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Effect of Zn addition on microstructure and mechanical properties of as-cast Mg−2Er alloy

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Abstract: The effect of Zn addition on microstructure and mechanical properties of the Mg−2Er alloy was investigated by X-ray diffraction (XRD) and scanning electron microscope (SEM). The results show that the alloys with 1% and 2% Zn (mass fraction) are composed of the *W*-phase and the *α*-Mg matrix. Meanwhile, the addition of 4%−10% Zn results in the formation of the *I*-phase, the *W*-phase and the *α*-Mg matrix. When the addition of Zn reaches 12%, the *W*-phase disappears and the phase constituents of the alloys mainly include the *I*-phase and the Mg_4Zn_7 phase besides the *α*-Mg solid solution. The alloy containing 6% Zn has better mechanical properties, of which the ultimate tensile strength (UTS) and the yield tensile strength (YTS) are about 224 MPa and 134 MPa, respectively, companying an elongation of 10.4%.

Key words: Mg−Zn−Er alloy; secondary phase; microstructure; mechanical properties

1 Introduction

As the lightest metallic structural material, magnesium alloys have received great attention in the last decade because of their potential for use in automotive and aerospace applications [1,2]. However, magnesium alloys generally exhibit moderate strength with limited ductility at room temperature due to their HCP structure [3]. To the best of our knowledge, the addition of the rare earth (RE) elements to magnesium alloys can improve the mechanical properties [4−6]. It can be seen from the Mg–Er phase diagram that the equilibrium solid solubility of Er in magnesium is relatively high, i.e., 32.7% (mass fraction) at 584 °C and decreases exponentially to about 16% as temperature decreases to 200 °C, forming an ideal system for precipitation hardening. ZHANG et al [7] have reported that the addition of Er significantly increased the mechanical properties of Mg alloys.

Zn is generally used as alloying element for magnesium alloy to enhance room temperature strength. A small amount of Zn can be dissolved into Mg matrix as solution strengthening element, while excess Zn will react with Mg to form (Mg, Zn)-containing phases [8,9]. LUO et al [10] have reported that the mechanical properties of the Mg−0.2Ce alloy containing Zn were superior to those of the Zn-free alloy. However, the effect of Zn addition on the microstructure and mechanical properties of the Mg−Er system alloy has not been studied in detail. Therefore, in the present work, the effect of Zn on the microstructure and phase formation of the Mg−2Er alloy was investigated.

2 Experimental

The as-cast Mg−2Er−*x*Zn (*x*=0, 1%, 2%, 4%, 6%, 8%, 10% and 12%, mass fraction) alloys were prepared from the pure Mg (99.99%), pure Zn (99.9%) and Mg−30%Er master alloys in a graphite crucible in an electric resistance furnace under an anti-oxidizing flux. The melt about 1200 g was poured into a steel mold. At last, an ingot with dimensions of 33 mm×120 mm× 200 mm was obtained.

The chemical compositions of alloys were analyzed by X-ray fluorescence (XRF) analyzer, as shown in Table 1. The phase analysis was performed by X-ray diffraction (XRD) with Cu K_{α} radiation. The

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Table 1 Chemical compositions of as-cast Mg−2Er−*x*Zn alloys

Nominal alloy	*w*(Zn)/%	*w*(Er)/%	*w*(Zn)/*w*(Er)
Alloy 1	0	1.9	0
Alloy 2	1.0	2.2	0.45
Alloy 3	2.1	2.0	1.05
Alloy 4	4.0	2.1	1.90
Alloy 5	6.1	2.0	3.05
Alloy 6	7.9	2.0	3.95
Alloy 7	10.0	1.9	5.26
Alloy 8	12.0	2.0	6.00

Note: Magnesium as balance

microstructure observations were carried out by scanning electron microscope (SEM, HITACHI S−450) and transmission electron microscope (TEM, JEM−2000FX, JEOL). The samples for SEM were mechanically polished and etched in a solution of 4 mL nitric acid and 96 mL ethanol. Specimens for TEM were prepared by electro-polishing and ion beam milling at an angle of incidence less than 10°.

Tensile test was carried out by using a DNS−20 universal testing machine under a constant speed of 1.0 mm/min at room temperature. Specimens for the tensile test were made into dog-bone shape with a size of 5 mm gauge diameter and 25 mm gauge length. Three specimens were tested for each sample.

