAl alloy was also confirmed by Ren et al.[6].

As an intermetallic phase, $Mg_{17}Al_{12}$ is always observed in the microstructure of Mg-Al alloys. The Mg-Al series alloy is the earliest binary alloy used for casting. Furthermore, most of the Mg-Al series alloys always contain other elements. The most typical series are Mg-Al-Zn and Mg-Al-Mn, which are the most widely used magnesium alloys in industrial production due to their high specific strength and specific stiffness, well castability, and damping and electromagnetic shielding properties[13]. However, because of their poor formability and corrosion resistance, application of these alloys has been limited to die-cast components, which must be subjected to a surface treatment before used. On the one hand, the researchers have been investigating the role of $Mg_{17}Al_{12}$ phase in the Mg-Al alloys. Generally, sec-

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ond-phase $Mg_{17}Al_{12}$ particles can give rise to various effects on the microstructure and texture evolution during thermomechanical processing, depending on the size and distribution of the particles. It was found that a large enough volume fraction of the β-$Mg_{17}Al_{12}$ phase (present in the AZ91 alloy) reduced twinning activity and promoted dynamic recrystallization, resulting in weak deformation textures at high strains[14]. Rare earths (RE) elements also have the ability to weaken the texture in Mg-Al alloys. It is likely that the boundary pinning caused by the RE elements in solid solution or in the form of particles plays an important role in the growth of different grain orientations[15]. One of the most important roles is that the adding of RE elements can improve the mechanical properties, such as wear resistance[16], fatigue properties[17] and tensile properties[18], of Mg-Al alloys. On the other hand, the corrosion resistance of the Mg-Al alloy is also affected by the volume fraction, distribution of the $Mg_{17}Al_{12}$ phase. With the increasing in Al content, the corrosion resistances of Mg-Al alloys are improved. For example, the mass losses of pure Mg and Mg-Al- Zn alloys, all of these alloys in the as-cast condition, follow the trend of pure Mg>AZ31>AZ91 in 3.5 wt.% NaCl solution[19]. The fabrication condition affects the microstructure of the alloy and then influences its corrosion resistance. The die-cast AZ91 alloy has a better corrosion resistance than as-cast one due to the network $Mg_{17}Al_{12}$ phase evenly distributing in the former[20]. Sometimes the distribution of the $Mg_{17}Al_{12}$ phase is more important than its volume fraction. AZ80 Mg alloy has a better corrosion resistance than AZ91 alloy in 3.5 wt.% NaCl solution[19]. In order to improve the corrosion resistance of Mg-Al alloys, adding RE is an effective method. Y, Nd, Gd, Dy, Er and Ce are always used to improve the corrosion resistance of the Mg-Al alloy[21,22].

However, the basic properties of the Mg-Al intermetallic are different from that of the Mg-Al alloys. As a potential structural or functional material, Mg-44.3Al alloy has always been studied as a hydrogen storage material[23–25]. In some investigations, Mg-44.3Al alloy was also used as a protective coating for Mg alloys[26]. Improving the properties of Mg-44.3Al alloy could make it a new material with low density, high hardness, and high corrosion resistance. However, a large number of experiments must be conducted to improve the performances of Mg-44.3Al alloy. This study aimed to focus on the effects of Er on the microstructures, composition, microhardness, electrochemical properties, and wear resistance of cast Mg-44.3Al alloy.

1 Experimental

Pure Mg (99.95 wt.%), pure Al (99.95 wt.%), and Mg-Er master alloy (Er content of 21.5 wt.%) were used as raw materials to prepare the Mg-xAl-yEr alloys (x=44.3, 44, 43.8, 43, 42; y=0, 0.5, 1.0, 3.0, 5.0. x and y represent the mass percentage of Al and Er element, respectively.) The raw materials were smelted in an electric resistance furnace. Dual-gas protection was ensured using SF_6 and Ar. Finally, the melt was cast in a low-carbon steel mold and cooled in air to room temperature.

Morphology observation and microstructure characterization of the specimens were performed using an MDS metallographic microscope and a JSM-6700F field emission scanning electron microscope (SEM, resolution ratio, 1 nm; accelerating voltage, 15 to 30 kV). The compositions of Mg-Al-Er alloys were analysed by TD3500 X-ray diffraction (XRD). The microhardness tests for the Er-containing alloys were performed using an HMV-2 micro-Vickers hardness tester. A loading force of 25 g was applied for 15 s. The electrochemical properties were analyzed using a PGSTAT30 electrochemical workstation. A three-electrode cell was employed in this test, where the sample was used as the working electrode, a saturated calomel electrode (SCE) was used as the reference electrode, and a platinum sheet was used as the counter electrode. The scanning rate was 1 mV/s. Based on the Tafel extrapolation method, the GPES software was used to measure the corrosion current density (I_{corr}) of the specimens. The friction coefficients of the alloys were recorded by a reciprocation wear tester (MFT-R4000), with a load of 5 N for 5 min.

2 Results

2.1 Microstructures of the Mg-Al-Er alloys

Fig. 1 shows the optical microstructures of the Mg-Al-Er alloys added with different contents of Er. The microstructure of the Mg-44.3Al alloy only consisted of coarse $Mg_{17}Al_{12}$ dendrites (Fig. 1(a)). The primary dendrite arm spacing is about 60 μm, and the arm spacing is 15 μm for the secondary dendrite. The black point in microstructure is not the second phase, which is caused by the metallographic etchant. With the addition of 0.5 wt.% Er, the microstructure of the Mg-44Al-0.5Er alloy showed granular Al_3Er intermetallic particles sparsely distributed in the $Mg_{17}Al_{12}$ matrix (Fig. 1(b)). Increasing the content of Er added in the Mg-43.8Al-1.0Er alloy increased the Al_3Er phase distribution in the matrix. Similar to the Mg-44Al-0.5Er alloy, only granular Al_3Er phases were observed in the Mg-43.8Al-1.0Er (Fig. 1(c)).

When the Er content was increased to 3.0 wt.%, several new worm-like microstructures (WLMs) were discontinuously distributed in the matrix (Fig. 1(d)). Unlike the two alloys described above, the Al_3Er phase in the Mg-43Al-3.0Er alloy was rod-like and granular in morphology (Fig. 1(d), site A). With the Er content increased to 5.0 wt.%, granular (Fig. 1(e), site B) and rod-like Al_3Er phases were also observed. The increase in Er