3 Results and discussion

3.1 Microstructure of as-cast Mg−2Er−*x*Zn alloys

Figure 1 displays the XRD patterns of the as-cast alloys with different Zn contents. It reveals that the alloy 1 mainly consists of *α*-Mg matrix. For alloys 2 and 3, the *w*(Zn)/*w*(Y) ratio is less than 2, and the main secondary phase is *W*-phase ($Mg_3Zn_3Er_2$). However, the main secondary phases in alloys 4, 5, 6 and 7 include the *W*-phase ($Mg_3Y_2Zn_3$) and *I*-phase ($Mg_3Zn_6Er_1$). When the *w*(Zn)/*w*(Er) ratio increases with the increasing addition of Zn, the strength of the diffraction peak of the *W*-phase gets gradually weak and the strength of the diffraction peak of the *I*-phase becomes intensive. When the content of Zn reaches 12% (*w*(Zn)/*w*(Er) ratio is 6), the *W*-phase disappears and the main secondary phases are the *I*-phase and Mg_4Zn_7. Therefore, the formation of the *I*-phase and *W*-phase depends on the *w*(Zn)/*w*(Er) ratio.

The SEM images of the as-cast alloys 1−8 are shown in Fig. 2. It can be seen that the microstructure of the alloy 1 is much coarser than those of alloys 2−8. In the Mg−2Er alloy, some bright phases which are the $Mg_{24}Er_5$ phases are observed. Adding 1% Zn, the fine granular and strip secondary phase is formed. According to the XDR result, the secondary phase is the *W*-phase. With the increase of Zn content, the volume fraction of the secondary phase as well as its size increases. When the content of Zn reaches up to 12% (*w*(Zn)/*w*(Er) ratio is 6), the dendritic spacing is about 40 μm, while the width of the strip secondary phase is 2−5 μm.

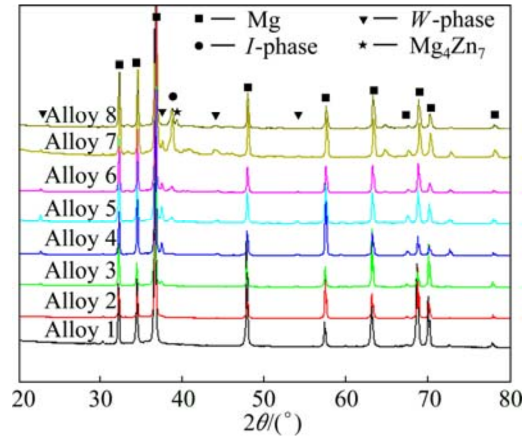

Fig. 1 X-ray diffraction patterns of as-cast Mg−2Er−*x*Zn alloys

To further confirm the existence of the *I*-phase, TEM observation was conducted for the as-cast Mg−2Er−12Zn alloy. Figure 3(a) shows the TEM image and the corresponding selected area diffraction pattern (SADP) of the *I*-phase. The SADP shows a distinct characteristic of the *I*-phase [3]. Figure 3(b) shows the TEM image of Mg−Zn phase. It indicates that the Mg_4Zn_7 phase appears in the as-cast Mg−2Er−12Zn alloy with a composition of $Mg_{41}Zn_{59}$ determined by EDS.

3.2 Mechanical properties of as-cast Mg−2Er−*x*Zn alloys

A comparison of the typical mechanical properties of all the alloys is shown in Fig. 4. The strength and elongation of the as-cast alloys tend to be improved with increasing Zn addition. The results show that the alloy 5 exhibits a higher strength, and the ultimate tensile strength (UTS) and tensile yield strength (TYS) are about 224 MPa and 134 MPa, respectively, with an elongation of 10.4%. Compared with the alloy 1, the TYS and UTS increase from 56 and 111 MPa to 134 and 224 MPa, respectively, when the content of Zn increases from 0 to 6%. Moreover, the elongation is nearly doubled. The improvement of mechanical properties of the alloys is mainly due to the strengthening effect of the secondary phase [11]. When the Zn content is in the range of 8%−12%, the content of the secondary phases (*W*-phase and *I*-phase) is high, and the size also becomes large. In the research of the cast Mg−Zn−Y−Zr alloys [12,13], it is suggested that the *α*-Mg/*I*-phase eutectic pockets could retard the basal slip and no cracks can be observed at the *α*-Mg/*I*-phase interface. However, the

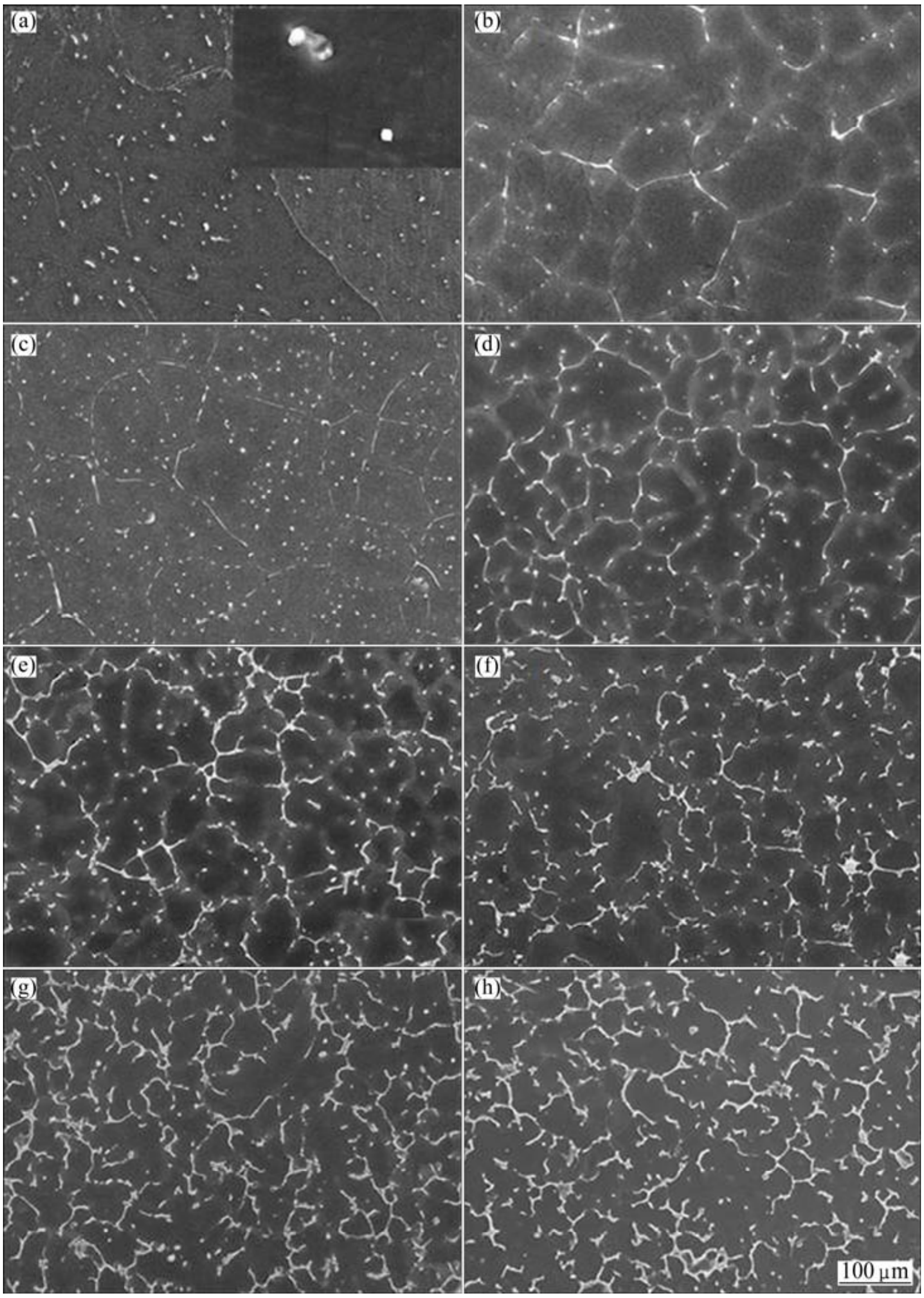

Fig. 2 SEM microstructures of as-cast Mg−2Er−*x*Zn alloys with different *x* values: (a) *x*=0; (b) *x*=1; (c) *x*=2; (d) *x*=4; (e) *x*=6; (f) *x*=8; (g) *x*=10; (h) *x*=12

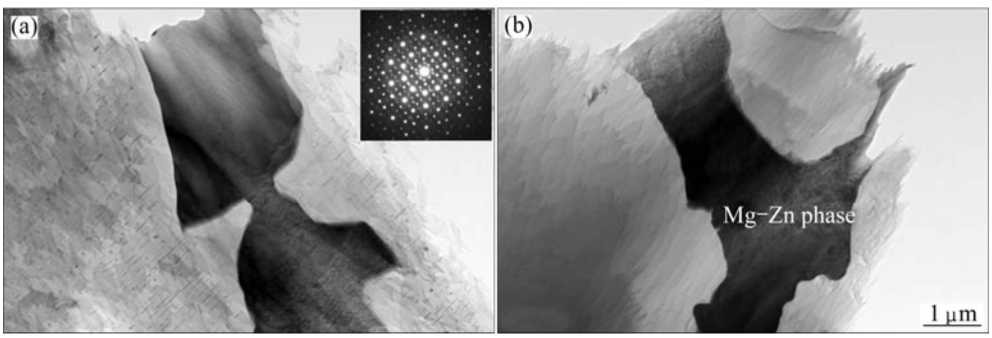

Fig. 3 TEM micrographs of as-cast Mg−2Er−12Zn alloy: (a) TEM image of I-phase and corresponding SAED pattern with five-fold symmetry; (b) TEM image of Mg−Zn phase

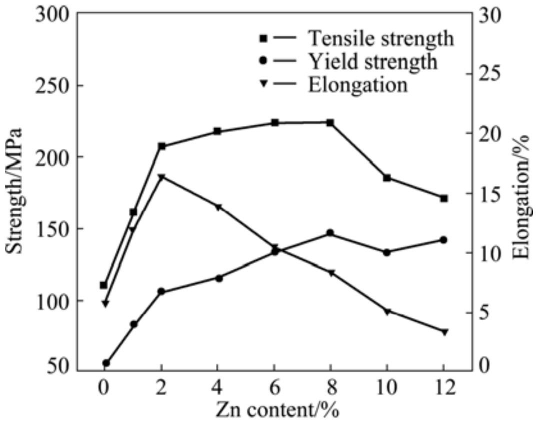

Fig. 4 Tensile properties of as-cast Mg−2Er−*x*Zn alloys

I-phase is brittle and hard to be deformed at room temperature [14]. Therefore, the *I*-phase may lead to an increment of crack sources because of its cracking. Furthermore, due to the cubic structure of the *W*-phase and the incoherency between *W*-phase and Mg matrix [15,16], the atomic bonding between *W*-phase and Mg matrix is weak. As a result, with the increase of the *W*-phase and *I*-phase content, the tensile strength of alloys would be improved unobviously and meanwhile the toughness decreases.

3.3 Fracture behavior

Figure 5 shows the typical room temperature tensile fracture surfaces of as-cast Mg−2Er−*x*Zn alloys observed

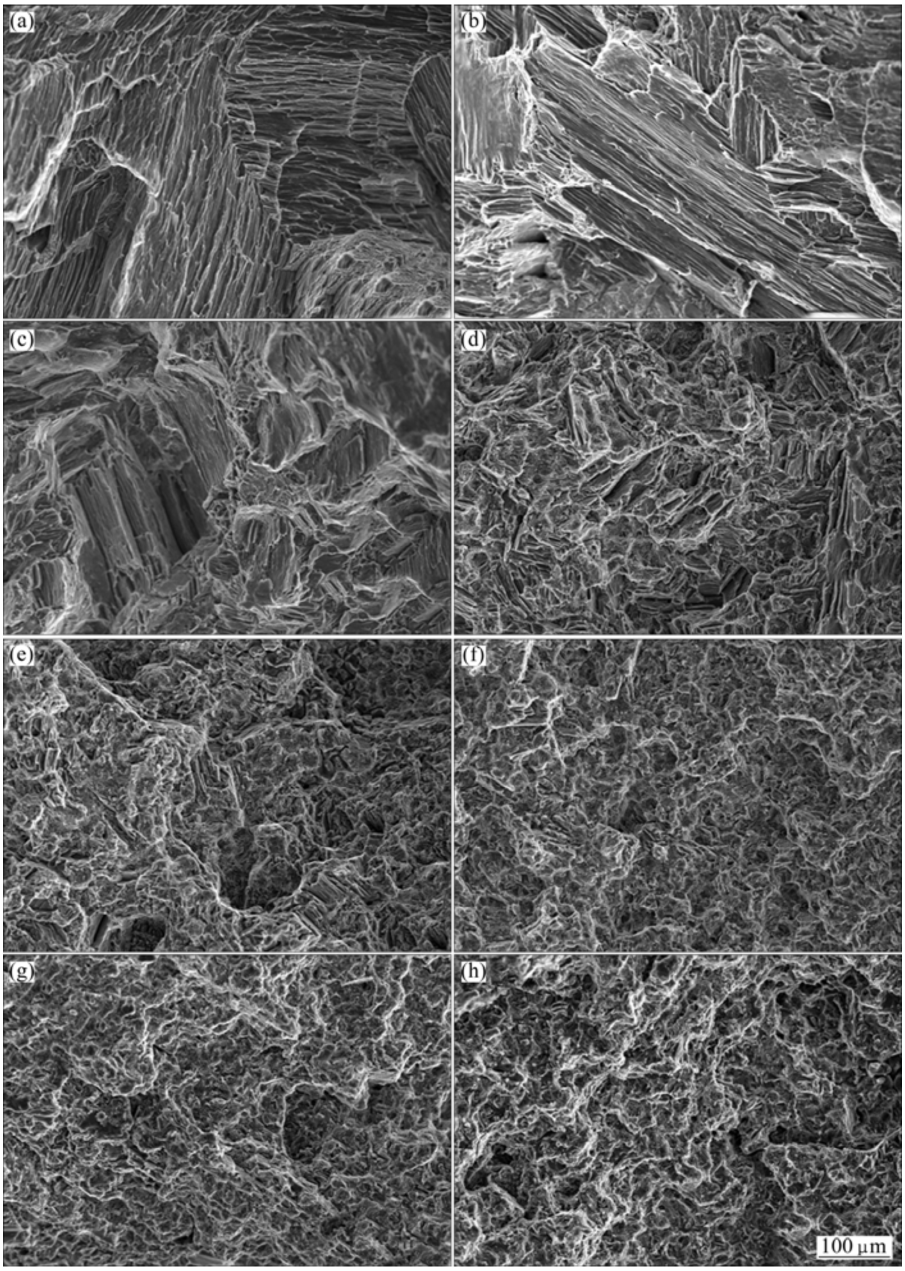

Fig. 5 SEM micrographs of fracture surfaces of as-cast Mg−2Er−*x*Zn alloys with different *x* values: (a) *x*=0; (b) *x*=1; (c) *x*=2; (d) *x*=4; (e) *x*=6; (f) *x*=8; (g) *x*=10; (h) *x*=12

by SEM. The figures indicate that the fracture behavior changes with variation of the alloy composition. When the alloy does not contain Zn, the main characteristics of the fracture surfaces of the studied alloys are cleavage fracture which are reflected by the cleavage planes and river pattern， as shown in Fig. 4(a). When the content of Zn addition is 1%−6%, some dimples and tearing ridges are observed, as shown in Figs. 5(b)−(e). Zn is added to form a secondary phase, and refine the grain size of alloys. Therefore, the alloy exhibits good ductility. When the content of Zn is above 8%−12%, serious segregation and aggregation of the secondary phases occur, causing the decrease of the amount of the dimples. A great amount of particle phases are observed on the fracture surfaces of alloys, as shown in Figs. 5(f)−(h). Therefore, there is a significant reduction in elongation.

4 Conclusions

1) When the Zn contents are 1% and 2%, the alloys mainly contain *W*-phase and α-Mg solid solution. Meanwhile, when the Zn content is 4%−10%, the *I*-phase will be formed together with the *W*-phase and α-Mg matrix. Furthermore, when the addition of Zn reaches 12% (w(Zn)/w(Er) ratio is 6), the *W*-phase disappears and the predominant secondary phases include the *I*-phase and Mg_4Zn_7.

2) Tensile results reveal that the alloy 5 (with Zn content of 6%) has better mechanical properties, and the UTS and TYS are about 224 and 134 MPa, respectively, with an elongation of 10.4%.

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Zn 含量对铸态 Mg−2Er 合金的微观结构及力学性能影响

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摘 要：采用 XRD 和 SEM 等微观表征技术研究不同 Zn 添加量对 Mg−2Er 合金微观组织和力学性能的影响。结果表明：当 Zn 添加量为 1%和 2%时，合金主要相组成为 *W* 相和 α-Mg；当 Zn 添加量为 4%~10%时，合金中则有 *I* 相析出，合金相成分变为 *W* 相、*I* 相和 α-Mg；当 Zn 添加量增加至 12%时，*W* 相消失，合金中主要第二相则为 *I* 相和 Mg_4Zn_7 相。当 Zn 添加量为 6%时，合金具有较好的拉伸力学性能，其抗拉强度、屈服强度和伸长率分别为 224 MPa、134 MPa 和 10.4%。

关键词：Mg−Zn−Er 合金；第二相；微观组织；力学性能

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